IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 22, 2021, accepted March 26, 2021, date of publication April 2, 2021, date of current version April 13, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3070702

Study on Electrical Properties of Multilayered Spherical Earth by Wireless Electromagnetic Method

YA GAO, QINGYUN DI, ZHENJUN MA, AND ZHE YUN

CAS Engineering Laboratory for Deep Resources Equipment and Technology, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
Key Laboratory of Shale Gas and Geoengineering, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
Innovation Academy for Earth Science, Chinese Academy of Sciences, Beijing 100029, China
College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

Corresponding author: Qingyun Di (qydi@mail.iggcas.ac.cn)

This work was supported by the National Natural Science Foundation of China under Grant 41874088.

ABSTRACT The wireless electromagnetic method (WEM), a new method combining geophysics and radio physics, can be used for seismic monitoring, ionospheric structure exploration and electrical structure detection within a depth of 10m underground. As the wavelength of an electromagnetic wave can be equal the circumference of the earth, the influence of ionosphere and earth curvature on electromagnetic waves shall be considered. Considering that the earth is a multi-layer geoelectric medium, a multi-layer ''Earth-ionosphere'' model is established to simulate the electromagnetic field more accurately in the actual complex underground structure. By combining the W.K.B method and the impedance recursion method, we initially obtained the response formula under such a model, calculated the Schumann Resonance within the low frequency range of 1-30Hz, and verified the correctness of the algorithm proposed by this paper; we subsequently obtained the propagation characteristics and the frequency characteristics of the electromagnetic field under different electrical structures by simulation and calculation, and analyzed the propagation law of the electromagnetic field at different times and at different equivalent heights of the ionosphere. The results revealed that the influence of the ionosphere and the earth curvature must be accounted for in large-scale deep detection, and different underground structures and the equivalent heights of ionosphere at different times may lead to differences in the value of the electromagnetic field. Therefore, the multi-layered spherical ''Earth-ionosphere'' model can better meet the requirements of high-power WEM for the forward calculation of underground complex electrical structure detection and assist the refined exploration by such a method.

INDEX TERMS Extremely low frequency electromagnetic method, spherical coordinate system, ''earth-ionosphere'' model, multilayered sphere, refined electrical structure.

I. INTRODUCTION

The wireless electromagnetic method (WEM) uses the limited long-distance cable source paved at the near-earth area with high resistance, whose transmitting dipole moment reaches 100km, the power of megawatt and transmitting frequency of electromagnetic wave is within 0.1-300Hz, to detect the underground electrical structure. It combines the advantages of the existing natural source magnetotellurics (MT) and controlled source audio frequency magnetotelluric (CSAMT), among which the controlled source is characterized by a strong signal strength, powerful anti-interference capacity, stable signals, small measurement error, large transmitting dipole moment, wide range of signal coverage, and can frequently detect underground information simultaneously on a large scale. The transmitting-receiving distance is extended from the conventional 10km to over 3,000km, which can perform the electromagnetic detection of the target 10km underground [1]–[4].

The WEM is cored with a high-power controlled source extremely low frequency (CSELF) electromagnetic wave technology. The conventional CSAMT has a relatively small

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Xu.

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detection scale, and the MT electromagnetic method presents weak signal intensity, with poor anti-interference capacity. Although it is complicated to establish a geoelectrical model, the influence of ionosphere is not considered [5]–[14]. The WEM solves the problem in large-scale detection. The high-power CSELF electromagnetic wave technology, dating back to the 1950s, was initially applied to the field of wireless communication, and played an especially important role in nuclear submarine deep water communication and command due to its low emission frequency, extremely long wavelength, stable propagation characteristics of electromagnetic waves in propagation, small attenuation, strong penetration ability, and the ability to penetrate very deeply into the seawater and to reach the safety depth of diving submarines [15]–[17].

As the early research focused on the telecommunication and navigation control, the models established based on the study of extremely low frequency (ELF) electromagnetic characteristics, equate the ''earth-ionosphere'' to an ideal conductor sphere. Waston [18], [19] obtained the sum of series of Hankel function and spherical Bessel function of the electromagnetic field transmitted from and received by the earth surface, and changed the form of the sum of series into that of the integral solution by way of the residue theorem. Wait [20]–[24] analyzed the theory of ELF electromagnetic wave propagation in planar earth-ionospheric waveguides and spherical waveguides, and solved the problem of the electromagnetic field in the inhomogeneous medium. Due to the existence of spherical waveguides, the electromagnetic field resonates within the range of ELF. Fock [25], Galejs [5], [26], [26] and Galejs [27] and other scholars have largely contributed to the study on the propagation of electromagnetic field under 'earth-ionospheric' waveguides and Schumann Resonance. Larsen and Egeland also confirmed the existence of ''resonance'' in the measured noise power spectrum in 1968 [28]. In recent years, Barrick [29]–[32] analyzed the propagation characteristics of the ELF electromagnetic field in a three-layer spherical waveguide of ''earth-ionosphere'' with non-ideal conductors. Many scholars have also achieved progress in the study of ionospheric structure by using the finite difference method and 3D-TML [37]–[40]. The application of WEM in the detection of underground electrical structure was originated from Di and other scholars [1], [4], [33]. This method is designated to detect the underground electrical structure by using the skywaves. The skywave refers to the signal transmitted from the transmitting dipole to the ionosphere, and then reflected back to the ground through the ionosphere. Therefore, it considers the influence of the ionosphere on the electromagnetic field, establishes a full-space horizontal model of ''earth-ionosphere'', and analyzes the propagation characteristics of the electromagnetic field. It has been proven by the research that the waveguides composed of ionosphere and the earth can mitigate the attenuation of the electromagnetic field. As they ignored the influence of the earth curvature, it is not applicable when the transmitting-receiving distance is extensive.

The electrical structure inside the earth's solid layer is complex, and the hypothesis of the earth's equivalent conductive sphere is far from adequate for the refined detection of ELF electromagnetic method. Thus, the primary problem is to study the ''earth-ionosphere'' model, which considers both the earth curvature and the multilayered sphere simultaneously, to promote the refined detection by employing this method. An ''earth-ionosphere'' model consisting of the ionosphere, air layer and solid layer jointly was established for this purpose. Initially the W.K.B method and the impedance recursion method [29], [32] were combined to analyze the electricity of the full-space multi-layer spherical earth and obtain the expression of the electromagnetic field. The correctness of the algorithm proposed by this paper was verified by calculating the Schumann Resonance within the low frequencies ranging from 1 to 30Hz. Subsequently, the propagation characteristics and the frequency characteristics of the electromagnetic field under different electrical structures were obtained by simulation and calculation, and the analysis on its propagation law was also performed. The results demonstrated that the obtained propagation characteristics differed from those of the conventional electromagnetic detection. Also, the influence of the ionosphere heights on the propagation of the electromagnetic field also was considered. Finally, we described the relationship between the electromagnetic field and the underground electrical structure, and applied it to the detection of the refined underground electrical structure.

II. FORWARD MODELING FOR THE MULTILAYERED SPHERICAL ''EARTH-IONOSPHERE'' MODEL

Considering the influence of the earth curvature and ionosphere on the WEM electromagnetic field, we analyzed the propagation characteristics of the electromagnetic wave under the spherical coupling of ''ionosphere-air-earth''. A multilayered spherical ''earth-ionosphere'' model was established with the spherical coordinate system, as shown in Figure 1(a). In the spherical coordinate system (r, θ, ϕ), the earth's core acts as the origin of coordinates, with the vertical electric dipole at the axle z in the air layer, and the ionosphere set above the air layer as the outermost space, thus forming the ''earth-air-ionosphere'' full-space coupling model.

To detect more refined underground electrical structures, a spherical layered medium with $N + 1$ layers, based on a three-layer model of earth-air-ionosphere, was established inside the earth, as shown in Figure 1(b). In the multilayered spherical medium, the electromagnetic fields E_j and H_j in the $j(j = 1, 2, \ldots, N + 1)$ layer were the fields excited by current source of air layer, and the origin of the coordinate system, which is located at the center of the earth, is positive outward. Each layer is l_n in terms of its thickness, with the dielectric constant of ε_j, a magnetic conductivity permeability of μ_j, conductivity of σ_j. The angular frequency is ω, the time factor is $e^{-i\omega t}$, and then the wave number (WN) is $k_j = \omega\sqrt{\mu_j\varepsilon_j(1 + i\sigma_j)/(\omega\varepsilon_j)}$, among which $i = \sqrt{-1}$, progressively increases towards the center of the earth from the first layer to the $N + 1_{th}$ layer.

The three-layered model solution consisting of earth, air and ionosphere was solved by using continuous boundary conditions of impedance. In terms of the underground multilayered spherical layered medium, it initiated the recursion from the impedance at the lowest layer, and obtained the surface equivalent impedance of the earth's surface or ionosphere with the recursion formula. With the direction of the vertical electric dipole as that of the polar axis, it is evident from the symmetry of coordinate axis that the electromagnetic field is independent from the azimuth angle ψ, and each component can be expressed as [29]:

$$\begin{cases} E_r = -\dfrac{\frac{\partial}{\partial\theta}\sin\theta\,\frac{\partial U}{\partial\theta}}{r\sin\theta} = \dfrac{1}{r}[\dfrac{\partial}{\partial r}\left(r^2\dfrac{\partial}{\partial r}\right) + k^2r^2]U \\ E_\theta = \dfrac{1}{r}\dfrac{\partial^2}{\partial r\partial\theta}(rU) \\ H_\varphi = i\omega\varepsilon\dfrac{\partial U}{\partial\theta} \\ E_\varphi = H_r = H_\theta = 0 \end{cases} \tag{1}$$

The potential function U in the above formula complies with the Helmholtz equation:

$$(\nabla^2 + k^2)U = 0 \tag{2}$$

The recorded observation position is $= a + z$, with the transmitting point as $r = a + z_0$, among which a indicates the earth's radius, z and z_0 indicate the heights between the observation point, the receiving point, and the ground. When the method of separation of variables is used to solve the partial differential equation, W.K.B [29]is used for an approximate solution as to the function of r, which is a second-order differential equation with a variable coefficient.

This paper is designated to analyze the characteristics of the electromagnetic field, including the underground electrical information. Different from the field of electromagnetic communications, the earth cannot be equaled to a well-conductive ground simply with a certain impedance. Therefore, the expression of electromagnetic field applicable to this problem is:

$$Er = -\frac{iIdl}{4\omega\varepsilon_0 r^2}\sum_{n=0}^{\infty}\frac{v(v+1)}{N_n\sin(v\pi)}F_n(z_0) \times F_n(z)P_v\left(\cos(\pi-\theta)\right) \tag{3}$$

$$E\theta = -\frac{iIdl}{4\omega\varepsilon_0 r}\sum_{n=0}^{\infty}\frac{1}{N_n\sin(v\pi)}F_n(z_0)\frac{dF_n(z)}{dz} \times \frac{\partial P_v\left(\cos(\pi-\theta)\right)}{\partial\theta} \tag{4}$$

$$H\varphi = \frac{Idl}{4r}\sum_{n=0}^{\infty}\frac{1}{N_n\sin(v\pi)}F_n(z_0)F_n(z)\frac{\partial P_v\left(\cos(\pi-\theta)\right)}{\partial\theta} \tag{5}$$

$$N_n = \frac{4R_g}{(1+R_g)^2}\frac{aC'_n}{3S_n^4}[C_n'^3 - C_n^3 + \frac{3S_n^2}{2}(C'_n(1-\frac{2h}{a}) - C_n)] - \frac{iC'_n\Delta_g}{2C_n^3 k} + \frac{i(1-\frac{2h}{a})[e^{-2ikH} - R_g^2 e^{2ikH}]}{2kC'_n(1+R_g)^2} \tag{6}$$

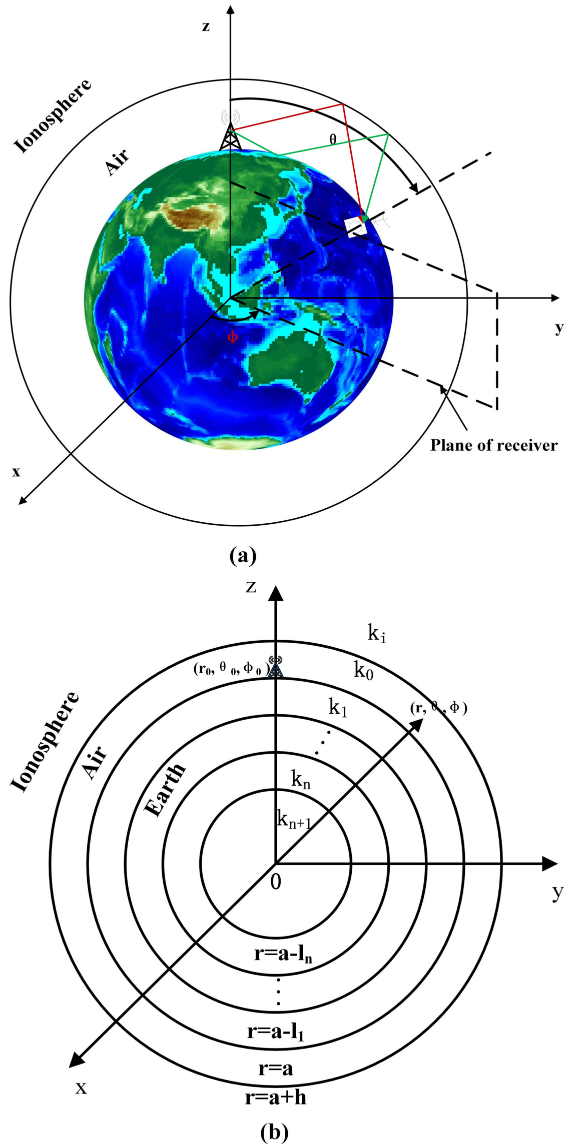

FIGURE 1. Geometry parameters for the spherical earth calculation. (a) "Earth-Air-Ionosphere" Full-space coupling model. (b) Multilayered spherical layered medium.

$$F_n(z) = \frac{1}{1+R_g}\exp\left(-ik\int_0^z (C_n^2 + \frac{2z}{a}S_n^2)^{\frac{1}{2}}dz\right) + \frac{R_g}{1+R_g}\exp\left(+ik\int_0^z (C_n^2 + \frac{2z}{a}S_n^2)^{\frac{1}{2}}dz\right) \tag{7}$$

$$R_g = \frac{C_n - Z_g/\eta}{C_n + Z_g/\eta} \tag{8}$$

$$H = \frac{a}{3S_n^2}[C_n'^3 - C_n^3] \tag{9}$$

$$C'_n = \sqrt{C_n^2 + \frac{2h}{a}S_n^2} \tag{10}$$

$$S_n^2 = \frac{v(v+1)}{k^2a^2},\ C_n^2 = 1 - S_n^2 \tag{11}$$

whereas Idl is a dipole moment of a vertical electric dipole; k indicates the wave number of the air layer; a indicates the earth radius, h indicates the equivalent height of the ionosphere, v indicates a variables separation constant, $P_v(\cos(\pi - \theta))$ indicates a complex-order Legendre function, η indicates the impedance of the air layer, Z_g indicates the equivalent impedance of the earth. C_n indicates the modular coefficient related to the impedance of the earth and the ionosphere.

The transmitting frequency analyzed in this paper ranges from $0.1to300Hz$, and, to simplify the calculation, C_n within the range of ELF, can be simplified as [34]:

$$C_n = \frac{n\pi}{2kh} + \sqrt{(\frac{n\pi}{2kh})^2 - \frac{i(\Delta_g + \Delta_i)}{kh}} \tag{12}$$

whereas, Δ_g and Δ_i indicate the normalized equivalent impedance of the earth and the ionosphere.

In terms of the underground multilayered spherical layered medium, the recursion formula can be applied to obtain the equivalent impedance of the earth's surface, which, under the excitation of vertical electric dipole, can be [32]

$$\begin{aligned} Z_0(r)|_{r=a} = -\frac{\omega\mu_0\gamma_1}{k_1^2}\tanh\{i\gamma_1 l_1 + \tanh^{-1}[\frac{\gamma_2 k_1^2}{\gamma_1 k_2^2}\cdot \\ \tanh[i\gamma_2 l_2 + \tanh^{-1}[\frac{\gamma_3 k_2^2}{\gamma_2 k_3^2}\cdot \\ \tanh[i\gamma_3 l_3 + \cdots \tanh^{-1}[\frac{\gamma_n k_{n-1}^2}{\gamma_{n-1} k_n^2}\cdot \\ \tanh[i\gamma_n l_n + \tanh^{-1}(\frac{k_n\Delta}{\gamma_n})]]]\cdots]]]\}, \end{aligned} \tag{13}$$

$$\Delta \approx \frac{k_n}{k_{n+1}}\sqrt{1 - (\frac{k_n}{k_{n+1}})^2} \tag{14}$$

$$\gamma_j = \sqrt{k_j^2 - k_0^2}, \quad j = 1, 2, \cdots, n \tag{15}$$

The recursion formula (13) equates the complex underground medium to the impedance of comprehensive underground electrical property; therefore, the electromagnetic field received at the surface shows a volume effect, and the information of the underground medium can be transmitted to the electromagnetic wave received at the surface, thus, the electrical structure of the underground medium can be inferred by analyzing the electromagnetic field received at the surface.

We find it difficult to calculate the complex Legendre function when computing the numerical solution. Therefore, we applied the algorithm proposed by Peng *et al.* [36] to calculate it and the Legendre's integral expression to express the electromagnetic field. The numerical method of Gauss integral is then used to calculate the integral in the formula.

$$P_v(\cos\theta) = \frac{2}{\pi}\int_0^\theta \frac{\cos[(v+0.5)t]}{\sqrt{2(\cos t - \cos\theta)}}dt \tag{16}$$

During the computation of the sum of series it was also discovered that the series converge when n is applied to 5.

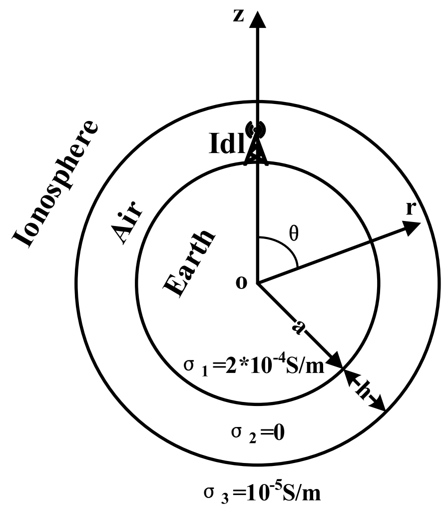

FIGURE 2. Geometry parameters for the spherical "Earth-Ionosphere".

As the ELF electromagnetic field is calculated, the wavelength $\lambda > 2h$, whereas h is the equivalent height of ionosphere, only the zero order TM wave can propagate, and the rest of the waves are ephemeral [31].

III. CALCULATION OF THE SCHUMANN RESONANCE

Within the range of ELF, the frequency can be as low as tens of Hertz, and the wavelength of the electromagnetic wave is comparable to the earth's circumference. Meanwhile, the earth and ionosphere exercise a relatively strong reflection effect on the electromagnetic wave when its wavelength is in a certain proportion to the earth's circumference, and the electromagnetic wave will resonate in the spherical cavity formed by the "earth-ionosphere" (Schumann Resonance). The noise power spectrum measured by Larsen and Egeland in 1968 [28] also proved the phenomenon of "resonance" near the frequencies of 7.5Hz, 14.5Hz and 20.5Hz.

To verify the correctness of the numerical results, we calculated the frequency response characteristics curve of the electromagnetic field within the frequencies ranging from 1 to 30Hz. Assuming that the equivalent height of ionosphere is h = 70km, the earth's radius is a = 6371km, the earth's electric conductivity is 2^*10^{-4}S/m, and the electric conductivity of the air layer is 0, the ionosphere conductivity is 10^{-5}S/m, both the relative dielectric constant ε_r and the magnetic conductivity permeability μ_r are 1, The electric dipole moment is $Idl = 1A \cdot m$, with the three-layered model shown in Figure 2.

The curves of the radial electric fields with varying frequency at the observation points $\theta = \pi/3, \theta = \pi/4, \theta = \pi/6$ and $\theta = \pi/8$, were calculated respectively, among which both the transmitting source and observation point were located on the surface z = z_0 = 0m, with the result shown in Figure 3. The figure demonstrates that the extreme points appear near the frequencies $= 8.8Hz, f = 16.7Hz$ and $f = 23.4Hz$, which were similar to the actual measurement

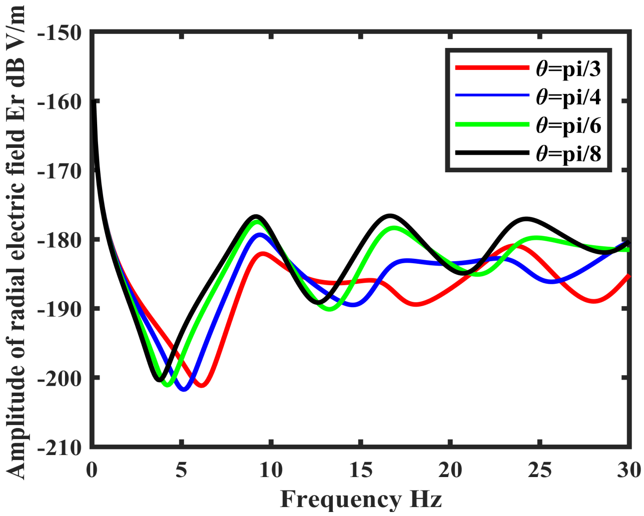

FIGURE 3. Schumann resonance diagram of radial electric field. The red, blue, green and black lines represent the field at the points of $\theta = \pi/3$, $\theta = \pi/4$, $\theta = \pi/6$ and $\pi/8$ respectively.

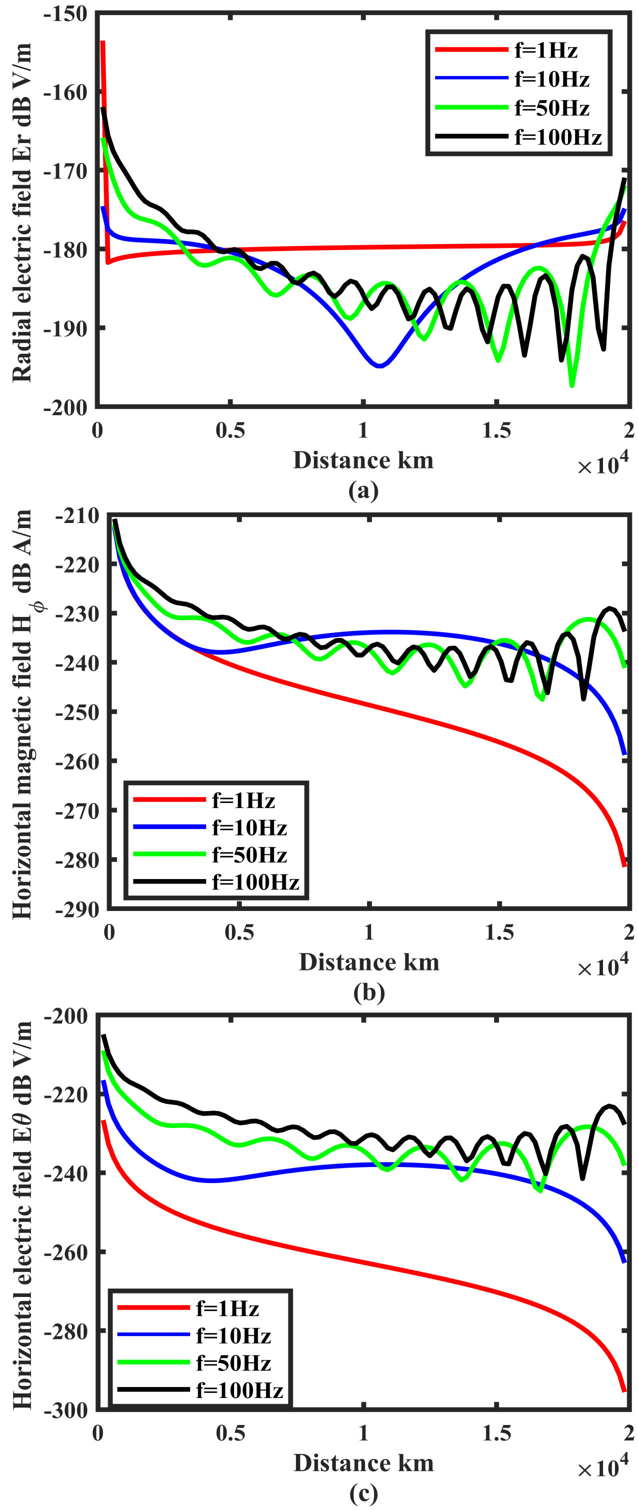

FIGURE 4. Propagation characteristics of the electromagnetic field at different frequencies (a) radial electric field;(b)horizontal magnetic field; (c) horizontal electric field; red, blue, green, and black lines represent the field at frequencies of 1, 10, 50, and 100 Hz, respectively.

results of the noise spectrum, proving the correctness of the algorithm proposed by this paper.

IV. RESEARCH ON THE CHARACTERISTICS OF THE ELECTROMAGNETIC FIELD

A. CHARACTERISTICS OF THE ELECTROMAGNETIC FIELD IN TYPICAL UNDERGROUND ELECTRICAL MODELS

1) "EARTH-IONOSPHERE" THREE-LAYERED MODEL

The earth is equated to a uniform dissipative medium, and the propagation characteristics of the electromagnetic field are analyzed under the three-layer model of "earth-ionosphere". The model diagram is the same as that in Figure 2, and the parameters are set in the previous section.

The propagation curve of the electromagnetic field from the transmitting source to the antipodal point of transmitting source was calculated at the transmitting frequencies of 1, 10, 50 and 100Hz respectively, with the results displayed in Figure 4. It can be observed from the radial electric field diagram, that the minimum point appeared near the equator in the low frequency section, as the electromagnetic waves propagate through the short great-circle path and the long great-circle path passing through the antipodal point overlap with each other, resulting in the "interference" phenomenon;

The higher the frequency, the stronger the oscillation, the closer to the antipodal point it will be; the lower the frequency, the "slower" the wave fluctuation will be, and the fluctuation valley value of the field intensity will gradually approach the source point [29].

As the frequency is extremely low, the wavelength of the electromagnetic wave is very long, and can equal the earth's circumference. In addition, the wavelength increases with the decrease of the frequency; therefore, the phase difference in the electromagnetic waves propagating through the short great-circle path and long great-circle path is minor, the in-phase superposition will form a standing wave, resulting in the minimum point. With the increase of the frequency, this extreme point will shift toward the antipodal point until it disappears and oscillates. The horizontal magnetic field and electric field exhibit the same phenomenon, and since the

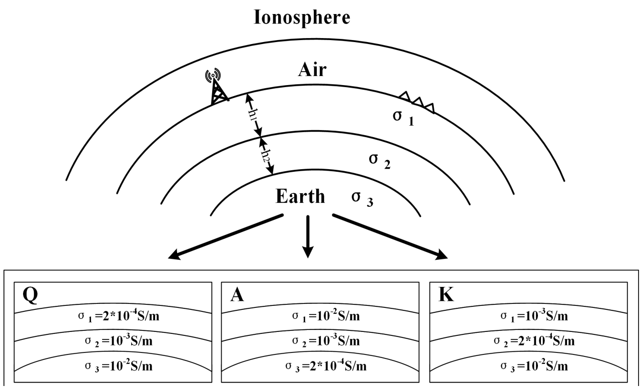

FIGURE 5. The diagram of the spherical "earth-ionosphere" with three layers of underground media.

transmitting source is a vertical electric dipole, the horizontal magnetic field and electric field will rapidly attenuate to zero (0) close to the antipodal point.

As can be seen from Figure 4, the propagation of the electromagnetic field is highly different from the conventional theory of underground electrical exploration when considering the spherical cavity composed of "earth-ionosphere". Due to the earth's natural environment, the electromagnetic wave propagating in the air layer will interfere with each other and superpose to produce a resonance phenomenon, thus, the influence of the ionosphere and the curvature of the earth shall be considered when the WEM is applied to detect the underground electrical structures.

2) THE EARTH'S MULTILAYERED MODEL IN THE "EARTH-IONOSPHERE" MODE

The differences in different multilayered underground electromagnetic field models were analyzed, as shown in Figure 5. The transmitting source is a vertical electric dipole on the ground, where the receiving point is also located, with a three-layered spherical medium with different underground conductivities. The influence of different underground electrical structures on electromagnetic field was also studied by assuming that the equivalent height of the ionosphere is h = 70km, the radius of the earth is a = 6371km, the electric conductivity of the air layer is 0, the ionosphere conductivity is $1*10^{-5}$S/m and that the thickness of the solid layer is h1 = 3km and h2 = 5km. Regarding the three-layered model in electrical detection, we designed three models: Form Q, A and K, as shown in Figure 5, and we analyzed the propagation characteristics of the electromagnetic field and their influence on Schumann Resonance. It was detected that both the relative dielectric constant ε_r and the magnetic conductivity permeability μ_r were 1, and the electric dipole moment was $Idl = 1A \cdot m$.

Figure 6 and Figure 7 display the propagation characteristics curves of the electromagnetic field with the transmitting frequencies of 100Hz and 10Hz from the transmitting source to the antipodal point of the transmitting source respectively. The shape of the curve is similar to that under the same even

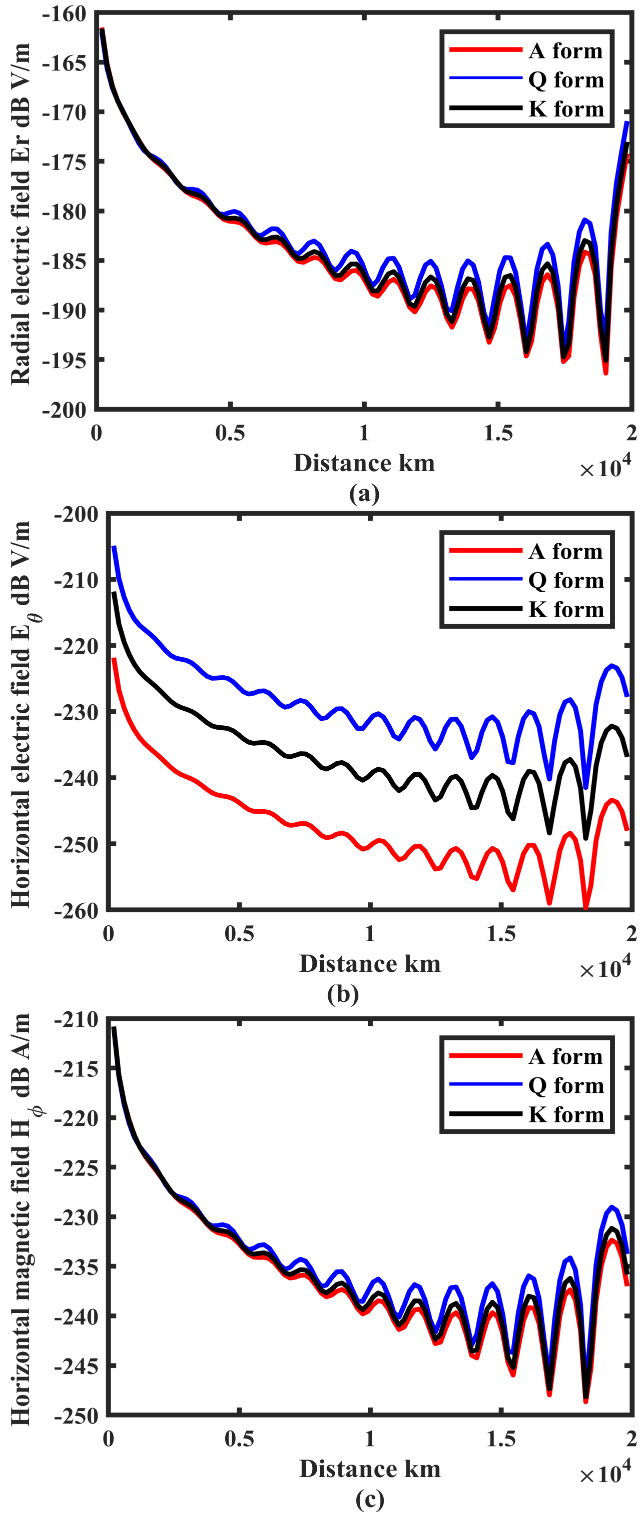

FIGURE 6. The propagation characteristics of the electromagnetic field in the different underground media(100Hz) (a)radial electric field; (b) horizontal electric field; (c) horizontal magnetic field. Blue, black and red lines represent the field at 'A form' 'Q form' and 'K form',respectively.

frequency as the ground in Figure 4, which proved that the multilayered impedance recursion formula can be applied to this method. The results revealed that the electromagnetic responses excited by different underground media were

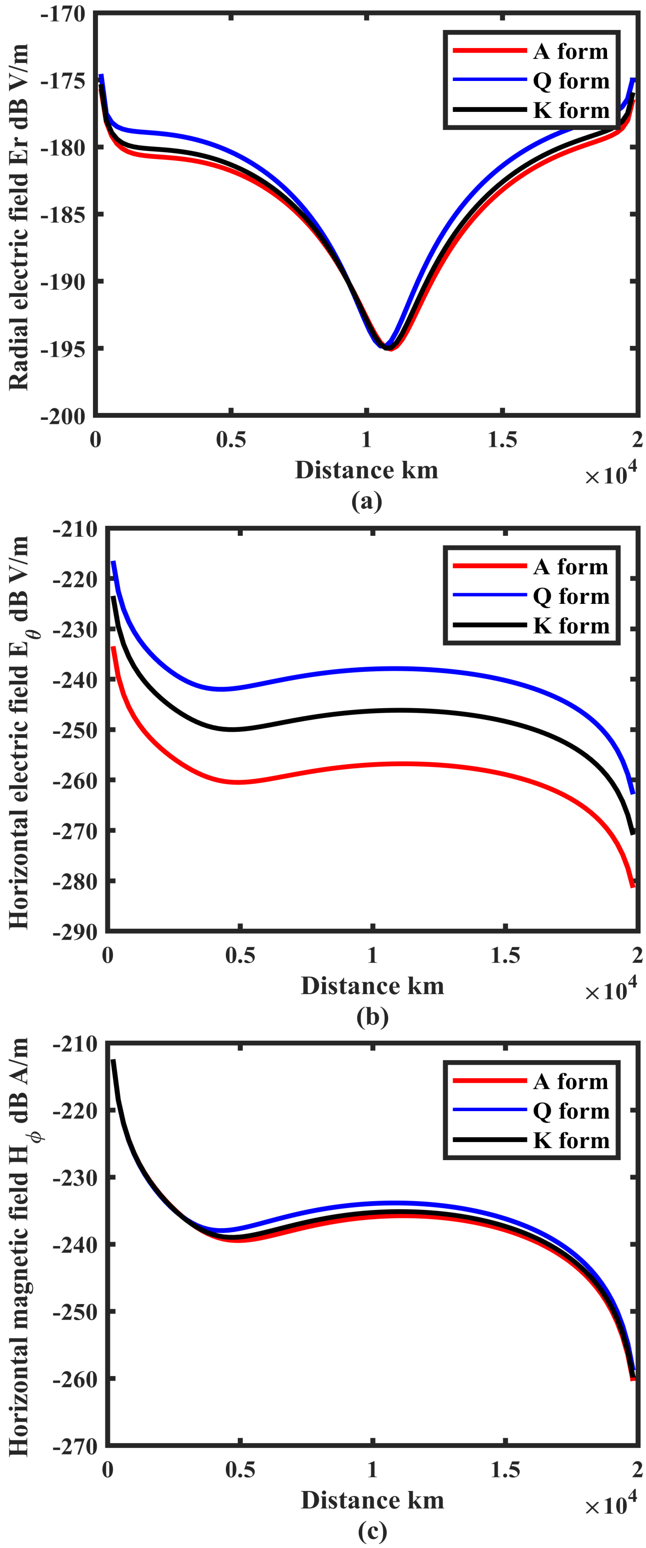

FIGURE 7. The propagation characteristics of the electromagnetic field in the different underground media (10Hz)(a) radial electric field; (b) horizontal electric field; (c) horizontal magnetic field. Blue, black,and red lines represent the field at 'A form' 'Q form' and 'K form',respectively.

different, whether at 10Hz or 100Hz. In summary, the field value calculated from Form Q model was the largest, while that from Form A model was the smallest. Although the

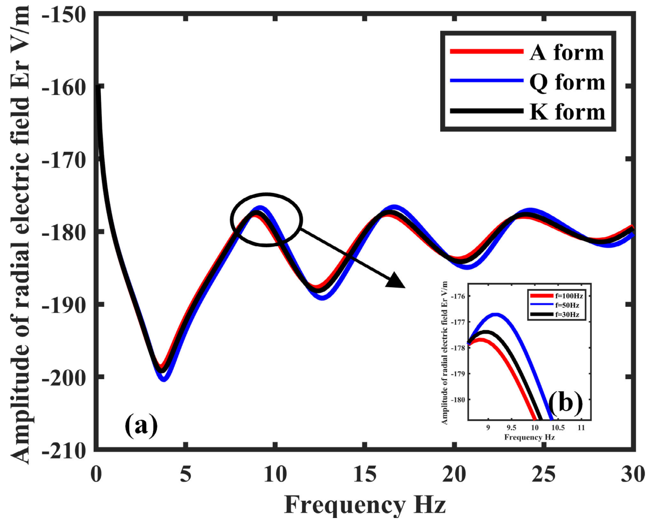

FIGURE 8. The Schumann resonance diagram of the radial electric field in the different underground media ($\theta = \pi/8$). Blue, black and red lines represent the field at 'A form' 'Q form' and 'K form',respectively. (a)Schumann resonance diagram;(b) Partial enlarged drawing.

conductivity values are identical, assigning different conductivity values at different locations will lead to different electromagnetic fields observed on the ground. Figure 8 exhibits the response of different underground media to the Schumann Resonance, and each model can reflect the resonant frequency within the frequency range of 1-30Hz. The resonant frequency calculated from Form Q model shifts evenly to the right, as compared with Form A model. During the propagation of waveguides, the loss of electromagnetic wave is mainly caused by the repeated polarization of the medium when passing through the medium and the conductor loss is caused by the finite conductivity at the upper and lower interfaces. The air layer conductivity is set to 0 in the simulation, and the main reason for the electromagnetic field differences can be attributed to the electromagnetic field difference of loss resulting from different finite conductivities of underground media. The media with a large equivalent conductivity presents a strong reflection of electromagnetic wave and minor conductor loss. We compared the equivalent conductivity of the Forms Q, A and K on the surface, and detected that Form Q presents the most powerful capacity to reflect the electromagnetic field, with the largest calculated amplitude of electromagnetic wave and the most obvious resonance, as it has the highest equivalent conductivity. The simulation results revealed that this method could reflect different underground electrical structures and can be used to analyze the more refined underground electrical structures.

B. THE EQUIVALENT HEIGHT OF THE IONOSPHERE

The ionosphere acts as a propagation medium in which electromagnetic waves are refracted, reflected, scattered and absorbed and some energy is lost in the propagation medium. The concentration of electrons distributed at altitudes in the ionosphere is greatly affected by solar activities; therefore, the equivalent height of Layer D of the lower ionosphere from

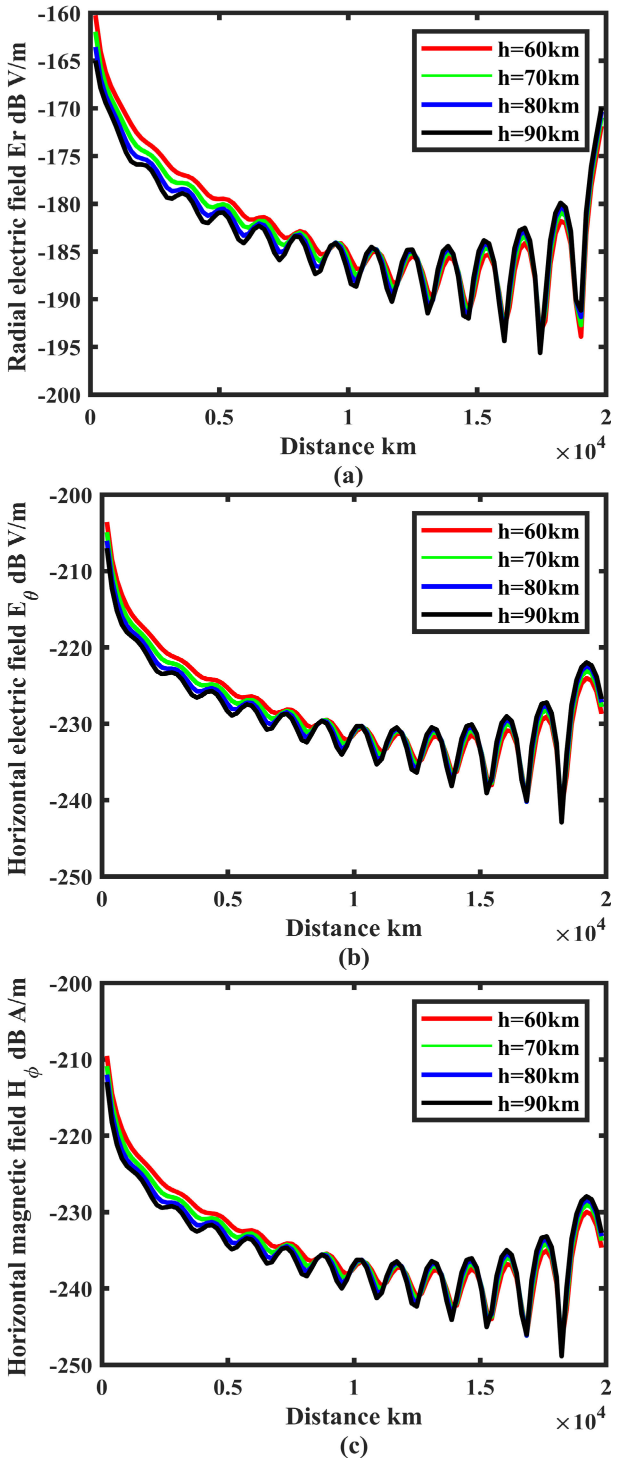

FIGURE 9. **The propagation characteristics of the electromagnetic field at different ionospheric equivalent heights (100Hz)(a) radial electric field; (b) horizontal electric field; c horizontal magnetic field. Red, green, blue and black lines represent the field at the equivalent ionosphere height of 60, 70, 80, and 90km, respectively. Red, green, blue and black lines represent the field at the equivalent ionosphere height of 60, 70, 80, and 90km, respectively.**

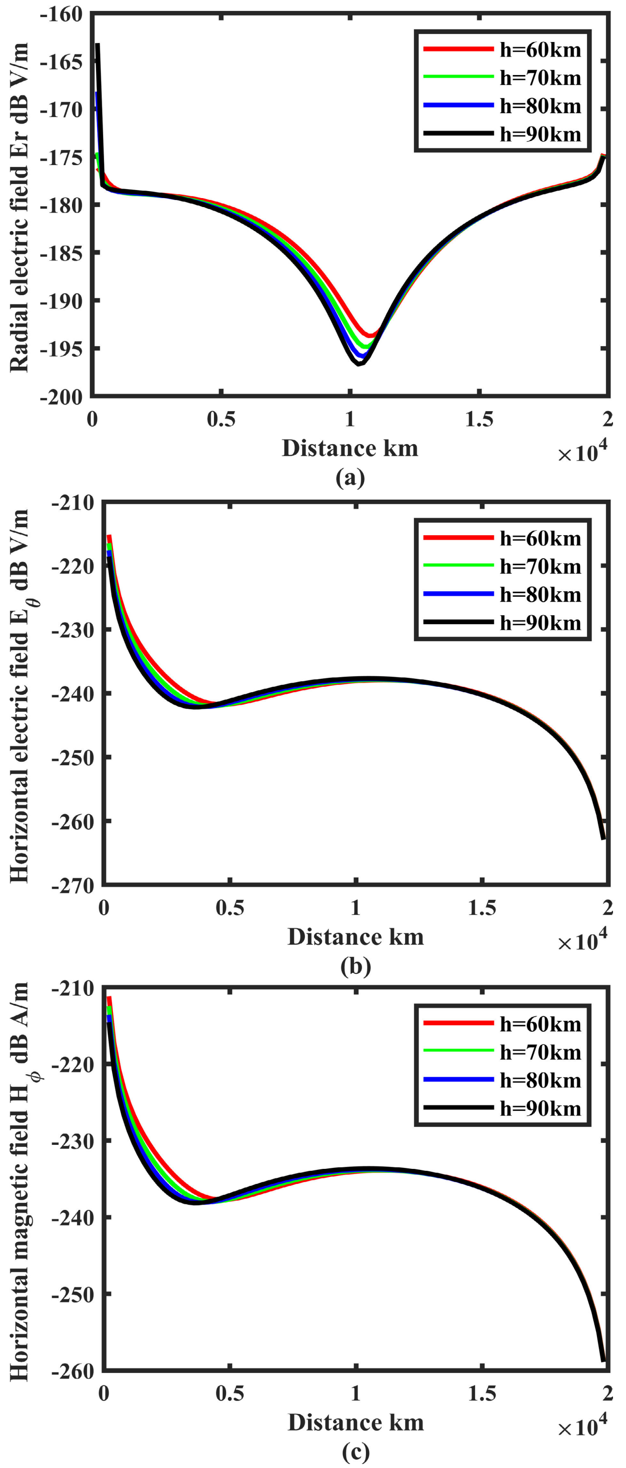

FIGURE 10. **The propagation characteristics of the electromagnetic field at different ionospheric equivalent heights (10Hz).(a) radial electric field; (b) horizontal electric field; (c) horizontal magnetic field. Red, green, blue and black lines represent the field at the equivalent ionosphere height of 60, 70, 80, and 90km, respectively. Red, green, blue, and black lines represent the field at the equivalent ionosphere height of 60, 70, 80, and 90km, respectively.**

the ground varies during the day and at night, generally about 50-90km above the ground. Since the earth is not exposed to the sun during the nighttime, while the density of the lower atmosphere is high, Layer D will disappear; consequently, the equivalent reflection height of the low ionosphere during the nighttime is greater than that during the day. As a result, it is necessary to analyze the influence of the different ionospheric equivalent heights on the ELF electromagnetic wave.

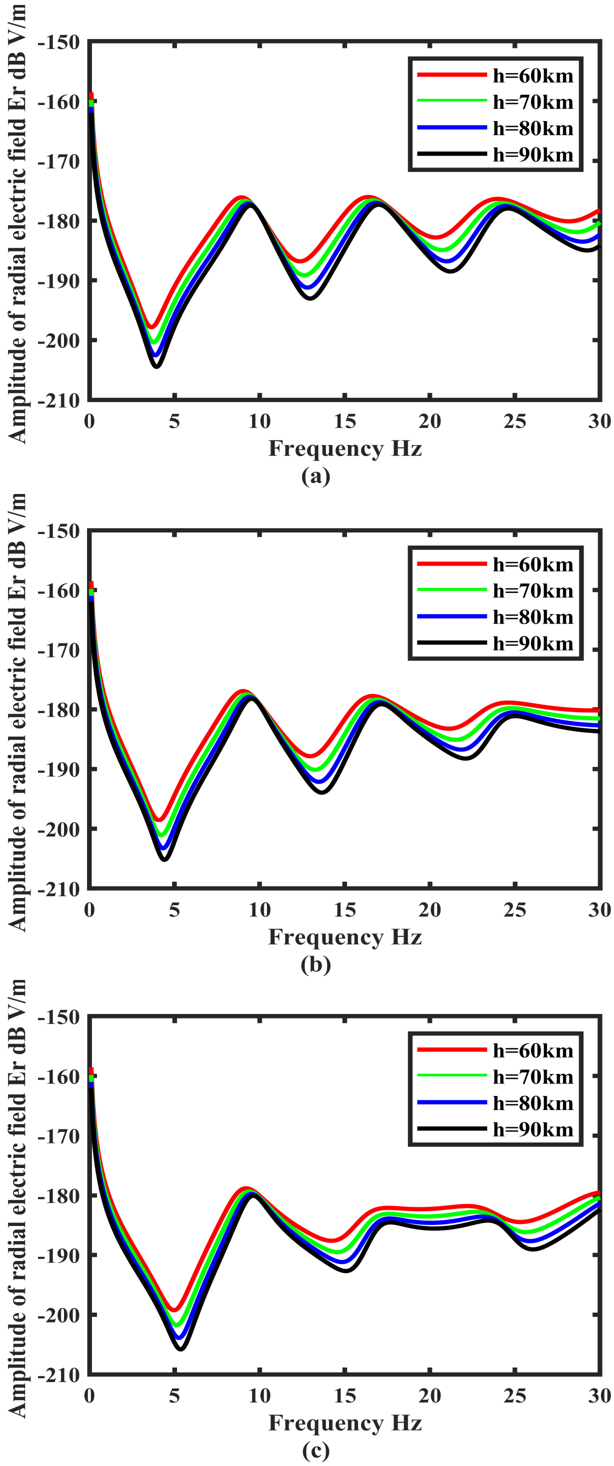

FIGURE 11. The Schumann resonance diagram of radial electric field at different equivalent ionospheric heights(a) Observation points of $\theta = \pi/8$; (b) Observation points of $\theta = \pi/6$; (c) Observation points of $\theta = \pi/4$.The red, green, blue and black lines represent the field at the equivalent ionosphere height of 60, 70, 80, and 90km, respectively. The red, green, blue and black lines represent the field at equivalent ionosphere height of 60, 70, 80, and 90km, respectively.

By using the model shown in Figure 2, with the same model parameters as Section 2, we analyzed the propagation characteristics of the electromagnetic field and the influence of the different ionosphere equivalent heights on the Schumann Resonance when the equivalent heights of the ionosphere were $h = 60km, 70km, 80km$ and $90km$, respectively. The fixed transmitting frequencies were $= 10Hz, 100Hz$, and the propagation characteristics curves of the electromagnetic fields at different equivalent heights of ionosphere are shown in Figure 9-10. It evident from the figures that; the amplitude of the electromagnetic field is slightly different in the hemisphere range near the transmitting source. The greater the equivalent height of the ionosphere, the smaller the amplitude of the field, and the stronger the oscillation of the electromagnetic field. Within the hemisphere range farther from the transmitting source, the oscillation of electromagnetic field in the tail is enhanced under the frequency of 100Hz; therefore, the maximum and minimum values of the electromagnetic field corresponding to the larger equivalent height of the ionosphere are larger and smaller, respectively. At the frequency of 10Hz, the difference in electromagnetic field generated due to the different equivalent heights of ionosphere is mainly reflected within the range of hemisphere close to the transmitting source, with the same trend as 100Hz; however, the low-frequency tail oscillation is weakened, thus, the electromagnetic fields generated by different equivalent heights of the ionosphere basically coincide with each other.

When the positions of fixed receiving points were $\theta = \pi/4$, $\theta = \pi/6$ and $\theta = \pi/8$, we simulated the influence of different equivalent ionosphere heights on the Schumann Resonance. As shown in Figure 11, the shapes of the frequency response characteristics curves are similar at different equivalent ionosphere heights. With the increase of the equivalent ionospheric heights, the overall amplitude of the curves decreases slightly, however, the difference is minor; meanwhile, the resonant frequency shifts to the right. With the decrease of the equivalent ionosphere height, the oscillation of the frequency response curve slows down, and the resonance decreases.

V. CONCLUSION

To enable the WEM to detect more refined underground electrical structures, we analyzed the characteristics of electromagnetic waves under the multilayered spherical coupling of ionosphere, air and solid earth, and solved the expression formula of electromagnetic field in the air layer under the excitation of vertical electric dipole in combination with the W.K.B and the impedance recursion methods.

we obtained the Schumann Resonance frequency by calculating the electrical field within the frequency range of 1-30Hz, verified the correctness of the numerical results, and performed the forward modeling for the electromagnetic characteristics of the three-layered "earth-ionosphere" model. The results revealed that the propagation characteristics of the electromagnetic field calculated by considering the ionosphere and the earth curvature, significantly differ from those calculated based on the horizontal layered model. Due to the existence of the spherical cavity model, the electromagnetic field will oscillate within the range of ELF, due to in-phase superposition. Therefore, while using the ELF electromagnetic field for underground electrical detection, it is necessary to consider the influence of the ionosphere and the earth curvature.

We also analyzed the difference in the electromagnetic fields received on the earth surface with the different underground media models. The electromagnetic field received at the surface responds to the electrical result of the subsurface as a whole, which is expressed as a volume effect. The different subsurface models correspond to different equivalent impedances, and different electromagnetic fields are observed at the surface. Therefore, the electrical structure of the underground medium can be inferred by analyzing the electromagnetic fields received at the surface.

Finally, considering the difference in the nature of the actual ionosphere during the daytime and nighttime, we investigated the effect of the ionospheric equivalent height on the electromagnetic field. The ionospheric equivalent height exerts a certain effect on the calculation results of the electromagnetic field, which is specifically demonstrated by the difference in the amplitude and resonance frequency of the electromagnetic field. Therefore, the influence of the ionosphere changes with time shall be considered in the actual electromagnetic detection, and all the differences in the electromagnetic field shall not be attributed to the differences in the underground electrical properties.

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YA GAO received the B.S. degree in geophysics from Jilin University, Jilin, China, in 2017. She is currently pursuing the Ph.D. degree with the Key Laboratory of Shale Gas and Engineering, Institute of Geology and Geophysics (subordinate to the Innovation Academy for Earth Science), and the College of Earth and Planetary Sciences, University of the Chinese Academy of Sciences. Her research interests include controlled source electromagnetic data forward modeling and inversion.

QINGYUN DI is currently a Researcher with the Key Laboratory of Shale Gas and Engineering, Institute of Geology and Geophysics (subordinate to the Innovation Academy for Earth Science), and a Professor with the College of Earth and Planetary Sciences, University of the Chinese Academy of Sciences, with an emphasis in electromagnetic exploration and instruments. Her research interests include controlled source electromagnetic data forward modeling and inversion, wave motion equation tomography for GPR wave, and electric resistivity tomography and its application.

ZHENJUN MA received the Ph.D. degree in geophysics from the Key Laboratory of Shale Gas and Engineering, Institute of Geology and Geophysics (subordinate to the Innovation Academy for Earth Science), and the College of Earth and Planetary Sciences, University of the Chinese Academy of Sciences. His research interests include theory and applications of the airborne electromagnetic method and the semi-airborne electromagnetic method.

ZHE YUN received the B.S. degree in geo-exploration technology and engineering from the Ocean University of China, Qingdao, China, in 2020. He is currently pursuing the M.S. degree with the Key Laboratory of Shale Gas and Engineering, Institute of Geology and Geophysics (subordinate to the Innovation Academy for Earth Science), and the College of Earth and Planetary Sciences, University of the Chinese Academy of Sciences. His research interests include controlled source electromagnetic data forward modeling and inversion.