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RESEARCH ARTICLE

Research on the Influence of Drone Countermeasure Equipment on the Surveillance System Used in Civil Aviation

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ABSTRACT Due to the lack of perfect regulations and standards in civilian drones field, drones sometimes fly illegally. When illegally flying drones invade airports, which causes flights to be diverted and even airports to be paralyzed. In order to protect the flight safety, drone countermeasure equipment is need to use for driving away illegally flying drones. But drone countermeasure equipment is a new active interference source. When it is used at or around airports, which may cause electromagnetic interference to the surveillance system, and it will not work correctly. Therefore, it is necessary to study protective distances of the surveillance system. In this paper, a method for analyzing the electromagnetic interference influence of drone countermeasure equipment on the surveillance system is proposed. Firstly the radiated field strength of drone countermeasure equipment is measured in an anechoic chamber, and then stray radiation field strengths at frequency bands of a secondary surveillance radar (SSR) and an automatic dependent surveillance-broadcast (ADS-B) also are acquired. Meanwhile, test results are compared with protection requirements of electromagnetic environment of SSR and ADS-B. Moreover, electromagnetic interference effects of drone countermeasure equipment on SSR and ADS-B are analyzed according to the electromagnetic compatibility theory and protection ratios of SSR and ADS-B. At last, protective distances of SSR and ADS-B are proposed separately. The results can provide some technical supports for the safe use of drone countermeasure equipment at airports.

INDEX TERMS Drone countermeasure equipment, surveillance system, stray radiation, electromagnetic interference, protection ratio, protective distance.

I. INTRODUCTION

The surveillance system is widely used for air traffic control in civil aviation, and it mainly consists of the secondary surveillance radar (SSR) and the automatic dependent surveillance-broadcast (ADS-B) [1], [2], [3], [4]. SSR and ADS-B play a considerable role in the flight safety of civil aviation. Air traffic Controllers are able to obtain dynamic information of aircrafts through SSR and ADS-B, which mainly include aircraft call signs, secondary codes, distances and altitudes [5], [6], [7]. Based on the dynamic information of aircrafts, air traffic controllers can direct flights in correctly. However, signals of SSR and ADS-B are susceptible to electromagnetic interference in the process of transmission, which may results in reducing the accuracy of signals, and maybe the flight safety of civil aviation also is affected. Therefore, researches about the electromagnetic environment safety of SSR and ADS-B have a great significance.

With the rapid development of the economic and social, high-voltage power lines, highways, high speed railways and metros have been built near airports. All above can be consider as interference sources, which cause the electromagnetic environment of airports becoming more and more complex [8], [9]. Meanwhile, with the rapid development of radio technology, intelligent driving systems, industrial

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networks and drone countermeasure equipment are widely used. When those are used around airports, which also can be consider as interference sources. Those also makes the electromagnetic environment of airports progressively complex, and SSR and ADS-B may be easily subject to electromagnetic interference [10].

In order to ensure the safety of electromagnetic environment of SSR and ADS-B, some studies about that have been carried out. In the matter of researches of electromagnetic environment of SSR, the intensity of electromagnetic interference generated by electrified railways was measured, and then the interference field strength at the position of SSR was calculated. At last, the interference effect of electrified railways on SSR was analyzed [11]. Electromagnetic interference ranges of maglev trains to SSR were given, which included the active jamming and passive jamming [12]. When the airport highway was considered as an interference source, the protection distance of SSR was proposed [13]. A method for evaluating the effect of wind farms on SSR had been presented, and the influence range of wind farms on the SSR signal under different modes was quantitatively analyzed [14], [15]. The influence of geographical environment around SSR on the SSR signal was introduced, and the method to suppress false targets of SSR was proposed [16]. In the aspect of electromagnetic environment of ADS-B, electromagnetic interference types of ADS-B mainly included the suppression jamming, the deception jamming and the same frequency interference. The method of suppressing electromagnetic interference was also presented [17]. The radiation field intensity of the pantograph arcing was measured in a real situation, and the protection distance between railways and ADS-B also was calculated [18]. A performance evaluation model of ADS-B was established, which can analyze the signal quality of ADS-B under different geographical environments and interference environments [19]. The signal environment of 1090 MHz used by SSR and ADS-B was assessed through the analysis of signal rates and signal amounts [20].

Electromagnetic interference influences of common interference sources and geographical environments on SSR and ADS-B are analyzed in the above studies, and those does not involve drone countermeasure equipment. At present, when drone countermeasure equipment is working around airports, which has affected the safe flight of aircrafts. Such as, the ADS-B signal and GPS signal have been seriously interfered by drone countermeasure equipment, which cause aircrafts to go around or abort approach. Under the premise of ensuring flight safety, the problem of proper use of drone countermeasure equipment is need to be resolved immediately. However, drone countermeasure equipment is a new type of interference sources, electromagnetic radiation characteristics of drone countermeasure equipment are not aware. Meanwhile, a method for analyzing the electromagnetic interference influence of drone countermeasure equipment on SSR and ADS-B is lacking. Moreover drone countermeasure equipment will be need to use at airport in order to protect the safety of airfield clearance zone [21]. Therefore, the research about influences of drone countermeasure equipment on SSR and ADS-B is of great significance. The safe use distance of drone countermeasure equipment can be clarified through this study.

FIGURE 1. The real picture of drone countermeasure equipment.

TABLE 1. Key Performance Indicators of Drone Countermeasure Equipment.

Interference frequency bands (MHz)	Interference powers (dBm)	Interference distances (m)
1550-1625	36	1500
2400-2500	45	1500
5700-5900	43	1500

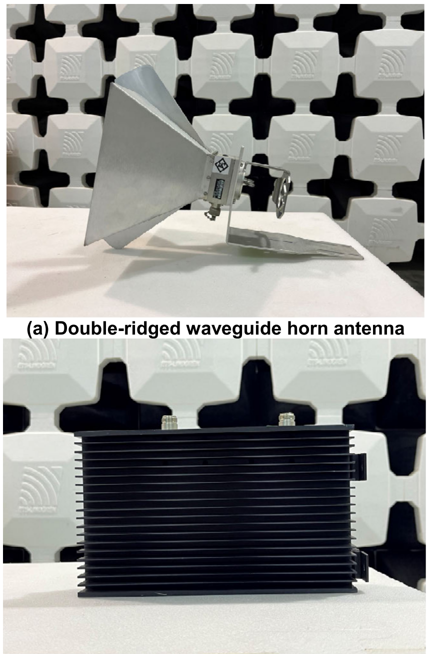
In this paper, firstly the electromagnetic radiation field strength of drone countermeasure equipment is measured base on the anechoic chamber. Then stray radiation field strengths at frequency bands of SSR and ADS-B are gained. At the same time, protection requirements of electromagnetic environment of SSR and ADS-B are presented. Moreover electromagnetic interference effects of drone countermeasure equipment on SSR and ADS-B are analyzed base on the electromagnetic compatibility theory. At last, protective distances of SSR and ADS-B are calculated according to above measured values and protection ratios of SSR and ADS-B.

II. EXPERIMENTAL SETUP

A. DRONE COUNTERMEASURE EQUIPMENT

As shown in Figure 1, the real picture of drone countermeasure equipment is given. It can transmit high-power jamming signals, which results in blocking remote links, graph links and navigation signals of unmanned aerial vehicle (UAV). At last, UAV will be forced landing and driven away. In addition, the rotation range of that is 360 degrees, and the pitch angle range of that is from -35 degrees to 65 degrees.

Key performance indicators of drone countermeasure equipment are given in Table 1. Those mainly include interference frequency bands, interference powers and interference distances.



(a) Double-ridged waveguide horn antenna

(b) Coaxial fixed attenuator

FIGURE 2. The real picture of the testing antenna and attenuator.

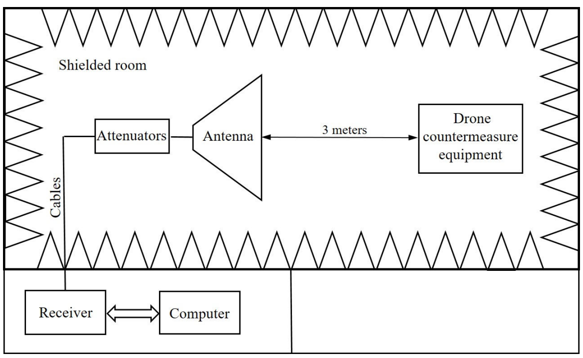


FIGURE 3. The testing method of electromagnetic radiation field strength of drone countermeasure equipment.

B. TESTING EQUIPMENT AND METHODS

The radiated emission test of drone countermeasure equipment has been carried out in the anechoic chamber. The geometric dimension of an anechoic chamber is 12m x 8m x 6m. Based on frequency ranges of drone countermeasure equipment, SSR and ADS-B, a double-ridged waveguide horn antenna (HF907, R&S) is used for the test. The frequency range of that is from 800MHz to 18GHz, and the gain of that is 5dBi. To ensure the safety of the test system, two models of attenuators (150-A-FFN-06, Bird; 150-A-FFN-20, Bird) are used for the test. The power rating of those is 150W, and standard attenuation values of those are 6dB and 20dB in several. Real pictures of the testing antenna and attenuator are shown in Figure 2.

The testing method of electromagnetic radiation field strength of drone countermeasure equipment is as shown in Figure 3.

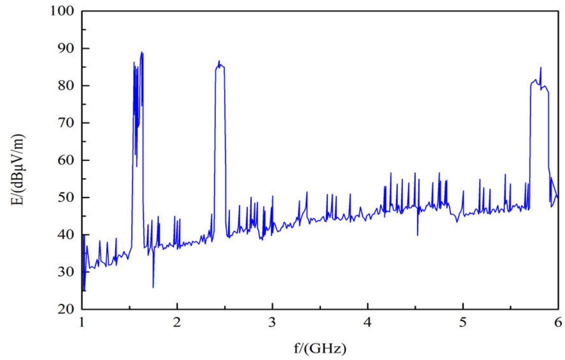


FIGURE 4. The result of radiation field intensity of drone countermeasure equipment.

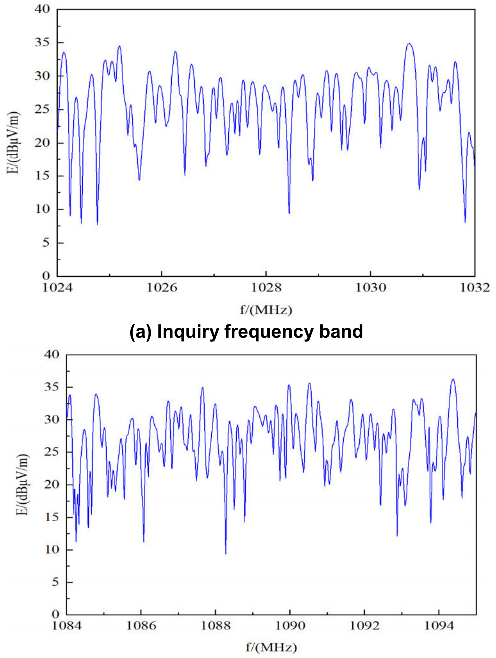
It can be clearly seen that the measuring distance between drone countermeasure equipment and an antenna is 3 meters. The antenna is fixed on a lifting platform, and the movement range of that in the vertical direction is set from 2 meters to 4 meters. Two types of attenuators are connected in series in the test loop. On the basis of GB/T12572-2008, the resolution bandwidth of a receiver is set to 1 MHz due to frequency bands of drone countermeasure equipment, SSR and ADS-B are larger than 1GHz. Meanwhile the detection mode of a receiver is set to a peak detection, and the data storage mode is set to a maximum peak hold. Moreover, polarization modes of an antenna are set to a horizontal polarization and a vertical polarization respectively. As we know, drone countermeasure equipment opens all interference frequency bands in practical use in order to achieve a good counter-drone effect. So, all interference frequency bands also are open in the test. In addition, test values have been converted from voltage values of a receiver to field strength values through a testing software. Due to the use of attenuators, the actual value of electromagnetic radiation field strength of drone countermeasure equipment is equal to the test value plus the attenuation value.

III. TEST RESULTS

Test results include two parts: first radiation field strengths of interference frequency bands of drone countermeasure equipment; Second stray radiation field strengths at frequency bands of SSR and ADS-B. Above test results have been measured in several times, which are as follows.

A. RADIATION FIELD STRENGTHS OF DRONE COUNTERMEASURE EQUIPMENT

As shown in Figure 4, the result of radiation field intensity of drone countermeasure equipment is given while the polarization mode of an antenna is vertical polarization. It can be easily found that curves of the test result have several obvious peaks at interference frequency bands of drone countermeasure equipment. Then maximum values at peaks can be obtained through the analysis software. When interference frequency bands are 1613.88MHz, 2441.28MHz and 5818.11MHz, maximum values of radiation field strengths



(a) Inquiry frequency band

(b) Response frequency band

FIGURE 5. Stray radiation field strengths in frequency bands of SSR.

TABLE 2. Electromagnetic Environmental Requirements of SSR and ADS-B.

Supervising device types	Operating frequencies (MHz)	Maximum allowable interference field strengths (dBm)
SSR	1030	-81
SSR	1090	-95
ADS-B	1090	-95

are 87.16dBμV/m, 86.70dBμV/m and 84.96dBμV/m severally. In the test loop, the attenuation value of the signal field strength is 26dB. Therefore, actual values of radiation field strengths of drone countermeasure equipment are 113.16dBμV/m, 112.70dBμV/m and 110.96dBμV/m respectively. It follows that the field strength at interference frequency bands is very strong.

As is well known to all, the L1 band used by a GPS system has a frequency of 1575.42MHz. Compared with Table 1, interference frequency bands of drone countermeasure equipment contain the L1 band. Meanwhile GPS signals are highly susceptible to interference because of the power of that is very low [22]. Moreover, the positioning information of a plane needed for ADS-B comes from the GPS signal. Thus, we can speculate that signals of ADS-B and GPS may be interrupted when drone countermeasure equipment is used in or around airports.

B. STRAY RADIATION FIELD STRENGTH S IN FREQUENCY BANDS OF SSR AND ADS-B

It is known that SSR mainly consists of a ground interrogator and an airborne transponder. The frequency of a ground interrogator is 1030MHz, and the frequency of an airborne transponder is 1090MHz. Results of stray radiation field strengths in above frequency bands are shown in Figure 5, and the polarization mode of an antenna is vertical polarization. It can be found that there are significant fluctuations of curves. The maximum value of the stray radiation field strength in frequency band of a ground interrogator is 34.91dBμV/m, and the corresponding frequency value is 1030.74MHz. Meanwhile the maximum value of the stray radiation field strength in frequency band of an airborne transponder is 35.68dBμV/m, and the corresponding frequency value is 1090.52MHz. Subsequently, actual values of stray radiation field strengths are 60.91dBμV/m and 61.68dBμV/m respectively. Finally, those are need to be compared with the maximum allowable interference field strength of SSR. Based on the comparison result, we can determine whether SSR is subject to electromagnetic interference. The detailed analysis of that will be presented in Section IV.

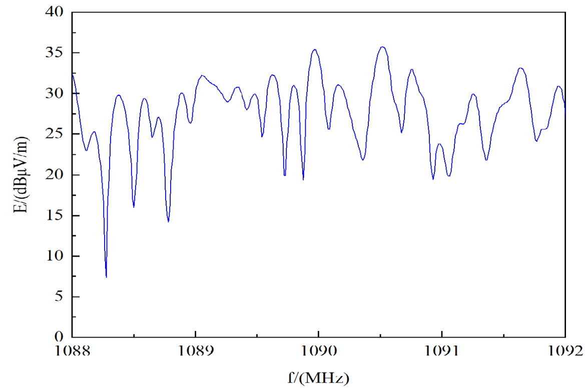


FIGURE 6. Stray radiation field strengths in frequency bands of ADS-B.

As we known, the data link of ADS-B is typically 1090MHz extended message, which is as the same as the frequency band of an airborne transponder of SSR. When the polarization mode of an antenna is vertical polarization, the result of the stray radiation field strength in frequency band of ADS-B is presented in Figure 6. It can be seen that the trend of a curve also is fluctuating. The maximum value of the stray radiation field strength in the frequency band of ADS-B is 35.75dBμV/m, while the frequency is 1090.51MHz. Then the actual value of that is 61.75dBμV/m, which has little difference with the actual value of the stray radiation field strength of an airborne transponder of SSR. The electromagnetic interference analysis of ADS-B will also be given at length in Section IV.

IV. ELECTROMAGNETIC INTERFERENCE ANALYSES

A. ELECTROMAGNETIC ENVIRONMENTAL REQUIREMENTS OF SSR AND ADS-B

In order to ensure the flight safety of civil aviation, electromagnetic environmental requirements of the SSR and ADS-B are very demanding. According to MH/T4046-2017, maximum allowable interference field strengths of those are shown in Table 2.

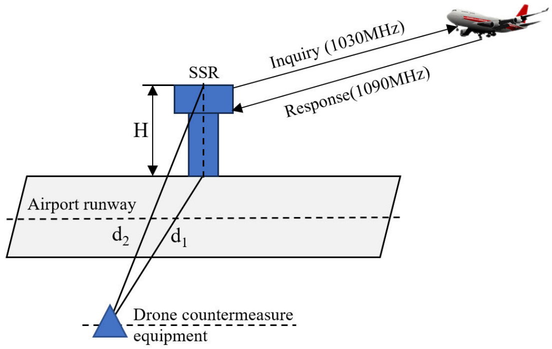


FIGURE 7. Diagram of the relative position of SSR and drone countermeasure equipment.

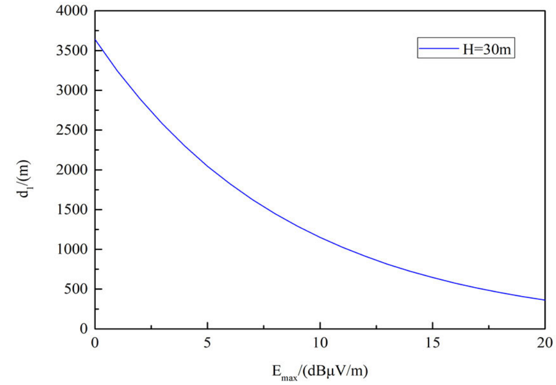


FIGURE 8. Changes of d_1 with an increase of E_{max}.

Because units of the actual value and the maximum allowable interference field strength are inconsistent, and then the unit of the latter needs to be converted from dBm to dBμV/m. The formula for the unit conversion is as follows.

$$P = U - 107 \tag{1}$$

In the equation (1), P is the signal power, and the unit of that is dBm. U is the signal voltage, and the unit of that is dBμV.

$$E = U + AF \tag{2}$$

In the equation (2), E is the field strength of a signal, and the unit of that is dBμV/m. AF is the antenna factor, and the unit of that is dB/m.

$$AF = 20log(f) - G_A - 29.78 \tag{3}$$

In the equation (3), f is the frequency of an antenna, and the unit of that is MHz. G_A is the antenna gain, and the unit of that is dB. At present, electromagnetic interference researches of SSR and ADS-B are mainly to analyze the interference effect of ground stations. Then the value of f is 1090MHz. Meanwhile, the antenna gain of SSR is about 27dB according to MH/T4010-2016. Afterwards, the antenna gain of a ground station of ADS-B usually is about 12dB [23]. At last, results of the unit conversion are 15.97dBμV/m and 30.97dBμV/m respectively. In Section III, actual values of stray radiation field strengths in frequency bands of SSR and ADS-B separately are 61.68dBμV/m and 61.75dBμV/m. By comparison, actual values are about two to three times maximum allowable interference field strengths. In other words, SSR and ADS-B will be subject to the serious electromagnetic interference, when drone countermeasure equipment is not used properly in or around airports. Therefore, it is necessary to propose protection distances of SSR and ADS-B.

B. ELECTROMAGNETIC INTERFERENCE ANALYSIS OF SSR

As shown in Figure 7, the relative position of SSR and drone countermeasure equipment is clearly provided. It can be easily found that the height difference between drone countermeasure equipment and the antenna of a ground station of SSR is set as H in the vertical direction. Then the distance in the horizontal direction from drone countermeasure equipment to the SSR is set as d_1. Meanwhile the distance between drone countermeasure equipment and the antenna of a ground station of SSR is set as d_2. At last, the working process of SSR also is given in the picture below.

According to the theory of radio wave propagation, the field strength of a signal when the radio wave propagates in free space can be calculated by the equation (4) [24]. In the following equation, where E is the signal field strength, and the unit of that is dBμV/m. Then P is the radiation power, and the unit of that is W. d is the propagation distance of a signal, and the unit of that is km. G is the antenna gain, and the unit of that is dB.

$$E = 74.77 + 10logP + G - 20logd \tag{4}$$

Based on the equation (4), the equation (5) can be derived as shown in follows. Then, E_s is the actual value of the stray radiation field strength in the frequency band of SSR, and d_s is the distance from drone countermeasure equipment to the testing antenna as shown in Figure 3. Values of those are 61.68dBμV/m and 3 meters. Meanwhile d_x is equal to d_2. What's more, E_x is the field strength of the interference signal at the antenna of a ground station of SSR.

$$E_x = E_s + 20log(d_s/d_x) \tag{5}$$

According to Figure 7, d_2 can be calculated by the equation (6).

$$d_2 = \sqrt{d_1^2 + H^2} \tag{6}$$

When the value of E_x is less than or equal to the maximum allowable interference field strength of SSR (E_{max}), and SSR will not suffer the electromagnetic interference. The calculation expression of d_2 can be obtained from the above equations, which is shown in the equation (7).

$$d_1 \geq \sqrt{10^{\frac{61.68+20\log 3 - E_{max}}{10}} - H^2} \tag{7}$$

In order to facilitate the analysis, the value of H is assumed to 30 meters. Then the change between d_1 and E_{max} is shown

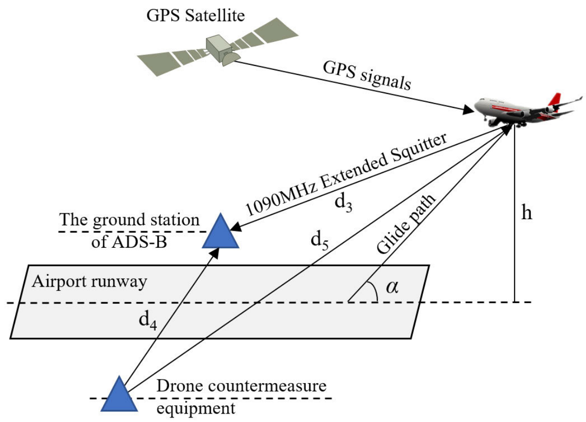


FIGURE 9. Diagram of the relative position of a ground station of ADS-B and drone countermeasure equipment.

in Figure 8. It can be clearly seen that the value of d_1 decreases with the increase of E_{max}. In other words, the value of maximum allowable interference field strength of SSR is greater, and the operating distance of drone countermeasure equipment is less. While the value of E_{max} is 15.97dBμV/m, the value of d_1 is 577.98 meters. Therefore, When the distance from drone countermeasure equipment to SSR is greater than 577.98 meters, SSR will not suffer the electromagnetic interference. In addition, the value of H should be determined according to the actual situation.

C. ELECTROMAGNETIC INTERFERENCE ANALYSIS OF ADS-B

As we know, the ADS-B system is mainly composed of an airborne transmitting equipment and a ground receiving equipment, and the working process of that is as follow. First, the position information of an airplane is obtained through Global Navigation Satellite System (GNSS), and the air pressure and altitude information of an airplane is acquired by means of the barometer and the altimeter. Then, the above information is integrated to form ADS-B data packets, which are periodically broadcast outwards through the airborne transmitting equipment. Whereafter, the ground receiving equipment receives ADS-B data packets, and those are processed to display the flight status of aircrafts on the screen. At last, air traffic controllers can know the flight status of each aircraft in real time, and the proper direction will be given to pilots. So, the electromagnetic interference analysis of ADS-B include the interference of GPS signal and ground receiving equipment.

As shown in Figure 9, the relative position of a ground station of ADS-B and drone countermeasure equipment is given. As can be seen from the figure below, the distance from the airplane to a ground station of ADS-B is set as d_3. Then the distance between drone countermeasure equipment and a ground station of ADS-B is set as d_4. Moreover, the distance from the airplane to drone countermeasure equipment is set as d_5. In addition, the flight altitude and the gliding angle of the airplane are set as h and α respectively.

As is known to all, the power of a GPS signal is lower, which is highly susceptible to interference, and the value of that is about −158dBW [17]. When the GPS signal is severely interfered, the signal of ADS-B will be interrupted. In other words, while drone countermeasure equipment is emitting high-powered suppression signals to interfere with a GPS signal, the signal of ADS-B will become abnormal or ineffective. After the unit conversion, the power of a GPS signal is about −128dBm. Meanwhile, the gain of spreading codes of a GPS signal is 43dB. The effective jamming power of a GPS signal is equal to the power of a GPS signal plus the gain of spreading codes of a GPS signal [25]. So, the calculation result of that is −85dBm. As shown in Table 1, the interference power of drone countermeasure equipment at the frequency band of GPS is 36dBm. At last, the difference value between the interference power and the effective jamming power of a GPS signal is 121dB.

An expression for calculating the propagation loss of radio waves in free space is shown in equation (8) [26].

$$L = 32.45 + 20log(f_0) + 20log(d_5) \tag{8}$$

In the above equation, where L is the propagation loss of radio waves, and the unit of that is dB. Then f_0 is the interference frequency band of drone countermeasure equipment, and the value range of that is from 1550MHz to 1625MHz. When the power of an interference signal after propagating a distance of d_5 is less than or equal to the effective jamming power of a GPS signal, signals of GPS and ADS-B may not be affected. So, the value of L is about 121dB. By calculation, the value range of d_5 is from 16.47km to 17.27km. It can be seen that the interference range of a GPS signal is very large. Therefore, when drone countermeasure equipment is used in or around airports, the interference frequency band from 1550MHz to 1625MHz must be shut down.

The electromagnetic interference effect of drone countermeasure equipment on the ground receiving equipment of ADS-B is analyzed as follows. First, the received signal strength (E_1) of the ground receiving equipment can be calculated based on the equation (4). P is the power of an airborne transmitting equipment, and the value of that is 250W. G is the antenna gain, and the value of that is 3dB [27]. So, E_1 is expressed by the equation (9).

$$E_1 = 125.73 - 20logd_3 \tag{9}$$

Then, the interference signal field strength (E_2) of the ground receiving equipment can be calculated based on the equation (5). E_2 is expressed by the equation (10).

$$E_2 = 61.75 + 20log(3/d_4) \tag{10}$$

When the difference between E_1 and E_2 is equal or greater than the protection ratio (R) of the ground receiving equipment, which will not suffer the electromagnetic interference. The expression is as shown in equation (11).

$$E_1 - E_2 \geq R \tag{11}$$

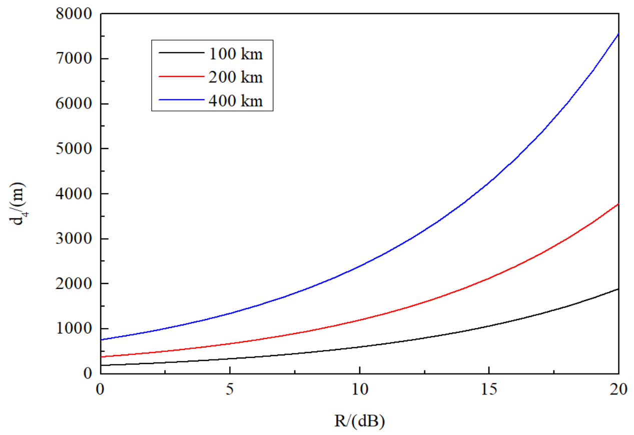


FIGURE 10. Changes of d_4 with an increase of R.

According to the above formulas, the expression of d_4 can be as shown in equation (12).

$$d_4 \geq 10^{\frac{R}{20}+logd_3+log3-3.2} \tag{12}$$

The change of d_4 with an increase of R is shown in Figure 10, and while values of d_3 are severally assumed to 100km, 200km and 400km. It can be easily found that d_4 significantly increases with the increase of R, and those are in direct proportion.

Meanwhile d_4 also obviously increases with the increase of d_3, when the value of R is changeless. That is to say, when the value of d_3 is larger, and the value of E_1 is less. The protection distance of the ground receiving equipment is need to be greater. While the value of d_3 is maximum, the protection distance can be calculated. The value of protection ratio of the ground receiving equipment is 8dB, and the maximum distance between a ground receiving equipment and an airborne transmitting equipment is about 370km [16]. So, the value of protection distance is about 1759.23 meters. When the value of d_4 is great than or equal to 1759.23 meters, the ground receiving equipment of ADS-B will not be affected by the electromagnetic interference. In addition, when drone countermeasure equipment is selecting a location on or around airports, protection distances of SSR and ADS-B are need to be considered simultaneously.

V. CONCLUSION

This paper presents a method to evaluate the electromagnetic interference effect of drone countermeasure equipment on the surveillance equipment. Detailed, stray radiation field strengths at frequency bands of the SSR, ADS-B and GPS are ascertained by the experimental test. Then electromagnetic interference effects of drone countermeasure equipment on the SSR and ADS-B are analyzed through theoretical analysis. Finally protection distances of the SSR and ADS-B are given. The major conclusions are given as follows:

1) Field strengths of spurious radiation at frequency bands of SSR and ADS-B are much greater than maximum allowable interference field strengths of those. The former is about two to three times the latter. Especially in the frequency band of GPS signals, the field strength of interference signals can reach about 113.16dBμV/m, and the interference range is about 17km. Therefore when drone countermeasure equipment is used in airports, SSR and ADS-B cannot work correctly.
2) When the height difference between drone countermeasure equipment and an antenna of SSR is 30 meters, the protection distance of SSR is about 577.98 meters. While the protection ratio of a ground station of ADS-B is 8dB, and the maximum effective propagation distance of ADS-B is 370km, the protection distance of ADS-B is about 1759.23 meters. It is worth noting that requirements of protection distances of those must be met simultaneously.
3) This work will be useful to the site selection of drone countermeasure equipment, while it is used at or around airports. The results may promote the application of drone countermeasure equipment in civil aviation.

REFERENCES

[1] V. Schejbal, P. Bezousek, J. Pidanic, and M. Chyba, "Secondary surveillance radar antenna [antenna designer's notebook]," *IEEE Antennas Propag. Mag.*, vol. 55, no. 2, pp. 164–170, Apr. 2013, doi: 10.1109/MAP.2013.6578015.
[2] S. Chiocchio, A. Persia, F. Santucci, F. Graziosi, M. Pratesi, and M. Faccio, "Modeling and evaluation of enhanced reception techniques for ADS-B signals in high interference environments," *Phys. Commun.*, vol. 42, Jul. 2020, Art. no. 101171, doi: 10.1016/j.phycom.2020.101171.
[3] S. Rudys, J. Aleksandravicius, R. Aleksiejunas, A. Konovaltsev, C. Zhu, and L. Greda, "Physical layer protection for ADS-B against spoofing and jamming," *Int. J. Crit. Infrastruct. Protection*, vol. 38, Sep. 2022, Art. no. 100555, doi: 10.1016/j.ijcip.2022.100555.
[4] M. R. Manesh and N. Kaabouch, "Analysis of vulnerabilities, attacks, countermeasures and overall risk of the automatic dependent surveillance-broadcast (ADS-B) system," *Int. J. Crit. Infrastruct. Protection*, vol. 19, pp. 16–31, Dec. 2017, doi: 10.1016/j.ijcip.2017.10.002.
[5] F. Le Neindre, G. Ferre, D. Dallet, F. Letellier, and K. Pitois, "A successive interference cancellation-based receiver for secondary surveillance radar," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 59, no. 2, pp. 805–816, Apr. 2023, doi: 10.1109/TAES.2022.3193649.
[6] T. Li, B. Wang, F. Shang, J. Tian, and K. Cao, "Threat model and construction strategy on ADS-B attack data," *IET Inf. Secur.*, vol. 14, no. 5, pp. 542–552, Sep. 2020, doi: 10.1049/iet-ifs.2018.5635.
[7] *Annex 10, Volume IV, Surveillance and Collision Avoidance Systems*, ICAO, Montreal, QC, Canada, 2014.
[8] Z. Y. Liu, "Electromagnetic environment testing and interference diagnosis for aeronautical ground station," M.S. thesis, School Inf. Commun. Eng, Dalian Univ. Tech, Dalian, China, 2014.
[9] Z. Wu, T. Shang, and A. Guo, "Security issues in automatic dependent surveillance–broadcast (ADS-B): A survey," *IEEE Access*, vol. 8, pp. 122147–122167, 2020, doi: 10.1109/ACCESS.2020.3007182.
[10] Y. Wu, "The influence of urban development on airport electromagnetic environment and its management," *J. Civil Avn.*, vol. 3, no. 1, pp. 5–8, Jan. 2019.
[11] D. Han and H. Jiang, "Electromagnetic environment assessment and analysis of secondary surveillance radar under the influence of electrified railway," *Value Eng.*, vol. 38, no. 12, pp. 152–154, Dec. 2019, doi: 10.14018/j.cnki.cn13-1085/n.2019.12.047.
[12] D. Han, H. Jiang, and X. J. Yang, "An electromagnetic environment assessment method for civil aviation radars," *Ct. Eng.*, vol. 56, no. 5, pp. 585–590, May 2016, doi: 10.3969/j.issn.1001-893x.2016.05.019.
[13] F. Duan and J. Huang, "Safety analysis and research on secondary surveillance radar site based on electromagnetic environment," *China Meas. Tes.*, vol. 43, no. 10, pp. 28–31, Oct. 2017, doi: 10.11857/j.issn.1674-5124.2017.10.006.

[14] R. B. Wu, H. Z. Fu, X. L. Wang, and Q. Q. Jia, "Impact assessment of wind farms on secondary surveillance radar utilizing signal characteristics," *J. Civil Avn. Univ. China*, vol. 31, no. 6, pp. 1–4, Dec. 2013.
[15] R. B. Wu, C. X. Ma, X. L. Wang, and W. K. He, "Analysis of impact of wind farms on the mode S secondary surveillance radar in air traffic control," *J. Elec. Inf. Tech.*, vol. 39, no. 8, pp. 1887–1893, Aug. 2017.
[16] W. Wang, "Thales secondary radar interference and false target suppression in Xining Airport," M.S. thesis, School Inf. Sci. Eng, Lanzhou Univ, Lanzhou, China, 2018.
[17] Q. Y. Wang and Y. Y. Zhou, "Research on electromagnetic interference in ADS-B system," *J. Civil Avn.*, vol. 7, no. 1, pp. 56–59, Jan. 2023, doi: 10.3969/j.issn.2096-4994.2023.01.012.
[18] Z. Y. Liu, Y. C. Liu, F. Zhu, H. D. Lu, and L. Lin, "Test and analysis of off-line arc in pantograph catenary on electromagnetic disturbance of airport ADS-B ground station system," *J. Elec. Meas. Inst.*, vol. 32, no. 2, pp. 56–61, Feb. 2018, doi: 10.13382/j.jemi.2018.02.009.
[19] Q. Q. Sun, "The key technologies research on ADS-B performance evaluation and promotion under complicated electromagnetic environment," M.S. thesis, School Inf. Commun. Eng, Univ. Electron. Sci. Technol. China, Chengdu, China, 2016.
[20] J. Honda, Y. Kakubari, and T. Otsuyama, "Estimation of 1090 MHz signal environment on airport surface by using multilateration system," in *Proc. Int. Appl. Comput. Electromagn. Soc. Symp. (ACES)*, Denver, CO, USA, Mar. 2018, pp. 1–2, doi: 10.23919/ROPACES.2018.8364281.
[21] J. Ye, J. Zou, J. Gao, G. Zhang, M. Kong, Z. Pei, and K. Cui, "A new frequency hopping signal detection of civil UAV based on improved K-means clustering algorithm," *IEEE Access*, vol. 9, pp. 53190–53204, 2021, doi: 10.1109/ACCESS.2021.3070491.
[22] R. Zhao, "Time-frequency domain analysis and evaluation of satellite navigation civil signals," M.S. thesis, Sino-European Inst. of Avn. Eng, Civil Aviation Univ. China, Tianjin, China, 2020.
[23] T. Zhong, "Analysis of lightning protection technology for ADS-B equipment," *China Sci. Tech. Inf.*, vol. 18, pp. 1–3, Sep. 2022.
[24] Y. H. Wen, "Free space and space wave propagation modes," in *Theory of Radio Wave Propagation*, 11th ed. Beijing, China: China Machine Press, 2013, pp. 42–43.
[25] D. G. Li, J. H. Lu, and X. Y. Ren, "Discussion on the causes of flight GPS interference and preventive measures," *China Rdo*, vol. 5, pp. 73–76, May 2022, doi: 10.3969/j.issn.1672-7797.2022.05.047.
[26] H. Gao and J. Yang, "A method of simulation of signal coverage about ADS-B ground station," *Inf. Tech. Informatization*, vol. 9, pp. 140–143, Sep. 2019, doi: 10.3969/j.issn.1672-9528.2019.09.045.
[27] Q. Cheng, H. R. Zhang, and W. Zhang, "Simulation study on layout of ADS-B ground station," *Comp. Sim.*, vol. 32, no. 5, pp. 19–23, May 2015, doi: 10.3969/j.issn.1006-9348.2015.05.005.

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