Study of DME Signal Strength Problem in Approach Direction

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ABSTRACT

Starting from the theory of phase superposition of radio wave specular reflection, the causes of DME signal intensity depression in the mid-long distance, which is common during flight inspection of GP DME, are deeply analyzed and studied. The variable conditional path gain Equation is derived by using the double line model and Snell's Law. By establishing the mathematical simulation model of MATLAB and comparing with the actual flight inspection results, Finally, it is found that the phase superposition of the direct signal of the gliding DME antenna and the ground reflected signal at a specific position in the air is the main reason for the depression of the GP DME signal strength at the mid-long distance, and an effective solution to eliminating the signal strength out of tolerance at a specific position is proposed.

INTRODUCTION

The inspection of DME signal strength is one of the most important subjects in the flight inspection subjects of DME equipment. Whether the flight inspection result of glide path DME (GP DME) signal strength is ideal directly affects the coverage distance of the equipment, the reliability of the equipment and the flyability of the flight procedure. In recent years, with the continuous increase in the number of GP DME equipment, it has become a common phenomenon for flight inspectors to find that the signal strength of GP DME is sunken in the middle and long distance during the flight inspection (see Fig. 1).

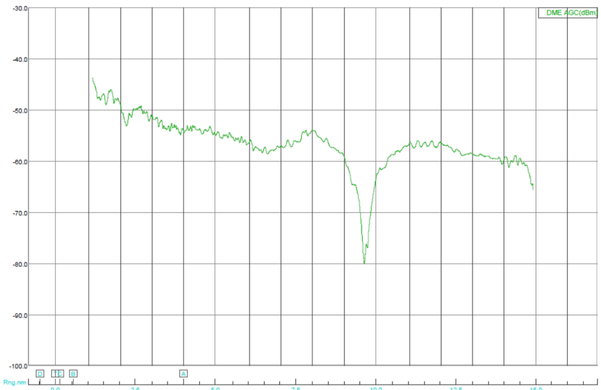

Figure 1 DME Signal Strength in Flight Inspection

In order to find out the root cause of the depression in the medium and long distance of the GP DME signal strength, the author has carried out a long-term and in-depth study on this problem. Based on the theory of phase superposition of radio wave specular reflection and the antenna radiation theory, the variable conditional path gain Equation is derived by Two-Ray model and Snell's Law. Through the establishment of MATLAB mathematical simulation model and the comparison with the actual flight inspection results, it is finally found that the phase superposition of the direct signal of the GP DME antenna and the ground reflected signal at a specific position in the air is the main reason for the depression of the GP DME signal strength in the middle and long distance.

As a ranging equipment for land-based navigation, DME plays an important role in the field of positioning and navigation [1-3]. According to the draft global air navigation plan released by the International Civil Aviation Organization (ICAO) in 2016, its installed capacity is still on the rise. The GP DME set with Instrument Landing System (ILS) is specially used to provide range positioning information for aircraft in the approach segment.

The height of GP DME antenna is generally about 5m and is installed near the glide-path antenna. GP DME antennas generally use biconical antennas, which are vertically polarized and isotropic in the horizontal direction. The DME signal received by the airborne DME transceiver of the aircraft is synthesized in space by the direct signal from the ground GP DME antenna and the ground reflected signal. In the actual flight inspection, due to the different interception altitude of the approach procedure and the distance of the intermediate approach positioning fix(IF point), the requirements for the operating distance of the GP DME are also different. In general, the operating distance of GP DME signals needs to meet the requirements of ILS approach procedures, and continuous, reliable and accurate DME distance positioning signals need to be provided within the IF point. The current GP DME signal strength depression mainly occurs in the intermediate segment of approach, so this paper will focus on the research and analysis of the GP DME spatial signal in this segment.

TWO-RAY MODEL AND APPLICATION OF SNELL'S LAW

In the research of radio wave propagation, we can refer to many radio wave propagation models, such as Okumura model, Hata model, etc. [4]. Different models are suitable for different propagation environments. In chapter 12.2 of the national standard "GB6364-2013 Electromagnetic Environment Requirements for Aviation Radio Navigation Stations (Stations)", the electromagnetic environment requirements for Distance Measurement Equipment stations are "the same as the glide-path localizer when combined with the glide-path localizer". However, in Section 7.2, the electromagnetic environment requirements for the glide-path is as follows: "Area A should not have any obstacles such as roads and airport-specific ring roads, and crops should not be planted. The height of weeds should not exceed 0.3m, the longitudinal slope is the same as that of runway, the transverse slope is not more than ±1%, and it should be leveled to the height difference range of ±4cm " (Area A refers to the range of at least 360m directly in front of the glide-path antenna) [5].

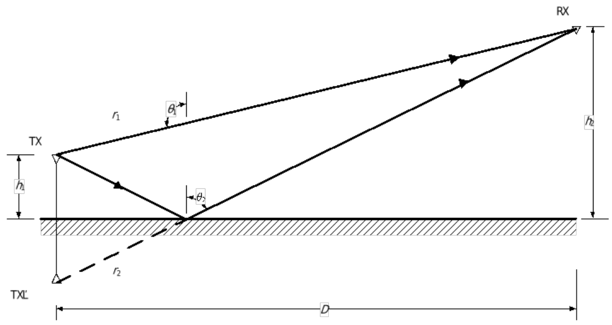

Figure 2 The Two-Ray Model

The glide-path requires a flat site as far as possible so that the signals radiated by the antenna are reflected, thus realizing spatial modulation and synthesis of signals. Since the GP DME transmitting antenna is installed near the glide-path, the signal radiated in the approach direction will also be reflected, and the space DME signal is also synthesized by superimposing and modulating the direct radiation signal and the ground reflection signal in space (as shown in Fig. 2). Through the analysis of the electromagnetic environment of the GP DME and the applicable conditions of the two-ray model, it is finally determined to use the two-ray model to analyze and study the signal strength of the GP DME in the middle and long distance. The subsequent research contents are all based on the two-ray model.

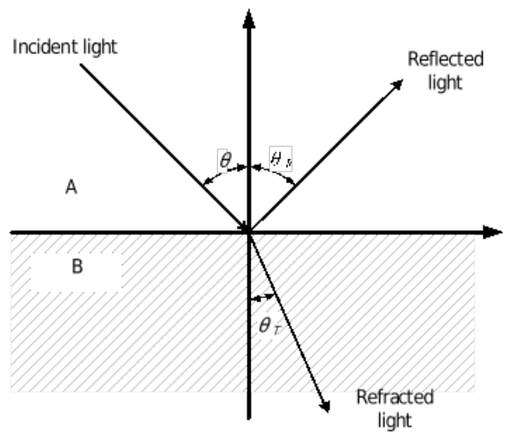

Figure 3 Schematic Diagram of Snell's Law in Physical Space

As shown in Fig. 3, in the propagation with only r_1 path, assuming that the transmitting antenna and the receiving antenna are isotropic, the free space path loss is expressed in dB

$$PG_{dB} = -32.4 - 20\log f - 20\log r \quad (1)$$

Where f is in GHz and r is in m; Free space path gain is

$$PG = \left(\frac{\lambda}{4\pi r}\right)^2 \quad (2)$$

Equation 2 is also satisfied for individual r_2 path. When calculating the total received power of spatial DME signals, considering the antenna gains in different directions, it is necessary to coherently synthesize the radiation fields in each individual path, and it is necessary to consider the influence of interference caused by different arrival times of spatial direct waves and ground reflected waves to the receiver.

When a plane wave propagating in one medium reaches a second medium boundary with different characteristics, it is partially reflected back into the first medium and partially transmitted (refracted) into the second medium. However, the propagation direction and amplitude of the reflected plane wave and the refracted plane wave are determined by the boundary conditions at the interface. Fig. 3 shows a schematic diagram showing the incident wave, the reflected wave, and the refracted wave at the plane interface of the two dielectrics [6].

PATH GAIN (PG) AND SIMULATION OF TWO-RAY MODEL

A. PG derivation of Two-Ray model [7]

Assuming that dielectric B in Fig. 3 is a dielectric having a pure real dielectric constant ε_r and dielectric A is air ($\varepsilon_r = 1$), the angle of incidence θ, the angle of reflection θ_R and the angle of refraction θ_T satisfy the following relationship according to Snell's Law

$$\sin\theta = \sin\theta_R = \sqrt{\varepsilon_r}\sin\theta_T \quad (3)$$

Furthermore, the reflection coefficient (the ratio of the electric field component of the reflected wave to the electric field component of the incident wave) of the vertically polarized wave is obtained as follows:

$$\Gamma_H = \frac{\sqrt{\varepsilon_r}\cos\theta - \cos\theta_T}{\sqrt{\varepsilon_r}\cos\theta + \cos\theta_T} \quad (4)$$

In Fig. 3, the relationship between r_1 and r_2, and distance D is as follows:

$$r_1 = \sqrt{D^2 + (h_2 - h_1)^2}$$
$$r_2 = \sqrt{D^2 + (h_2 + h_1)^2} \quad (5)$$

The received power caused by incident wave and reflected wave is deduced to be

$$P_R = P_T\left(\frac{\lambda}{4\pi}\right)^2\left|\frac{e^{-jkr_1}}{r_1} + \Gamma_H\frac{e^{-jkr_2}}{r_2}\right|^2 \quad (6)$$

After the two sides are divided P_T at the same time, the path gain PG of the double line model can be obtained:

$$PG = \left(\frac{\lambda}{4\pi}\right)^2\left|\frac{e^{-jkr_1}}{r_1} + \Gamma_H\frac{e^{-jkr_2}}{r_2}\right|^2 \quad (7)$$

k is the wave number in the dielectric, $k = \omega/c$.

B. Simulation with MATLAB

After obtaining the Equation of the path gain (PG) of the two-ray model, as in (7), we synthesize various conditions and use MATLAB to simulate the corresponding relationship between the path gain (ordinate, unit dB) and the horizontal distance of the receiving antenna (abscissa, unit meter) and the free space path gain ($\Gamma = 0$) (as shown in Fig. 4). The curve setting conditions in the figure are: the height of the transmitting antenna $h_1 = 5m$, the flying height, i.e. the height $h_2 = 600m$ and frequency $f = 1000MHz$ of the receiving antenna.

As can be seen from Fig. 4, when the horizontal distance D between the receiving antenna and the transmitting antenna increases from 100m to 40km, the path gain (PG) presents sinusoidal jitter phenomenon with irregular amplitude and frequency, which is caused by phase superposition and interference phenomenon caused by repeated changes from in-phase to out-phase when the reflected wave r_2 and the direct wave r_1 are combined in space. Simply put, the path gain (PG) increases when the direct wave and the reflected wave are in phase and decreases when the direct wave and the reflected wave are in phase.

According to (5), the difference with the distance r_1 and r_2 can be obtained

$$\Delta r = r_2 - r_1 \quad (8)$$

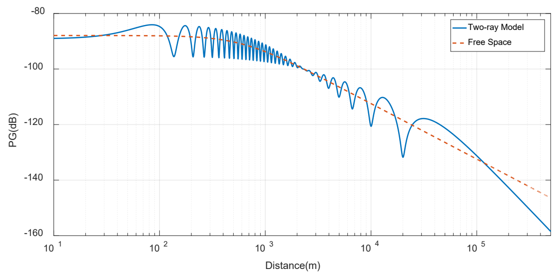

Figure 4 Vertical polarization path gain and free space path gain in two-ray model

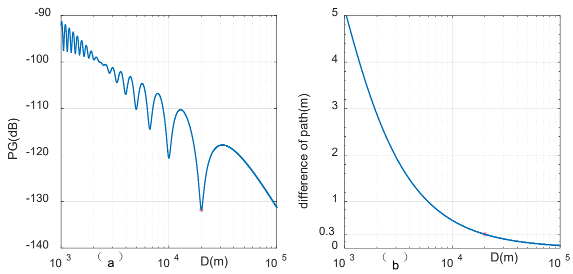

Figure 5 Distance vs. Path Gain and Distance Difference

C. Sensitive distance

As can be seen from (8), with the increase of D, the path difference Δr between the direct wave and the reflected wave becomes smaller and smaller. When D is infinite $\Delta r \to 0$, since the incident wave with vertical polarization is incident at greater than Brewster angle, the reflected wave will produce a phase difference of 180 degrees. Therefore, when the distance difference reaches an integer multiple of the wavelength $\Delta r = n\lambda$, the minimum path gain (the minimum value in a certain range, not the absolute minimum value) is obtained, and when the distance difference is equal to one wavelength $\Delta r = \lambda$ as the distance increases, the last minimum value is obtained.

Fig. 5 shows the relationship between distance and path gain and distance difference. The setting conditions of the curve are: transmitting antenna height $h_1 = 5m$, flying height, i.e. receiving antenna height $h_2 = 600m$ and frequency $f = 1000MHz$. As shown in Fig. 6-a, the last extreme point is obtained at $D = 2 \times 10^4 m$, and the corresponding distance difference is $\Delta r = 0.3m$, which exactly equals to one wavelength. For convenience of description, the corresponding distance D when the distance difference is equal to one wavelength is called sensitive distance and recorded as D_{min}.

VERIFICATION OF MODEL AND SOLUTION OF SIGNAL STRENGTH OUT OF TOLERANCE

A. Verification of the model

In order to verify the accuracy of the above GP DME signal spatial synthesis model and its consistency with the actual situation. We need to compare the MATLAB simulation results with the actual flight inspection results.

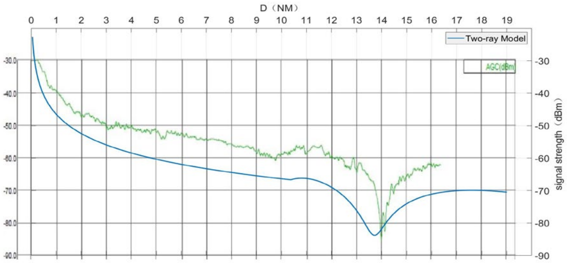

Figure 6 Signal Strength in Two-Ray Model and Flight Inspection

Fig. 6 shows the comparison between the signal strength obtained by an airport GP DME in flight inspection and the path gain of the two-ray model under the same parameters. The dotted line is the signal strength curve of the airport's GP DME flight inspection, and the solid line is the path gain curve of the two-ray model under the same parameters. The path gain curve is set according to the actual conditions. The measured signal strength in Fig. 6 is obtained during approach check.

Since the two-ray model studied in this paper does not consider the actual gain of the transmitting antenna and the receiving antenna (the default is isotropic and the gain is 1), there will be some differences between the actual signal strength of DME and the theoretical value. By comparing the two curves, the depression position of the actual spatial signal intensity of the GP DME is basically the same as that of the simulated two-ray model. Although the reflection field type is not an ideal mirror surface, the overall trend of the simulation curve and the actual curve is relatively consistent, which also shows the accuracy and feasibility of using the two-ray model to study the DME signal intensity in the approach direction.

B. Solution of signal strength out of tolerance

According to (5) and (7), it can be concluded that the signal strength of the receiving end is related to h_1 and h_2. Therefore, during the flight inspection process of the GP DME, under the condition that the glide interception height cannot be changed, we can try to solve the problem of signal strength exceeding the limit by changing the height of the transmitting antenna.

As shown in Fig. 7, we take the flight inspection of a typical GP DME as an example for MATLAB simulation. The simulation model sets conditions according to the actual situation, i.e. The height of the GP DME antenna is 5m, the height of the horizontal flight section above the GP DME antenna is 600m, the path angle is 3 degrees, the IF point (the intermediate approach positioning point, the starting point of the approach program) is 12 nautical miles(nm) away from the antenna, and the GP DME frequency is 22X, i.e. 983MHz [8].

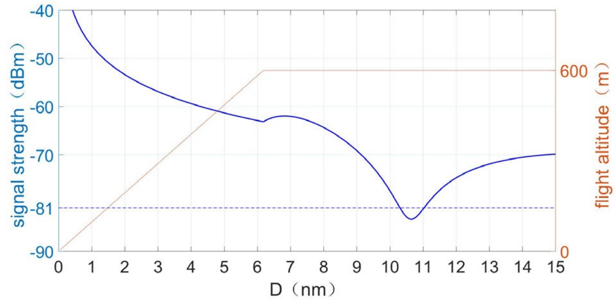

Figure 7 GP DME signal Strength (h1=5m h2=600m f=983MHz P=100W)

As can be seen from Fig. 7, the DME signal strength exceeds the limit between 10 and 11nm (according to the flight inspection rules of CAAC, the tolerance of DME signal strength is -81dBm [9]). In actual work, the common scheme to solve such problems is to change the height of the transmitting antenna. Fig. 8 is the corresponding signal strength curve after changing the height of the transmitting antenna.

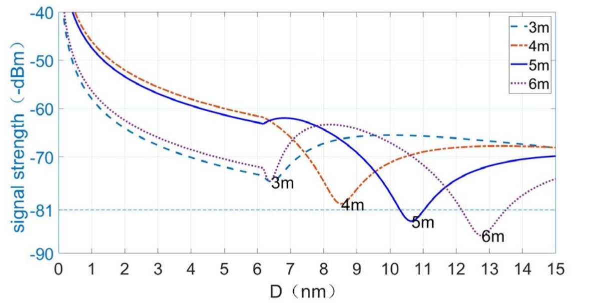

Figure 8 Signal Strength for Different Transmitting Antenna Heights

As can be seen from Fig. 8, the rise or fall of the GP DME antenna will change the signal strength between 10 and 11nm. When the flight procedure is shorter than 12nm and the antenna height is 6 meters, the improvement effect is obvious. When the signal strength is the lowest, it will increase by at least 5dBm compared with the antenna height of 5m. However, at this time, the signal strength will be lower at the further position of 12 to 13nm. Therefore, for the case where the flight procedure is longer than 12nm, raising the antenna cannot solve the problem that signal strength is out of tolerance. When the antenna height is 4m, the minimum signal strength appears between 8 and 9nm, which is about 5dBm higher than when the antenna height is 5m. At a further distance, the signal strength is obviously improved compared with the original. When the antenna height is 3m, the minimum signal strength appears between 6 and 7nm, which is about 10dBm higher than the minimum value when the antenna height is 5m, and the improvement is most obvious. Therefore, in this example, the sensitive distance can be reduced by reducing the height of the transmitting antenna, thus increasing the path gain to a certain extent, thus solving the problem that the signal strength is lower than the tolerance due to improper setting of the height of the GP DME antenna.

In conclusion, using the relevant MATLAB simulation model can provide theoretical calculation and analysis for solving the problem of signal strength out of tolerance due to the height setting of the GP DME antenna, and can give a reasonable height adjustment value of the GP DME antenna, providing a comprehensive and integrated reference and solution for finally solving similar problems.

CONCLUSION

In the two-ray model, the lower the height of the transmitting antenna, the smaller the sensitive distance, and the smaller the path loss in the sensitive distance, thus improving the minimum signal strength in the whole approach program and solving the problem of out of tolerance caused by signal strength depression at specific positions. Of course, considering the headroom of the transmitting antenna, the height of the transmitting antenna cannot be reduced indefinitely. When lowering the height of the transmitting antenna still cannot meet the signal strength requirements. According to the actual distance of IF points in flight procedure, the height of the transmitting antenna should be appropriately increased so that the depression position appears outside of the distance required by approach procedure, but at this time, attention should be paid to the signal strength when the distance difference between the direct wave and the reflected wave is two wavelengths. Some idealized conditions and parameters are used in research and modeling, such as the directivity diagram of the transmitting antenna and the receiving antenna, the slope of the reflected field, etc. This is also the deficiency of this paper and needs further research.

REFERENCES

[1] Chapter 3, Vol I, ICAO Annex 10(Sixth Edition), July 2006, Page 3-36.

[2] CCAR-86, Management Rules for Flight Inspection of Civil Aviation Communication Navigation Monitoring Equipment [S].

[3] Chapter 3, Vol I, Doc8071(Fourth Edition),2000,Page 3-6.

[4] Zhou Yiwen. Prediction of radio wave propagation based on ray tracing method [D]. Heilongjiang: Harbin Institute of Technology, 2006, 17-19.

[5] GB 6364-2013, Electromagnetic Environment Requirements for Aviation Radio Navigation Stations (Stations) [S], 12.2, 12.

[6] Lu Houqing, Song Ge, Chen Liang, Chen Zhuo, Zhang Xiaochen. Prediction Model of Microcellular Radio Wave Propagation Based on Ray Tracking Method [J], Journal of PLA University of Science and Technology (Natural Science Edition), 2015, 16 (3), 281-285.

[7] Bertoni, Henry L. Radio Propagation for Modern Wirless Systems[M], Publishing House of Electronics Industry, 2002, 4.3: 75-78.

[8] Chapter1,Vol I,DME FSD 40/45-Technical Manual,May 2008,Page 1-15.

[9] MH2003-2000, Flight Inspection Rules [S].