Numerical study of radio wave propagation in clear air acoustic scatterer

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Abstract: This paper numerically investigates the radio wave scattering by the artificial acoustic disturbance in the atmospheric boundary layer. The numerical model is based on the finite-difference time-domain (FDTD) method for radio wave propagation and fluid simulation for atmospheric disturbance by acoustics waves. The characteristics of radio wave scattering propagation in the artificial acoustic perturbations are investigated by this numerical model. The numerical simulation results demonstrate that the radio wave propagation scattered by acoustic scatterer has the characteristic of forward tropospheric scatter. When the radio waves are scattered, they distribute in all directions; a majority of radio waves continues to propagate along the original direction, and only a small part of the energy is scattered. For the same acoustic scatterer, if we merely change the radio wave emission elevation, the horizontal spans of forward scattering radio wave packets centers gradually decrease with the increasing of emission elevations; and the energy of wave packets increases firstly and then decreases with launching elevation, reaching the maximum at a certain angle. If we merely change the wave emitting position, the horizontal spans decrease with the increasing of emission positions, and the energy of wave packets also increases firstly and then decreases with launch position, reaching the maximum at a certain position. This approach can be very promising for atmospheric scatter communications.

Keywords: radio waves scattering propagation; clear air atmosphere; acoustic scatterer; scatter communication.

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1. Introduction

Tropospheric scattering communication may be defined as a radio wave communication method, using the heterogeneous bodies of tropospheric medium to achieve over-the-horizon (OTH) communication of ultra-short waves and microwaves. The method typically includes a radio communication system with excellent reliability and great information capacity [1,2]. Compared with shortwave

communications and multichannel microwave line-of-sight relay communication, tropospheric scattering communication has some advantages [3]. Therefore, it attracts a large amount of research and engineering efforts. Many researchers did plentiful studies and tests in aspects of the scattering propagation theory [4–9] and scattering communication circuit design [10–13].

As the studies for the radio wave scattering propagation in the clear air, Browning et al. described the structure and evolution of clear air turbulence and vertical soundings of wind and temperature [14]. Barat presented the analysis of clear-air turbulence measurements obtained from highly sensitive balloon-borne instrumentation [15]. Gage et al. studied the scattering and reflection mechanism contributing to clear air radar echoes from the troposphere stratosphere and mesosphere [16]. Wiryosumarto observed the planetary boundary layer over equatorial Indonesia with an L band clear-air Doppler radar [17].

Unlike traditional tropospheric communication, in this paper, we propose a method of radio wave scattering by artificial acoustic perturbations in the boundary layer. Radio wave scatter communication based on clear air acoustic scatterer [18] uses the acoustic wave as the atmospheric scatterer. An acoustic wave generator with high-power is used to inject elastic mechanical waves in the lower atmosphere, which results in the local atmosphere disturbance, and the local atmospheric refractive index changes, with the acoustic scatterer obtained. Radio waves propagate upward and are scattered by the acoustic scatterer, then the radio wave scattering communication is achieved. Comparing with the atmospheric turbulence, sound waves are controlled elastic longitudinal waves, and we can artificially control the intensity and location, which is more conducive to the study of atmospheric radio wave scatter communication.

In this paper, a numerical model, describing the scattering propagation of radio wave in the acoustic waves disturbance medium is constructed. By adopting the finite-difference time-domain (FDTD) method [19–21], the

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electromagnetic wave equation in disturbance medium is solved. The model is used to simulate and evaluate the tropospheric radio wave scattering propagation process and the scattering propagation characteristics. Under the background of acoustic wave disturbance, the effects of launch angles and positions of radio waves on propagation characteristics are simulated and analyzed, and the numerical simulation results are expounded from the aspects of the propagation path and the transmission energy. Numerical simulation results show that, the changes of radio wave emission elevation and emission point will significantly affect the waves scattering propagation. In addition, the limitations of the numerical simulation results are also discussed in this paper.

The outline of this paper is as follows. In Section 2, we present the model of radio wave propagation in acoustic disturbance medium. In Section 3, we demonstrate the numerical simulation result and analysis of the scattering propagation process. In Section 4, the propagation characteristics effected by the radio wave emission elevations and positions are analyzed. In Section 5, we discuss the precondition and limitations of this numerical simulation results. The summary of this study is presented in Section 6.

2. Radio wave propagation model

2.1 Electromagnetic wave equation in disturbance medium

In the passive disturbance medium, the divergence of the vector field is zero. According to the vector identical relation $\nabla \times \nabla \times \mathbf{E} = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E}$, Maxwell's equations can be unified as

$$\nabla^2 \mathbf{E} - \frac{n^2}{c_0^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} + \nabla \left(\frac{\nabla n^2}{n^2} \cdot \mathbf{E} \right) - \frac{1}{c_0^2} \frac{\partial n^2}{\partial t} \frac{\partial \mathbf{E}}{\partial t} = 0 \quad (1)$$

where $\mathbf{E}$ is the electric field intensity, t is the time of simulation, ∇^2 is the Laplace operator, c_0 is the velocity of light in the vacuum, and n is the atmospheric refractivity.

Compared with the speed of radio waves, the refractive index varying with time caused by acoustic wave can be ignored, so we neglect the first time partial derivatives of n^2 above.

According to the famous Smith-Weintraub equation, the atmospheric troposphere refractive index [22] is

$$N = (n - 1) \cdot 10^6 = \frac{0.776p}{T} + \frac{3730e}{T^2} \quad (2)$$

where p (in Pascal) is atmospheric pressure, e (in Pascal) is partial pressure of water vapor, and T (in Kelvin) is thermodynamic temperature.

Importing the acoustic disturbance in the atmospheric background, the background pressure and density are p_0 and ρ_0 , and the disturbance pressure and density caused by acoustic waves are p_1 and ρ_1 , respectively, then $p = p_0 + p_1$, $\rho = \rho_0 + \rho_1$.

For simplicity, ignoring the vapor pressure term and combining the mathematical expression of Clapeyron law $p = RT\rho$, then, the refractivity n can be obtained

$$n = 10^{-6}N + 1 = 7.76 \times 10^{-7}R(\rho_0 + \rho_1) + 1 \quad (3)$$

where R (in $J/(kg \cdot K)$) is the gas constant. Substituting (3) into (1), the radio wave propagation equation in acoustic disturbance medium is obtained.

2.2 Spatial and time interval

For the numerical simulation, the stability and convergence of numerical format, which defer to the Courant Friedrichs Lewy (CFL) condition [23] in the finite-difference and finite-volume method, are very important. Thus, the time and space interval must satisfy the following relationship:

$$\Delta t \leq \Delta t_c = \frac{1}{c_0 \sqrt{1/\Delta x^2 + 1/\Delta z^2}}. \quad (4)$$

Based on the simulated radio frequency, in order to accurately depict the propagation process, set spatial interval $\Delta x = \Delta z = \lambda/12$, where λ is the wavelength, that is, there are 12 grid points in one wavelength scale in horizontal and vertical directions, respectively. Since a short time interval of the mesh can effectually improve the calculation accuracy in actual calculation, take time interval $\Delta t = 0.5\Delta t_c$ here.

3. Numerical simulation of radio wave scatter propagation

3.1 Atmospheric background

Under normal conditions, the temperature in troposphere decreases with height. Atmospheric density and temperature profiles are given by empirical models MSISE-00. Fig. 1(a) is the profile of atmospheric density, and Fig. 1(b) is the sectional view of atmospheric temperature, with the turbulence and impact viscous phenomena ignored.

Fig. 1 Profiles of the atmospheric background

For the convenience of numerical simulation, we suppose that, the electromagnetic wave straightly propagates in the atmosphere, and the curvature of path is ignored.

3.2 Simulation parameters

In this paper, we use the Cartesian coordinate system with x -axis in the horizontal direction and z -axis in the vertical direction, respectively, and only the components of the acoustic waves and radio waves in plane are considered. The emission elevation angle is defined as the angle between the emission direction and the positive direction of x -axis.

The frequency of acoustic waves is set as 102 Hz. Since atmospheric absorption of such a low-frequency acoustic wave is less effective, the acoustic wave can propagate to a relatively higher altitude [24]. The transmitting elevation of acoustic waves is 90° , with the launch points located at (1 000, 300) in the initial emission moment.

For the carrier frequency, in the actual application, frequencies ranging from 100 MHz to 5 000 MHz are used [1]. In this paper, the radio frequency range of 100–1 000 MHz is adopted in the simulation.

At the initial time ($t = 0$), when the wave packet is static, a Gaussian monochromatic sine acoustic wave packet spreads vertically upward in the atmosphere, and the disturbance form [25] is

$$\rho(x, z) = A_a \sin[k_{ax}(x - x_a) + k_{az}(z - z_a)] \cdot$$

$$\exp[-(x - x_a)^2/2\sigma_{ax}^2] \cdot \exp[-(z - z_a)^2/2\sigma_{az}^2] \quad (5)$$

where A_a (in kilogram per cubic meter) is amplitude of the acoustic disturbance density; x_a and z_a are initial geometry positions of the acoustic wave packets centers in x and z directions, respectively; σ_{ax} and σ_{az} are the half widths of the acoustic wave packets in x and z directions, respectively; k_{ax} and k_{az} are the horizontal component and the vertical component of the wave number of acoustic wave packets, respectively.

In this paper, set $A_a = 0.005 \text{ kg/m}^3$; $\sigma_{ax} = 30 \text{ m}$, $\sigma_{az} = 9 \text{ m}$. At the initial time ($t = 0$), the wave packet center located at $x_a = 1 \text{ km}$, $z_a = 0.3 \text{ km}$; as the acoustic emission elevation is 90° , then $k_{ax} = 0$.

At the initial time ($t = 0$), a Gaussian monochromatic sine radio wave packet spreading upward is added in the medium, and the mathematical form is

$$E(x, z) = A_e \sin[k_e \cos \theta \cdot (x - x_e) + k_e \sin \theta \cdot (z - z_e)] \cdot$$

$$\exp[-(x - x_e)^2/2\sigma_{ex}^2] \cdot \exp[-(z - z_e)^2/2\sigma_{ez}^2] \quad (6)$$

where A_e (in volt per meter) is the amplitude of the electric field intensity; x_e and z_e are initial geometry positions of radio wave packets centers in x and z directions, respectively; σ_{ex} and σ_{ez} are the half widths of the wave packets

in x and z directions, respectively; θ is the incidence elevation between the launch direction and the horizontal plane; k is the wave number of radio wave packages. In this paper, set $A_e = 2.0 \text{ v/m}$; $\sigma_{ex} = 3 \text{ m}$, $\sigma_{ez} = 2 \text{ m}$.

3.3 Numerical simulation of scattering propagation process

Radio wave scattering communication in this simulation uses the acoustic scatterer as the atmospheric scatterer. In the clear air, acoustic waves are emitted upward, causing the troposphere disturbance, and the heterogeneous bodies with the refractive index distinct from the surrounding atmosphere are produced. When the heterogeneous bodies reflect the radio signals, the second radiation signals are generated in every direction, with some of the scattered signals forward, as shown in Fig. 2.

Fig. 2 Schematic diagram of the scattering span under acoustic disturbance background

Fig. 2 is a sketch map of a scattering communication span in the medium interfered by acoustic waves. This graph is merely a symbolic representation, and the circuit utilizes bistatic radar in a general way. This section focuses on the radio wave scattering of local heterogeneous bodies caused by acoustic waves, and the numerical simulation results are the radio wave scattering propagation process nearby the reflection region. In this section, set the radio wave packet centered at (600,100) at the initial time; the radio wave frequency is set to 200 MHz, with the transmit elevation of 45° .

Since the propagation velocity of acoustic waves is much smaller than that of the radio wave, and the accuracy limitations of computer simulation, we believe that, when the radio waves propagate upward in the microsecond timescale, the corresponding acoustic scatterer is relatively static.

Fig. 3 is the wave packet energy contour maps of the radio wave scatter propagation process near reflection regions. The acoustic wave packet center is located at (1 000, 600). Fig. 3(a), (b) and (c) are state diagrams of different propagation times, respectively. Fig. 3(a) is the transient state of radio waves after launching with a certain elevation; Fig. 3(b) is radio wave propagating across the

acoustic scatterer, and the scattering occurs; in Fig. 3(c), the radio waves are scattered, with part of the waves continuing to spread in the original direction, and part of the forward scattering echo propagating to the ground. It can be seen from Fig. 3, the upward propagated radio waves are scattered by the atmospheric inhomogeneity caused by acoustic wave packets, then the secondary radiation waves produce and propagate in different directions.

Fig. 3 Wave packet energy contour maps of acoustic disturbance and radio wave scattering propagation process near the scattering region

The scattering directional diagram of radio wave packets near the scattering region is shown in Fig. 4. The scattering region is the region near the scattering point. Fig. 4(a) is the distribution of secondary radiation waves for the horizontal distance range of 720–920 m; Fig. 4(b) is the distribution of scattered and transmitted waves within the range of 1 000–1 400 m. It is showed in Fig. 4 that, when the radio waves pass through the heterogeneous bodies, the scattered waves emerge in all directions, while the scattering wave intensity is distinct in different directions.

Fig. 5 is continuous capture modes (contour map of electric field amplitude) of the scattering propagation process of radio wave packets near the scattering region under

the acoustic disturbance background. Under standard atmospheric pressure, the acoustic pressure perturbation P_1 is micro scale. The acoustic disturbance in the atmosphere is small amplitude perturbation, and the scattering of the acoustic scatterer is feeble.

Fig. 4 Scattering directional diagram of radio wave packet in the acoustic disturbance medium

Fig. 5 Continuous capture modes (contour map of electric field amplitude) of scattering propagation process of radio wave packet near the scattering region

Combining Figs. 3, 4 and 5, it can be seen that, when passing through heterogeneous bodies, most of radio wave packets continue to propagate along the original propagation direction, only a small part of the energy is scattered, wherein, a portion of the scattered wave forms the forward scattering wave. Due to the scattering, the transmitted electromagnetic energy is attenuated, as shown in Fig. 5.

4. Simulation results

When the radio wave propagates in the atmosphere, the scattering abilities relate to the size, the shape and electrical characteristics of the scatterer. In addition, the inherent characteristic of radio, such as frequency; or device configuration, such as the emission elevation of radar beam, the relative position of scatterer and radio waves, will have a great impact on the scattering results. Under the same atmospheric conditions and acoustic scatterer, the effects of different radio wave launching elevations and emission positions on the radio waves propagation characteristics are qualitatively discussed in this section.

4.1 Effects of emission elevation on the scattering propagation of radio waves

The frequency of radio waves used in this section is 200 MHz, and the wave packet center of the acoustic scatterer is located at (1 000, 600).

Fig. 6 is the propagation trajectories of the radio wave packet centers corresponding to different emission elevations near the scattering region. The initial radio wave packet center is located at (600,100); the range of launching elevation is $35^\circ - 75^\circ$, with the angular interval of 5° . As shown in Fig. 6, for the same scatterer, different radio transmitting elevations correspond to different scattering trajectories. Within the angles range of $35^\circ - 75^\circ$, the horizontal spans of the forward scattered wave gradually decrease with the increase of emission elevations.

Fig. 6 Scattering propagation trajectories of the radio wave packet centers near the scattering region corresponding to different wave emitting elevations with the same acoustic scatterer

The horizontal span Δx is defined as the horizontal distance between the forward scattering waves and the initial transmission wave at the same height. The horizontal spans of launching elevation at 35° are about twice the span at 75° .

Combining the geometric relationships of wave scattering propagation at the scattering height shown in Fig. 2, this phenomenon can be roughly explained: with the different radio waves emitted elevations, the positions of wave scattering points are different. For a fixed acoustic scatterer, and within a certain range of elevation, the greater the wave elevation is, the smaller the horizontal span is, and the smaller the horizontal span of the forward scattering wave at the same height is. Fig. 7 describes this phenomenon in a more direct way (data represented by “*”). It is clear that, the numerical simulation results in Fig. 6 and Fig. 7 well match the physical processes of radio wave scattering propagation.

Fig. 7 Horizontal spans Δx of radio wave forward scattering wave packet centers (at the same height) varying with emission elevations corresponding to different launch points with the same acoustic scatterer

Fig. 7 is the horizontal span of forward scattering wave packet centers (at the same height) varying with emission elevations corresponding to different launch points under the same acoustic scatterer. The initial radio wave packet centers are successively located at (400,100) and (600,100). In Fig. 7, on the one hand, for different radio wave emission points, and within a certain angles range ($30^\circ - 75^\circ$), the variation tendencies of the horizontal spans with emission elevations are consistent, and gradually reduce with the increasing of the emission elevations.

On the other hand, for a fixed emission elevation, such as the angle of 50° , the horizontal spans corresponding to different radio emission positions are different. The horizontal span Δx is larger when the emission point is located at $x = 400$ m (data represented by “□”), comparing with that when $x = 600$ m (data indicated by “*”). Thus, for the same emission elevation and heterogeneous bodies, the

farther the relative location (within certain limits) between the acoustic scatterer and the wave emitting point is, the larger the horizontal span of the forward scattering echo is.

Fig. 8 is the ratio of the total energy of the initial incident radio wave packet and the forward scattered wave packet varying with emitted elevation, and the initial radio wave packets centers are located at (400,100) and (600,100), respectively. In the practical application, the forward scattering waves are meaningful for scatter communication, therefore, only the ratio of the total energy of the incident wave and the forward scattered wave is given here. In Fig. 8, for the radio emission points at different locations, and within a certain range of angles, the energy variation tendencies of forward scattering wave with emission elevations at a fixed height are consistent. It is observed that, with the increase of emission elevations, the energy of forward scattering echo no longer changes monotonously, but increases firstly and then decreases. Within the angles range of $20^\circ - 75^\circ$, there is an elevation corresponding to the maximum value of the forward scattering energy. When the relative position of the acoustic scatterer and the radio wave emission point changes, the emission elevation corresponding to the maximum forward scattering energy changes. When $x = 400$ m (data denoted by “□”), the energy of forward scattering echoes gradually increases with the increase of elevations, and maximizing at the elevation of 35° , then, the echo energy gradually decreases with the increase of elevations. When $x = 600$ m (data denoted by “*”), the trend is consistent with that when $x = 400$ m, but the maximum energy of forward scattering echo appears at the elevation of 50° in this simulation.

Fig. 8 Ratio of the total energy of forward scattered wave packet (E_f) and the initial incident radio wave packet (E_i) varying with emitted elevation at a fixed height with the same acoustic scatterer

This phenomenon can be roughly explained by the shape of the acoustic wave packet scatterer. The acoustic packet used in this simulation is the Gaussian sine wave packet, with the sound pressure maximum at the wave packet center, and the edge pressure of the acous-

tic wave packet is much smaller. It can be perceived in Fig. 6 that, the scattering points vary with the elevations. When the radio wave is scattered at the edge of the acoustic wave packet, the energy of forward scatters radio waves is weaker; when the radio wave is scattered at or near the center of the wave packet, the scattered energy is stronger, and the maximum energy of the forward scattering echo appears. When the relative location of the radio wave emission point and scatterer changes, the wave emission angle corresponding to the scatterer center changes, and the farther the distance (within certain limits) between them is, the smaller the elevation corresponding to the maximum energy is.

In addition, the elevation values used in this simulation with the interval of 5° , and the numerical simulation results show that, the maximum energy of forward scattering echo appears at the elevation of 35° and 50° , respectively, but these elevations may be a certain angle between 30° and 40° or between 45° and 55° in practice.

Combining Fig. 7 and Fig. 8, it can be observed that, when the relative location of the radio wave emission point and heterogeneous bodies changes, the emission elevation that the maximum forward scattered energy emerges will be different. Nevertheless, the overall variation trends of the horizontal spans and energy with emitted elevation are consistent.

4.2 Effects of emission location on the scattering propagation of radio waves

The simulation results in Fig. 7 manifest that, for a certain radio emission elevation, the horizontal spans of forward scattering echo corresponding to different transmitter positions are different; and the farther the relative distances between wave emitting points and heterogeneous bodies are, the bigger the horizontal spans are. For the same acoustic scatterer, the effects of different radio wave emitting positions on the scattering propagation trajectory and energy are simulated in this section. The radio frequency used in this section is 200 MHz, with the wave emitting elevation of 45° and acoustic wave packet scatterer centered at (1 000, 600).

Fig. 9 is the scattering propagation trajectories of radio wave packet centers near the scattering region, with radio emission at different positions. In the initial time, the range of the horizontal positions of the emission radio wave packet center is 150–750 m, with the distance interval of 150 m, and the vertical positions are 100 m. The horizontal position of the wave packet center of the acoustic scatterer is 1 000 m, with the vertical position of 600 m.

As shown in Fig. 9, with the increase of the horizontal

emitted positions of radio waves, the horizontal position of the forward scattering echo gradually increases. It is clear that, at the height of almost 200 m, the horizontal position of the forward scattering wave packet center locates at 1 400 m when $x = 150$ m (data denoted by “*”), and nearly 1 700 m when $x = 750$ m (data denoted by “.”). This phenomenon can also be explained by the position change of scattering points. With the scatterer and the emission elevation unchanged, and with the increase of the horizontal emission position, the horizontal distance of forward scattering echo increases.

Fig. 9 Scattering propagation trajectories of the radio wave packet centers near the scattering region with radio emission at different positions under the same acoustic scatterer background

Fig. 10 is the horizontal span Δx of forward scattering wave packets varying with the initial radio wave emission positions. As we can see from Fig. 10, with the gradually increasing (within a certain range) of horizontal emission positions, the distance between acoustic scatterer and the initial horizontal launch position decreases, and the horizontal spans Δx of the forward scattering wave echoes gradually decrease. Combining Fig. 9 and Fig. 10, it is distinct that, with the increasing of horizontal emission posi-

tions of radio waves, the horizontal position of the forward scattering echoes are gradually increasing, but the horizontal spans Δx decrease.

Fig. 10 Horizontal span Δx of forward scattering wave packet centers at the same height varying with the initial launch position of radio wave under the same acoustic scatterer background

Fig. 11 is the horizontal positions of forward scattering wave packets varying with the radio wave emission points. The horizontal positions of the initial emitting radio wave are 150 m, 300 m, 450 m and 600 m in the Fig. 11(a), (b), (c) and (d), respectively. Since the energy of the forward scattering wave packet is feeble, the amplitude of the echo wave packet is normalized with A_f/A_c ; where A_f is the electric field amplitude of the forward scattered wave packet (without normalization), and A_c is the maximum electric field amplitude of the original wave packet (without normalization) in Fig. 11(c). As shown in Fig. 11, on the one hand, the horizontal positions of the forward scattering wave packets at the same height gradually increase with the increasing of horizontal emission positions, which is in accordance with the trajectories in Fig. 9. On the other hand, the intensity of forward scattered wave packets, change along with the position of the radio wave emission point.

Fig. 11 Horizontal positions of forward scattering wave packets at the same height varying with the radio emission points under the same acoustic scatterer background

Fig. 12 is the ratio of the total energy of forward scattered wave packet (E_f) and the initial incident radio wave packet (E_i) varying with emission locations. Combining Fig. 11 and Fig. 12, it is obvious that, in the range of 150–750 m, with the increasing of radio wave horizontal emitting positions, the energy changing of forward scattering echoes increases firstly and then decreases.

Fig. 12 Ratio of the total energy of forward scattered wave packet (E_f) and the initial incident radio wave packet (E_i) varying with emission locations at a fixed height with the same acoustic scatterer

The reason for this phenomenon is consistent with that in Fig. 8. That is, the shapes of heterogeneous bodies affect the radio wave scattering process, and we do not give unnecessary explanation here. In this section, the maximum energy of the forward scattered wave packet appears in the case of $x = 450$ m in the simulation. However, due to the large interval of emission position, the position may locate between 300 and 600 in practice. In addition, according to Fig. 8, we can deduce that, even if the radio emission elevation is changed, the variation trend of the forward scattered wave packet energy with launching points remains consistent with that in Fig. 12. Combining Figs. 10, 11 and 12, we can conclude that, for the acoustic wave packet scatterer, to get stronger reception signals and larger horizontal spans, the most optimal configuration should be selected by considering the relative position of wave emitting point and acoustic scatterer.

5. Conclusions

By applying the finite-difference time-domain method in radio wave propagation equation in acoustic disturbance medium, a numerical model is constructed. The model is used to simulate the radio wave scattering propagation process in acoustic disturbance medium, and the effects of transmission elevation and emission position on scattering propagation trajectories and energy are studied. Moreover, the applicable conditions of simulation results are discussed. The numerical simulation analysis results are

summarized as follows:

(i) The radio wave scattered by the acoustic scatterer has the characteristic of the tropospheric forward scatter. When the radio waves are scattered, they distribute in all directions, with the waves scattering intensity distinct in different directions. The atmospheric acoustic perturbation is small amplitude perturbation. Thus, only a small part of energy is scattered, with part of the scattered wave forming the forward scattering echo.

(ii) For the same acoustic scatterer, with the radio emission points at a fixed position, and within a certain range of angles, the horizontal spans of forward scattering echoes wave packets centers at the same height gradually decrease with the increasing of emitted elevations; the energy of radio wave packets increases firstly and then decreases with the increasing of emission elevations, and reaches the maximum at a certain angle. Besides, different radio emission positions do not change the changing trend of horizontal spans and energy.

(iii) For the same acoustic scatterer and radio emission elevation, the horizontal distances of forward scattering echoes increase with the increasing of launch horizontal positions; while the horizontal spans decrease with the increasing of the launch positions; the forward wave packet energy increases firstly and then decreases with the increasing of wave emitting points, and reaches a maximum value at a certain position.

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