Three-dimensional Communication Channel Model of UAV Data Link

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Abstract: In the paper, it makes analysis the characteristics of UAV communication channel in the tree-dimensional space. The UAV small scale model base on multipath propagation is analyzed, the fundamental conditions, extended function of azimuth angle and extended function of pitch angle are researched, which are satisfied with WSS (Wide-Sense Stationary) model. The three-dimensional system of coordinate is established, the parameter of channel is set, the line-of-sight component, reflecting component and scattering multipath component and the function related with time are analyzed and calculated, finally, three-dimensional model of UAV communication channel is established and related simulation is done to testify its validity.

Keywords: UAV; Data Link ; Channel Model ; Three-dimensional;

1. Introduction

In the space, radio waves may go through many times of reflection, refraction, scattering and diffraction, and it is affected by the free space path loss, shadow effect, multipath effect, Doppler effect, etc. the influence of time dispersion, angle extension of the radio waves propagation will produce all sorts of decline and extension. In large scale sense, radio waves are mainly affected by slower factors, such as free space path loss and shadow fading change [1-2].

Channel modeling should not only satisfy requirements of the practical application, but also it should be able to reflect the statistical characteristics of wireless channel specific accurately. Validation of the model accuracy is the most effective method for the model compared with the measured value in the real environment, but now the open measurement data and conclusion the of all sorts of small scale fading channel of the unmanned aerial vehicle (UAV) are less . Therefore, the study on the UAV channel model is relatively difficult.

In the paper, we make the assumption that the electromagnetic wave is plane wave; setting transmission space of the radio wave is in the two-dimensional space, we make the detailed analysis of the UAV channel. The whole process of research was conducted under setting conditions, we assume distance between receiving antenna and sending antenna is far, and the scattering body are located in the far area of antenna, namely that the radio waves of the scattere and receiving antenna are plane wave [3].

At the same time, in the paper [4], it is shown that if the actual electromagnetic waves are taken as space radio waves, and the waves transfer space is extended to three dimensions, and takes electromagnetic wave arrival angle into consideration, it can make the model proposed more accurately. Therefore, based on the spread of more complex situation, it focuses on the research of small scale three-dimensional model of the UAV radio waves.

2. Small Scale Three-dimensional Propagation Model of the Radio Wave

In the space, the N incident waves are in the form of plane wave spread to the receiving end, just as shown in figure. 1.

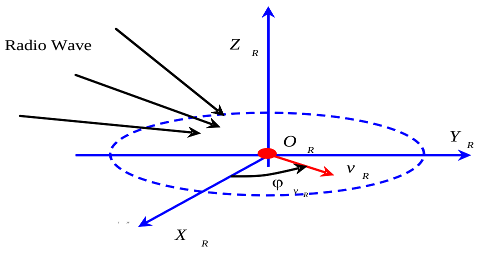

Fig.1 Graph of space receive wave

g_i and ϕ_i respectively represent path gain and random phase, and we put the unit power waves launching from the transmitter antennas into consideration, the equivalent transfer function of the broadband wireless channel can be expressed as [5] :

$$
\begin{aligned}
h(\vec{r}, f, t) &= \sqrt{\frac{1}{N}} \sum_{i=1}^{N} G(a_i, \beta_i)\, g_i exp\left(j\phi_i - jk_0 \vec{k}_i \bullet \vec{r} - jk_0 c \xi_i \right) \\
&= \sqrt{\frac{1}{N}} \sum_{i=1}^{N} G(a_i, \beta_i)\, g_i exp\left(j\phi_i - j\frac{2\pi(f + f_c)}{c} \upsilon \vec{k}_i \bullet \vec{\upsilon} t - j2\pi(f + f_c)\xi_i \right) \\
&= \sqrt{\frac{1}{N}} \sum_{i=1}^{N} G(a_i, \beta_i)\, g_i exp\left(j(\phi_i + 2\pi f_c \xi_i) - j\frac{2\pi(f + f_c)}{c} \upsilon \vec{k}_i \bullet \vec{\upsilon} t - j2\pi f \xi_i \right)
\end{aligned} \tag{1}
$$

Among them, $G(a_i, \beta_i)$ represents the direction of figure receiving antenna, a_i , β_i respectively represent the direction angle and pitching angle waves reaching in the first i article path; $\vec{k}_i = k_0\left(cos(\beta_i)cos(a_i), cos(\beta_i)sin(a_i), sin(\beta_i)\right)$ represents the direction of the vector in the first i article path; $k_0 = 2\pi/\lambda$ represents free space wave number. ξ_i represents time delay in the first i article path; f_c represents the center of carrier frequency; f represents baseband frequency; c represents the velocity of electromagnetic wave; λ represents the wavelength, then $c = \lambda(f + f_c)$; υ represents the receiver's movement speed, $\vec{\upsilon} = (cos(a_v), sin(a_v), 0)$ represents the direction of the vector of movement speed, a_v represents azimuth. $\phi_i + 2\pi f \xi_i$ can be considered the phase change being caused by the interaction of the antenna and scattering body and the cumulative of path propagation delay. generally speaking, different paths caused by phase are independent of each other, and presents evenly distributed between $[0, 2\pi]$; The space item $\vec{k}_i \bullet \vec{r}$ can be considered the phase change being caused by the Doppler extension made by the receiver movement; the frequency item can be considered the phase change being caused by the path propagation delay and carrier frequency offset, for narrow band system, the carrier frequency f displacement is zero, this phase can be ignored, so the channel is not a frequency selective fading channel. The amplitude gain g_i in path i mainly consists of two parts of scattering decline and path of decline. In the narrow band channel, we generally consider attenuation is caused by scattering body, but in broadband channel attenuation may be caused by scattering object and the path attenuation. When the receiver is in a diffuse and highly scattering wireless channel, we generally assume each path in the channel has gain with stochastic, and the gain of different paths is independent of each other. If the receiver works in a highly scattering wireless channel, we generally do not limit the gain.

In a specific environment, in order to make accurate model of the spread waves, the number N of paths needed may be infinity, and the gain of each path is infinitesimal. In the random channel model based on scattering geometry, in paper [6-7] , it assumes that each path of the channel has stochastic gain; in paper [7] it assumes that different paths has the same gain. In the purely random channel model, some papers make no restriction on each path gain, and in some literatures they think each path has stochastic gain. As for channel model with stochastic gain, we generally think that introduced gain and phase in the same path are independent of each other.

2.1 The Basic Conditions of WSS

From the physical view, the time domain of WSS represents a second order channel which does not change with time. While actually, the characteristics of channel can't meet stationary in infinitely long time. Usually if channel meets stationary conditions in the dozens of relative times, the channel can be thought that it satisfies the WSS conditions. According to the channel equivalent transfer function (1), we define the autocorrelation function as:

$$
\begin{aligned}
R_h\left(\vec{r}_1,\vec{r}_2; f_1, f_2;t_1,t_2\right) &= E\left(h\left(\vec{r}_1, f_1,t_1\right)h^*\left(\vec{r}_2, f_2,t_2\right)\right)\\
&= \frac{1}{N}\sum_{i=1}^{N}\left(G\left(a_i,\beta_i\right)\right)^2 E\left(g_i^2\right)\bullet \\
& exp\left(-j2\pi\left(f_1-f_2\right)\xi_i - j2\pi\frac{\left(f_1+f_c\right)t_1-\left(f_2+f_c\right)t_2}{c}\upsilon\vec{k}_i\bullet\vec{\upsilon}\right)
\end{aligned}
\qquad (2)
$$

In order to meet the conditions of WSS, type (2) must be represented as $\Delta f = f_1 - f_2$, $\Delta t = t_1 - t_2$. Obviously it should meet the following conditions:

① $B = max\left(\Delta f\right) \ll f_c$;

② $\left|\frac{f_i t_i \upsilon}{c}\right| \ll 1, \quad i = 1,2$;

In type (2), in the cross terms $2\pi\upsilon\left(\left(f_1+f_c\right)t_1-\left(f_2+f_c\right)t_2\right)/c$ of the frequency terms and time terms, influence of frequency item can be ignored, it can be expressed as $2\pi\upsilon f_c \Delta t/c$.

We assume that the maximum of frequency f_i deviating from the center carrier is $f_{max} = max(f_i) \le B/2$, the maximum of mobile rate is υ_{max}, the maximum time meeting for WSS channel is t_{max}, $c = f_c \lambda_c$, the sufficient conditions meet with ② can be represented as $\frac{B/2\, t_{max} \upsilon_{max}}{f_c \lambda_c} \ll 1 \Leftrightarrow t_{max} \ll \frac{2 f_c \lambda_c}{B \upsilon_{max}}$.

In the physical point, the largest coherent time of channel is less than $2 f_c \lambda_c / B\upsilon_{max}$, the influence of frequency items on the cross terms of frequency and time can be ignored. If channels meet stationary conditions among the dozens of relative times, we can think the channel satisfies WSS conditions. Therefore, type (2) can be expressed as,

$$\begin{aligned} R_h\left(\bar{r}_1, \bar{r}_2; f_1, f_2; t_1, t_2\right) = \frac{1}{N}\sum_{i=1}^{N}\left(G\left(a_i, \beta_i\right)\right)^2 E\left(g_i^2\right) \\ exp\left(-j2\pi\left(\Delta f\right)\xi_i - j2\pi\upsilon\frac{\Delta t}{c}\bar{k}_i \bullet \bar{\upsilon}\right) \quad (3) \\ = R_h\left(\Delta f; \Delta t\right) \end{aligned}$$

2.2 Azimuth Extension Function

In the choice of angle expand distribution function, it should not only consider the accuracy of the describing function, but also consider the convenience of calculation for mathematic expression of the describing function, and it should be able to deduce the channel correlation function with complete, concise expression.

In the half random channel model based on the geometric distribution of scattering body, first we should need to determine the location of the scatterer. Selection of the location of the scatterer may be random selection according to certain probability distribution function, and it can also be a determined position in the specific area, usually the influence of near scatterer on channel are the main consideration, it also can consider the impact of distance scatterer's on channel. Then we further assume that waves scattering between sending and receiving only after the limited times, usually a (single jump model) or twice (double jump model). Finally through a simple ray path we can calculate the impulse response. In general, a random channel model mainly reflects the channel long-term statistical properties.

The directional characteristic of the wave propagation in wireless channel is obvious. In the channel model, the direction of the emergent Angle (AOD: Angle of Departure) and the Angle of the direction of Arrival (AOA) of multipath signal is commonly used in AOD (AOA: Angle of concatenated) to describe the probability distribution function. In different models and different environments, distribution function to describe the azimuth extension has a large difference. There are several kinds of function to be used to describe the extension of Azimuth (Azimuth Angle: AA),the commonly used continuous probability density functions are uniform distribution, cosine distribution, truncated Gaussian distribution, Laplace distribution, and Von Mises distribution. Other different specific model will have different expand distribution function.

2.3 Pitching Angle Extension Function

In the channel, the direction of arrival of radio waves is the omnidirectional and heterogeneity, so the relevant characteristics of the channel transfer function, the performance of the wireless channel and the corresponding wave Angle extension have a close relationship. In the paper [8] under the condition of NLOS in the wireless channel the scattering signal has a larger pitching Angle (EA) extension is confirmed, so in some research cases, we must consider the extension of EA and need to establish a model of the three-dimensional (3D) model. In the paper [9], it refers the literature [8] and proposes the three-dimensional GBS model, but in this paper, we assume that received signals in the receiving end presents evenly distributed in angle extended range. In the paper [10] according to different receiving array, the three-dimensional (3-D) channel model is established, takes the expansion of the pitching angle into consideration, but in this paper we assume that the expansion of the azimuth and pitching angle are uniformly distributed within the extended range.

In the literature [11], it sets up three-dimensional random channel model, but it fails to presents facilitate function of expression and joint frequency correlation and it also lack of effective comparing verification. In the paper [12] it assumes that scatterer discrete uniform distribution of rectangular area in the distance, then it aims at the receiver array to build the three-dimensional model, and makes analysis of channel characteristics, but it gives no concise expression of joint space-time correlation function which contains all the array parameters and channel.

3.Three Dimensional Channel Model of the UAV

3.1 The establishment of coordinate system

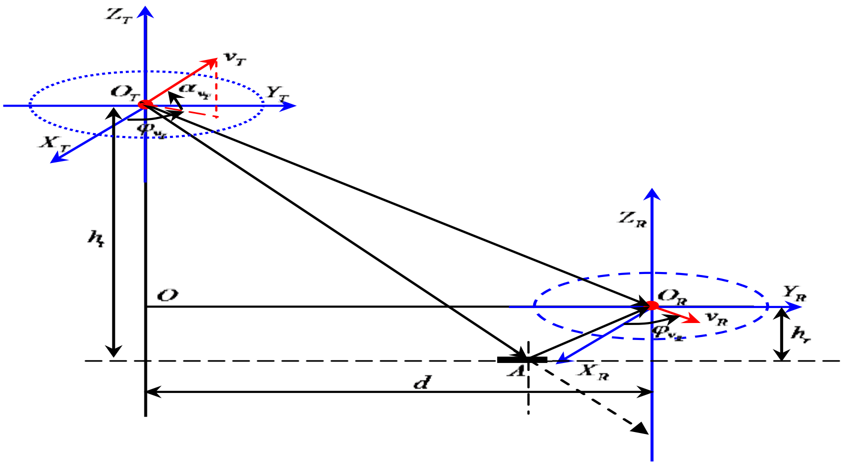

Fig 2 line-of –sight and specular reflecting component

In order to facilitate analysis, we establish the coordinate system as shown in figure 2.

First of all, we use receiving antenna to define O_R as receiving coordinate center, the plane $X_R - Y_R$ is parallel to the earth plane, the axis Z_R is perpendicular to the earth plane; we use the UAV transmitting antenna to define O_T for launch coordinate system center, in the plane $X_R - Y_R$ projection is O, and it connects $O - O_R$, in order to facilitate analysis, launch coordinate system $O_T - X_T Y_T Z_T$ and receive coordinate system $O_R - X_R Y_R Z_R$ will have the same parallel attribute.

3.2 Setting of parameters

We sets the height of ground station as h_r ,and the UAV flight height is set as h_t meter, the level distance between the UAV and the ground control station is set as d meter. In general, the UAV often have the movements of leveled off, climbing, subduction and hovering flight in the air. In the coordinate system has been established it is a space vector, υ_T represents the speed of the UAV, α_{υ_T} and φ_{υ_T} respectively represents pitching angle and azimuth angle of the UAV movement speed; In general, the ground receiving station will not be moved, but in order to prevent the enemy attacks, it may also have certain parallel moves, υ_R represents the movement speed of the ground station, φ_{υ_R} represents the velocity azimuth of the ground station. (Pitching angle refers to the angle which is parallel to the earth plane, azimuth angle refers to the angle between the projection to parallel to the earth plane and the corresponding X_R or X_T).

Generally speaking, the UAV ground control station is set in a relatively open area, around the UAV launch site it should have no tall buildings, mountains or woods; but, it is impossible to have the vast open plains, it usually has a certain height buildings, mountains, etc; As for the ground control station location, it is generally surrounded by these buildings, mountains. The scatterer around the ground control station like a cylinder. We sets the radius of the cylinder (scattering area) is R , the height which is higher the UAV ground station is h_c .

3.3 Channel component composition and the simulation analysis

Generally speaking, the components of the composition for the UAV channel mainly include direct, specular reflection and scattering of electromagnetic waves [107]. Γ represents the ratio of the specular reflection component and the specular direct component, namely the reflection coefficient the of the reflection surface. Ω represents the normalized power, K_{Rice} represents the ratio of the power value between the direct component and scattering component , then,

$$K_{Rice} = \frac{\left|h^{LOS}(t)\right|^2}{E\left[\left|h^{DIF}(t)\right|^2\right]}, \quad \Gamma = \frac{h^{SPE}(t)}{h^{LOS}(t)} \tag{4}$$

We make energy normalize of the channel, then the following type is obtained.

$$\left|h^{LOS}(t)\right|^2 + \left|h^{SPE}(t)\right|^2 + E\left[\left|h^{DIF}(t)\right|^2\right] = \Omega \le 1 \tag{5}$$

$$E\left[\left|h^{DIF}(t)\right|^2\right] = \frac{\Omega}{1 + K_{Rice} + K_{Rice}\left|\Gamma\right|^2} \tag{6}$$

$$\left|h^{LOS}(t)\right|^2 = \frac{K_{Rice}\Omega}{1 + K_{Rice} + K_{Rice}\left|\Gamma\right|^2} \tag{7}$$

$$\left|h^{SPE}(t)\right|^2 = \frac{\Omega K_{Rice}\left|\Gamma\right|^2}{1 + K_{Rice} + K_{Rice}\Gamma^2} \tag{8}$$

$$h(t) = h^{LOS}(t) + h^{SPE}(t) + h^{DIF}(t) \quad (9)$$

3.3.1. The direct component

As shown in figure 2, we setting azimuth angle and elevation angle of the radio wave which are emitted from the UAV by the electromagnetic wave are φ_T^{LOS} and α_T^{LOS} respectively, and the azimuth angle and elevation angle to reach the terminal respectively are φ_R^{LOS} and α_R^{LOS}, and the direct component can be expressed as:

$$h^{LOS}(t) = \sqrt{\frac{K_{Rice}\Omega}{1+K_{Rice}+K_{Rice}\Gamma^2}} exp\left\{-j\left(k_0 D_{O_T \to O_R} - \vec{k}_R^{LOS} \bullet \vec{r}_R^{LOS} + \vec{k}_T^{LOS} \bullet \vec{r}_T^{LOS}\right)\right\} \quad (10)$$

k_0 represents free space wave number, and it have the relation of $k_0 = 2\pi/\lambda$ with the wavelength of the electromagnetic wave, $D_{O_T \to O_R}$ represents the space distance of the direct component.

$$k_0 D_{O_T \to O_R} = \frac{2\pi}{\lambda}\sqrt{(h_t - h_r)^2 + d^2} \quad (11)$$

$\vec{k}_T^{LOS} \bullet \vec{r}_T^{LOS}$ and $\vec{k}_R^{LOS} \bullet \vec{r}_R^{LOS}$ respectively represent the phase change of the direct component caused by the movement between the UAV and the ground station, and $\bullet$ represents inner product.

$$\begin{aligned}
\vec{k}_T^{LOS} \bullet \vec{r}_T^{LOS} &= \frac{2\pi}{\lambda}\left(cos\alpha_T^{LOS} cos\varphi_T^{LOS}, cos\alpha_T^{LOS} sin\varphi_T^{LOS}, sin\alpha_T^{LOS}\right) \bullet \left(cos\alpha_{\upsilon_T} cos\varphi_{\upsilon_T}, cos\alpha_{\upsilon_T} sin\varphi_{\upsilon_T}, sin\alpha_{\upsilon_T}\right)\upsilon_T t \\
&= \frac{2\pi f}{c}\upsilon_T t\left(cos\alpha_T^{LOS} cos\varphi_T^{LOS} cos\alpha_{\upsilon_T} cos\varphi_{\upsilon_T} + cos\alpha_T^{LOS} sin\varphi_T^{LOS} cos\alpha_{\upsilon_T} sin\varphi_{\upsilon_T} + sin\alpha_T^{LOS} sin\alpha_{\upsilon_T}\right) \\
&= \frac{2\pi f}{c}\upsilon_T t\left(cos\alpha_T^{LOS} cos\alpha_{\upsilon_T} cos\left(\varphi_T^{LOS} - \varphi_{\upsilon_T}\right) + sin\alpha_T^{LOS} sin\alpha_{\upsilon_T}\right)
\end{aligned} \quad (12)$$

$$\begin{aligned}
\vec{k}_R^{LOS} \bullet \vec{r}_R^{LOS} &= -\frac{2\pi}{\lambda}\left(cos\alpha_R^{LOS} cos\varphi_R^{LOS}, cos\alpha_R^{LOS} sin\varphi_R^{LOS}, sin\alpha_R^{LOS}\right) \bullet \left(cos\varphi_{\upsilon_R}, sin\varphi_{\upsilon_R}, 0\right)\upsilon_R t \\
&= -\frac{2\pi f}{c}\upsilon_R t\left(cos\alpha_R^{LOS} cos\left(\varphi_R^{LOS} - \varphi_{\upsilon_R}\right)\right)
\end{aligned} \quad (13)$$

3.3.2. The reflection components

As shown in figure 2, we set azimuth angle and elevation angle which are emitted from the UAV by the electromagnetic wave are φ_T^{SPE} and α_T^{SPE}, and the azimuth angle and elevation angle to reach the terminal are φ_R^{SPE} and α_R^{SPE}, and the specular component can be expressed as:

$$h^{SPE}(t) = \sqrt{\frac{\Omega K_{Rice}}{1+K_{Rice}+K_{Rice}\Gamma^2}}\Gamma exp\left\{-j\left(k_0\left(D_{O_T \to A} + D_{A \to O_R}\right) - \vec{k}_R^{SPE} \bullet \vec{r}_R^{SPE} + \vec{k}_T^{SPE} \bullet \vec{r}_T^{SPE}\right)\right\} \quad (14)$$

$D_{O_T \to A}$ represents the space distance from specular component to specular reflection points, $D_{A \to O_R}$ represents the space distance from specular reflection points to the ground receiving station.

$$k_0\left(D_{O_T\to A}+D_{A\to O_R}\right)=\frac{2\pi}{\lambda}\sqrt{\left(h_t+h_r\right)^2+d^2} \qquad (15)$$

$\vec{k}_T^{SPE}\bullet\vec{r}_T^{SPE}$ and $\vec{k}_R^{SPE}\bullet\vec{r}_R^{SPE}$ respectively represents the phase change of the specular component caused by the movement between the UAV and the ground station, and $\bullet$ represents inner product.

$$\begin{aligned}\vec{k}_T^{SPE}\bullet\vec{r}_T^{SPE}&=\frac{2\pi}{\lambda}\left(cos\alpha_T^{SPE}cos\varphi_T^{SPE},cos\alpha_T^{SPE}sin\varphi_T^{SPE},sin\alpha_T^{SPE}\right)\bullet\left(cos\alpha_{\upsilon_T}cos\varphi_{\upsilon_T},cos\alpha_{\upsilon_T}sin\varphi_{\upsilon_T},sin\alpha_{\upsilon_T}\right)\upsilon_T t\\&=\frac{2\pi f}{c}\upsilon_T t\left(cos\alpha_T^{SPE}cos\varphi_T^{SPE}cos\alpha_{\upsilon_T}cos\varphi_{\upsilon_T}+cos\alpha_T^{SPE}sin\varphi_T^{SPE}cos\alpha_{\upsilon_T}sin\varphi_{\upsilon_T}+sin\alpha_T^{SPE}sin\alpha_{\upsilon_T}\right)\\&=\frac{2\pi f}{c}\upsilon_T t\left(cos\alpha_T^{SPE}cos\alpha_{\upsilon_T}cos\left(\varphi_T^{SPE}-\varphi_{\upsilon_T}\right)+sin\alpha_T^{SPE}sin\alpha_{\upsilon_T}\right)\end{aligned} \qquad (16)$$

$$\begin{aligned}\vec{k}_R^{SPE}\bullet\vec{r}_R^{SPE}&=-\frac{2\pi}{\lambda}\left(cos\alpha_R^{SPE}cos\varphi_R^{SPE},cos\alpha_R^{SPE}sin\varphi_R^{SPE},sin\alpha_R^{SPE}\right)\bullet\left(cos\varphi_{\upsilon_R},sin\varphi_{\upsilon_R},0\right)\upsilon_R t\\&=-\frac{2\pi f}{c}\upsilon_R t\left(cos\alpha_R^{SPE}cos\left(\varphi_R^{SPE}-\varphi_{\upsilon_R}\right)\right)\end{aligned} \qquad (17)$$

3.3.3. The scattering component

We assume that the ground station is in a 3D cylindrical scattering environment with radius of R metre , which is h_c metre higher than the ground control station. As shown in figure.3. In figure 3, S_i represents the first i of N scatterer, as for any scatterer, we use φ_T^i and α_T^i respectively to represent azimuth angle and elevation angle which are emitted from the UAV by the electromagnetic wave. Through scatterer S_i, the azimuth angle and elevation angle reaching terminal are respectively φ_R^i and α_R^i, and the scattering component can be expressed as:

$$h^{DIF}(t)=\sqrt{\frac{\Omega}{1+K_{Rice}+K_{Rice}\Gamma^2}}\lim_{N\to\infty}\frac{1}{\sqrt{N}}\sum_{i=1}^{N}g_i\cdot exp\left\{-j\left(-\varphi_i+k_0\left(D_{O_T\to S_i}+D_{S_i\to O_R}\right)-\vec{k}_R^i\bullet\vec{r}_R^i+\vec{k}_T^i\bullet\vec{r}_T^i\right)\right\} \qquad (18)$$

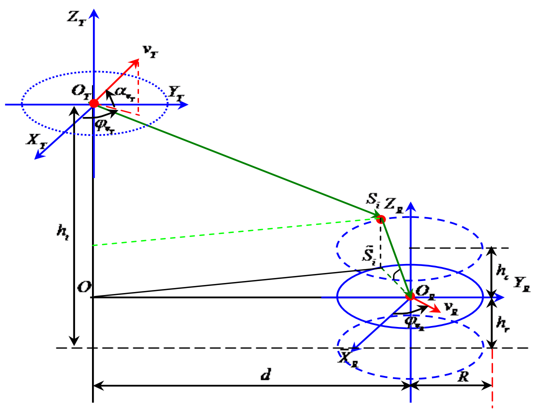

Fig 3 dispersion component

$D_{O_T\to S_i}$ represents the space distance from scattering component to scatterer , $D_{S_i\to O_R}$ represents the space distance from scatterer to ground station .

$$k_0\left(D_{O_T\to S_i}+D_{S_i\to O_R}\right)=\frac{2\pi}{\lambda}\left(\frac{h_t-h_r-Rtga_R^i}{sina_T^i}+cosa_R^iR\right) \quad (19)$$

$\vec{k}_T^i\bullet\vec{r}_T^i$ and $\vec{k}_R^i\bullet\vec{r}_R^i$ respectively represent the phase change being caused by the movement of the UAV and ground station.

$$\begin{aligned}\vec{k}_T^i\bullet\vec{r}_T^i&=\frac{2\pi}{\lambda}\left(cos\alpha_T^icos\varphi_T^i,cos\alpha_T^isin\varphi_T^i,sin\alpha_T^i\right)\bullet\left(cos\alpha_{\upsilon_T}cos\varphi_{\upsilon_T},cos\alpha_{\upsilon_T}sin\varphi_{\upsilon_T},sin\alpha_{\upsilon_T}\right)\upsilon_Tt\\&=\frac{2\pi f}{c}\upsilon_Tt\left(cos\alpha_T^icos\varphi_T^icos\alpha_{\upsilon_T}cos\varphi_{\upsilon_T}+cos\alpha_T^isin\varphi_T^icos\alpha_{\upsilon_T}sin\varphi_{\upsilon_T}+sin\alpha_T^isin\alpha_{\upsilon_T}\right)\\&=\frac{2\pi f}{c}\upsilon_Tt\left(cos\alpha_T^icos\alpha_{\upsilon_T}cos\left(\varphi_T^i-\varphi_{\upsilon_T}\right)+sin\alpha_T^isin\alpha_{\upsilon_T}\right)\end{aligned} \quad (20)$$

$$\begin{aligned}\vec{k}_R^i\bullet\vec{r}_R^i&=-\frac{2\pi}{\lambda}\left(cos\alpha_R^icos\varphi_R^i,cos\alpha_R^isin\varphi_R^i,sin\alpha_R^i\right)\bullet\left(cos\varphi_{\upsilon_R},sin\varphi_{\upsilon_R},0\right)\upsilon_Rt\\&=-\frac{2\pi f}{c}\upsilon_Rt\left(cos\alpha_R^icos\left(\varphi_R^i-\varphi_{\upsilon_R}\right)\right)\end{aligned} \quad (21)$$

3.3.4. The time correlation function

As for Rice fading channel, its second-order statistical properties can describe the basic characteristic of the channel, so the analysis of channel characteristics need correlation function to be deduced. The correlation function of Rice fading channel is defined as:

$$\rho(t,\tau)=\rho(\tau)=\frac{E\left(h(t)h^*(t-\tau)\right)}{\Omega} \quad (22)$$

The correlation function of scattering component is the correlation function of the complex stochastic process, which can be defined as:

$$\rho^{DIF}(t,\tau)=\rho^{DIF}(\tau)=\frac{E\left(h^{DIF}(t)h^{DIF*}(t-\tau)\right)}{\Omega} \quad (23)$$

Correlation function of the line-of-sight component is the correlation function to determine the signal, just defined as:

$$\rho^{LOS}(t,\tau)=\rho^{LOS}(\tau)=\frac{E\left(h^{LOS}(t)h^{LOS*}(t-\tau)\right)}{\Omega} \quad (24)$$

The correlation function of reflection components is the correlation function to determine the signal, defined as:

$$\rho^{SPE}(t,\tau)=\rho^{SPE}(\tau)=\frac{E\left(h^{SPE}(t)h^{SPE*}(t-\tau)\right)}{\Omega} \quad (25)$$

It can be seen clearly that, the correlation function is formed the direct, reflection and scattering, the three components of the UAV channel model is the sum of the independent correlation function, namely that:

$$\rho(\tau)=\rho^{LOS}(\tau)+\rho^{SPE}(\tau)+\rho^{DIF}(\tau) \quad (26)$$

(1)The related functions of the sight distance component

$$\rho^{LOS}(\tau)=\frac{K_{Rice}}{1+K_{Rice}+K_{Rice}\left|\Gamma\right|^2}exp\left\{\begin{aligned}&j\frac{2\pi f}{c}\upsilon_T\tau\left(cos\alpha_T^{LOS}cos\alpha_{\upsilon_T}cos\left(\varphi_T^{LOS}-\varphi_{\upsilon_T}\right)+sin\alpha_T^{LOS}sin\alpha_{\upsilon_T}\right)\\&+j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R^{LOS}cos\left(\varphi_R^{LOS}-\varphi_{\upsilon_R}\right)\right)\end{aligned}\right\} \quad (27)$$

According to the figure 2,

$$\begin{aligned}\varphi_T^{LOS} &= -\pi + \varphi_R^{LOS} \\ \alpha_T^{LOS} &= -\frac{\pi}{2} + \alpha_R^{LOS}\end{aligned} \tag{28}$$

Then,

$$\begin{aligned}\rho^{LOS}(\tau) &= \frac{K_{Rice}}{1+K_{Rice}+K_{Rice}|\Gamma|^2} exp\left\{\begin{array}{l} j\frac{2\pi f}{c}\upsilon_T\tau\left(cos\left(-\frac{\pi}{2}+\alpha_R^{LOS}\right)cos\alpha_{\upsilon_T}cos\left(-\pi+\varphi_R^{LOS}-\varphi_{\upsilon_T}\right)+sin\left(-\frac{\pi}{2}+\alpha_R^{LOS}\right)sin\alpha_{\upsilon_T}\right) \\ +j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R^{LOS}cos\left(\varphi_R^{LOS}-\varphi_{\upsilon_R}\right)\right)\end{array}\right\} \\ &= \frac{K_{Rice}}{1+K_{Rice}+K_{Rice}|\Gamma|^2} exp\left\{\begin{array}{l} j\frac{2\pi f}{c}\upsilon_T\tau\left(sin\left(\alpha_R^{LOS}\right)cos\alpha_{\upsilon_T}cos\left(\varphi_{\upsilon_T}-\varphi_R^{LOS}\right)+sin\left(\alpha_R^{LOS}\right)sin\alpha_{\upsilon_T}\right) \\ +j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R^{LOS}cos\left(\varphi_R^{LOS}-\varphi_{\upsilon_R}\right)\right)\end{array}\right\}\end{aligned} \tag{29}$$

Among them,

$\alpha_R^{LOS} = arctg\left(\frac{h_t-h_r}{d}\right)$， $\varphi_R^{LOS} \in [0,2\pi]$。

(2) The related functions of reflection components

$$\rho^{SPE}(\tau) = \frac{K_{Rice}|\Gamma|^2}{1+K_{Rice}+K_{Rice}|\Gamma|^2} exp\left\{\begin{array}{l} j\frac{2\pi f}{c}\upsilon_T\tau\left(cos\alpha_T^{SPE}cos\alpha_{\upsilon_T}cos\left(\varphi_T^{SPE}-\varphi_{\upsilon_T}\right)+sin\alpha_T^{SPE}sin\alpha_{\upsilon_T}\right) \\ +j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R^{SPE}cos\left(\varphi_R^{SPE}-\varphi_{\upsilon_R}\right)\right)\end{array}\right\} \tag{30}$$

According to the figure 2.

$$\begin{aligned}\varphi_T^{SPE} &= -\pi + \varphi_R^{SPE} \\ \alpha_T^{SPE} &= -\frac{\pi}{2} - \alpha_R^{SPE}\end{aligned} \tag{31}$$

Then,

$$\begin{aligned}\rho^{SPE}(\tau) &= \frac{K_{Rice}|\Gamma|^2}{1+K_{Rice}+K_{Rice}|\Gamma|^2} exp\left\{\begin{array}{l} j\frac{2\pi f}{c}\upsilon_T\tau\left(cos\left(-\frac{\pi}{2}-\alpha_R^{SPE}\right)cos\alpha_{\upsilon_T}cos\left(-\pi+\varphi_R^{SPE}-\varphi_{\upsilon_T}\right)+sin\left(-\frac{\pi}{2}-\alpha_R^{SPE}\right)sin\alpha_{\upsilon_T}\right) \\ +j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R^{SPE}cos\left(\varphi_R^{SPE}-\varphi_{\upsilon_R}\right)\right)\end{array}\right\} \\ &= \frac{K_{Rice}|\Gamma|^2}{1+K_{Rice}+K_{Rice}|\Gamma|^2} exp\left\{\begin{array}{l} j\frac{2\pi f}{c}\upsilon_T\tau\left(-sin\left(\alpha_R^{SPE}\right)cos\alpha_{\upsilon_T}cos\left(\varphi_{\upsilon_T}-\varphi_R^{SPE}\right)-cos\left(\alpha_R^{SPE}\right)sin\alpha_{\upsilon_T}\right) \\ +j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R^{SPE}cos\left(\varphi_R^{SPE}-\varphi_{\upsilon_R}\right)\right)\end{array}\right\}\end{aligned} \tag{32}$$

Where ， $\alpha_R^{SPE} = -arctg\left(\frac{h_t+h_r}{d}\right)$， $\varphi_R^{SPE} \in [0,2\pi]$.

(3)The related functions for scattering component

$$\rho^{DIF}(\tau) = \frac{\Omega}{1+K_{Rice}+K_{Rice}|\Gamma|^2}\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N}E\left(g_i^2\right)exp\left(\begin{array}{l} j\frac{2\pi f}{c}\upsilon_T\tau\left(cos\alpha_T^icos\alpha_{\upsilon_T}cos\left(\varphi_T^i-\varphi_{\upsilon_T}\right)+sin\alpha_T^isin\alpha_{\upsilon_T}\right) \\ +j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R^icos\left(\varphi_R^i-\varphi_{\upsilon_R}\right)\right)\end{array}\right) \tag{33}$$

Because $\{g_i\}_{i=1}^{\infty}$ presents independent identically distributed, through scattering component energy normalized processing, then,

$$\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N}E\left(g_i^2\right)=1 \tag{34}$$

As for the frequency selective channel, $E\left(g_i^2\right)/N$ can be approximately expressed as $f\left(\alpha_R,\varphi_R\right)d\alpha_R d\varphi_R$, among them, $\left(\alpha_R,\varphi_R\right)$ represent the pitching angle and azimuth of scatterer S_i, $f\left(\alpha_R,\varphi_R\right)$ represent the joint probability density function of pitching angle and azimuth distribution at the receiving end, so there is

$$\rho^{DIF}\left(\tau\right)=\frac{\Omega}{1+K_{Rice}+K_{Rice}\left|\Gamma\right|^2}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{-\pi}^{\pi}\left\{\begin{array}{l} exp\left(\begin{array}{l} j\frac{2\pi f}{c}\upsilon_T\tau\left(cos\alpha_T cos\alpha_{\upsilon_T}cos\left(\varphi_T-\varphi_{\upsilon_T}\right)+sin\alpha_T sin\alpha_{\upsilon_T}\right)\\ +j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R cos\left(\varphi_R-\varphi_{\upsilon_R}\right)\right)\end{array}\right)\\ f\left(\alpha_R,\varphi_R\right)d\alpha_R d\varphi_R\end{array}\right\} \tag{35}$$

It adopts von Mises probability density function to describe the receiving end distribution of the scattering AA and the Gaussian distribution to describe the scattering EA distribution around the receiving end ,we assume that AA and EA present the distribution independently, so there is

$$\begin{aligned} f\left(\alpha_R,\varphi_R\right)&=f\left(\alpha_R\right)f\left(\varphi_R\right)\\ &=\frac{exp\left(\kappa cos\left(\varphi_R-\varphi_0\right)\right)}{2\pi I_0\left(\kappa\right)}Aexp\left(-\left|\left(\alpha_R-\alpha_0\right)^2\right|/2\sigma^2\right)\end{aligned} \tag{36}$$

According to the figure 3, when $d\gg R$, there is

$$\begin{aligned} &sin\left(\varphi_T\right)=\frac{R}{d}sin\left(\varphi_R\right)\Leftrightarrow\varphi_T\approx\frac{R}{d}\varphi_R\\ &\alpha_T=-arctg\left(\frac{h_t-h_r-Rtga_R}{d}\right)\end{aligned} \tag{37}$$

Then,

$$\rho^{DIF}\left(\tau\right)=\frac{\Omega}{1+K_{Rice}+K_{Rice}\left|\Gamma\right|^2}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{-\pi}^{\pi}\left\{\begin{array}{l} exp\left(\begin{array}{l} j\frac{2\pi f}{c}\upsilon_T\tau\left(\begin{array}{l} cos\left(-arctg\left(\frac{h_t-h_r-Rtga_R}{d}\right)\right)cos\alpha_{\upsilon_T}cos\left(\frac{R}{d}\varphi_R-\varphi_{\upsilon_T}\right)\\ +sin\left(\frac{h_t-h_r-Rtga_R}{d}\right)sin\alpha_{\upsilon_T}\end{array}\right)\\ +j\frac{2\pi f}{c}\upsilon_R\tau\left(cos\alpha_R cos\left(\varphi_R-\varphi_{\upsilon_R}\right)\right)\end{array}\right)\\ \frac{exp\left(\kappa cos\left(\varphi_R-\varphi_0\right)\right)}{2\pi I_0\left(\kappa\right)}Aexp\left(-\left|\left(\alpha_R-\alpha_0\right)^2\right|/2\sigma^2\right)d\alpha_R d\varphi_R\end{array}\right\} \tag{38}$$

We make hypothesis that $\kappa=0$, namely the scatterer is omnidirectional evenly distributed around the ground control station. When I do not consider the extension of EA, namely taking $f\left(\alpha\right)=\delta\left(\alpha\right)$, then three-channel model will be turned into two-dimensional random channel model. Further we can assume that the UAV has no movements, i.e. $\alpha_{\upsilon_T}=0$, $\varphi_{\upsilon_T}=0$, $\upsilon_T=0$.

According to

$$J_n(z) = \frac{1}{2\pi i^n} \int_0^{2\pi} e^{iz\cos\varphi} e^{in\varphi} d\varphi \qquad (39)$$

Then type (38) can be simplified into

$$\begin{aligned} \rho^{DIF}(\tau) &= \frac{\Omega}{1 + K_{Rice} + K_{Rice}|\Gamma|^2} \int_0^{2\pi} exp\left(\frac{j2\pi f}{c} \upsilon_R \tau cos\left(\varphi_R - \varphi_{\upsilon_R}\right)\right) \frac{1}{2\pi} d\varphi_R \\ &= \frac{\Omega}{1 + K_{Rice} + K_{Rice}|\Gamma|^2} J_0\left(\frac{2\pi f}{c}\upsilon_R \tau\right) \end{aligned} \qquad (40)$$

$J_0(x)$ represents zero order Bessel function, it is exactly the same as that of Clarke model, it also explains type (38) contains Clarke model, the simulation results are as shown as in figure 4. Its graphic trend has correspondence with the two-dimensional of the UAV channel model. Auto-correlation function of this two models and auto-correlation function of the classical model are corresponding. Thus it can indirectly prove that the UAV three-dimensional model is correct and has the reference value.

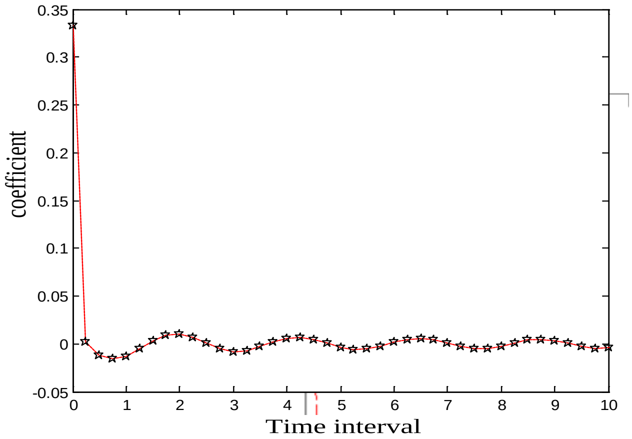

Fig 4 Auto correlation function of 3D degenerate 2D channel model when UAV stop

The direct components and reflection component of the correlation coefficient are both the certain function, when the other parameters are the constant, the relationship between the correlation coefficient and the time delay meet certain periodicity, its simulation results are shown as in figure 5, 6.

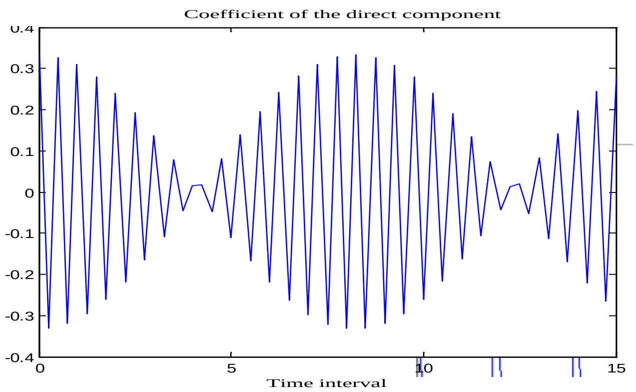

Fig 5 Autocorrelation function of LOS component

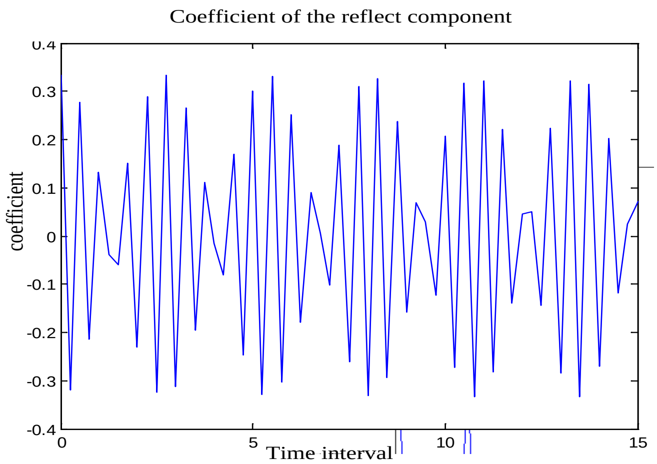

Fig 6 Autocorrelation function of reflecting component

4. Conclusion

In the paper, it analyzes the UAV communication channel in the three-dimensional propagation environment. Assuming conditions are more comprehensive, the space of the transfer is the three dimensional space, and takes the actual electromagnetic as electromagnetic wave. It makes analysis of the space in a three-dimensional space channel, and the azimuth extension function and pitching angle extension function are studied.

According to the UAV channel in three-dimensional space is mainly the characteristics of the multi-path propagation, the small scale propagation model is analyzed, the received electromagnetic waves in the three dimensions can be thought as be formed by the point-blank, secular reflection and scattering components. As the flight altitude UAV is high and the flight distance is far, so we put the ground receiving station in the cylindrical obstacle. The scattering component meets the basic conditions of WSSUS model. We establish a three-dimensional coordinates for the UAV channel model, the expression of three components are respectively discussed and the three-dimensional model channel of the UAV is established.

The correlation function of each component is deduced and the simulation results are also presented. In the paper through using Von Mises function the azimuth distribution is described, the Gaussian distribution is used to describe the elevation angle; we get the impulse response of the channel model. The research shows that when the constraint is proper, the three-dimensional UAV channel model is exactly the same as classical Clarke model, which indirectly proves the correctness of the model.

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