Waveform estimation of spaceborne lightning pulse signal

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When the Lightning Electromagnetic Pulse (LEMP) propagates to outer space, it will pass through the complex ionospheric channel. With the collision between ionospheric particles, the LEMP will appear loss and dispersion, which will affect the pulse detected by spaceborne receiver. In this paper, the ionospheric statistical data of multiple regions and typical periods are selected as samples, to compute the amplitude and phase of each frequency for LEMP, which will obtain the frequency response of the ionospheric channel. With difference on the position of field source and spaceborne receiver, the ionospheric channel is not stationary, which varies at amplitude loss and phase delay of each frequency. Due to the impenetrability in low frequency band via ionosphere channel, the pulse cannot be effectively received by receiver in this band. Finally, this paper provides reference models of waveform estimation and proposes a suggestion of receiving the LEMP in VHF band.

Key Words : *lightning pulse, ionospheric channel, frequency response, waveform estimation*

1. INTRODUCTION

In the process of transmission to outer space, the LEMP will pass through complex ionosphere. Due to the inhomogeneity of the ionospheric at different time and position, the amplitude and phase of the LEMP passing via ionosphere channel produce complex effects. Nowadays, there are a few of modeling methods of ionospheric channel including methods of analytical, ray tracing and frequency response[1-2)]. Among these methods, the frequency response method used in this paper is suitable for calculating of multiple samples by its mature theory[3)]. In addition to considering electron collisions which makes main effect via ionosphere, the impact of other particle collisions in the ionosphere and atmosphere is also considered, and the statistical study is carried out with the samples of typical regions and time. After establishing the ionospheric channel model of multiple regions and typical periods, the waveform estimation model of spaceborne lightning pulse signal can be calculated. With analyzing the waveform estimation model, the characteristic can be discovered at time domain and frequency domain, which can also provide a reference for the follow-up research including signal detection and positioning.

2. MODELING

(1) Ionospheric model

The ionosphere is divided into D layer, E layer and F layer, which has different distribution of particle concentration with time and space[4-5)]. In order to study the influence of ionosphere on signal in different situations, IRI-2016 ionosphere model and NRLMSISE-00 atmospheric model as a widely used empirical model is selected to get ionosphere empirical data samples of several regions and typical dates and times in the world.

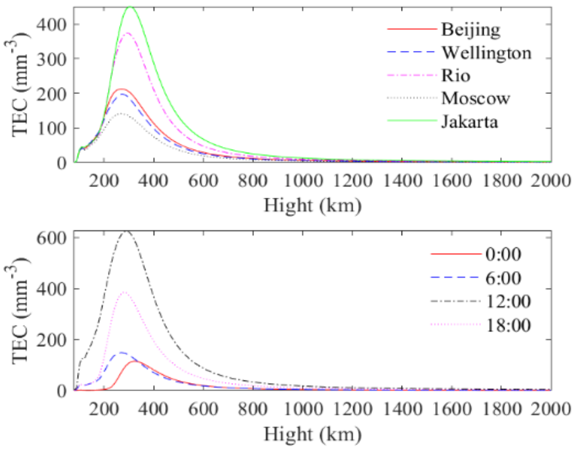

Fig.1 The mean value of TEC at each height.

In the empirical data of ionosphere model, one of the most critical factors affecting the pulse signal passing via ionosphere channel is the Total Electron Concentration (TEC). As shown in **Fig.1**, the TEC data at different times and regions are presented. Considering that the ionospheric electron concentration will fluctuate greatly at different time and place, it is necessary to model several typical ionospheric models and analyze their channel characteristics[6-7)].

(2) LEMP model

LEMP comes from the electromagnetic radiation produced by the lightning discharge in nature, which has strong interference to the satellite. As shown in **Fig.2**, the waveform and amplitude spectrum of the original signal of a typical LEMP are characterized by short duration, and its energy concentration is below 1MHz and has little energy in high frequency part[8-11)].

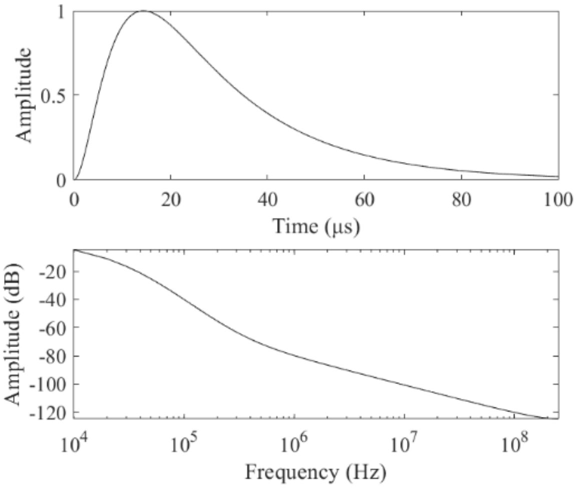

Fig.2 Waveform and amplitude spectrum of the LEMP model in this paper.

3. CHANNEL MODELING METHOD

When the signal passes via ionosphere channel, there will be existing multipath effect such as loss, dispersion and reflection. In this paper, the amplitude and phase responses of each frequency component in the case of vertical incidence are modeled to obtain the ionospheric transmission characteristics under different conditions[12)].

There are corresponding amplitude loss and phase delay on each frequency component which are related to the characteristics of ionosphere itself and the amplitude loss in free space propagation[13-15)].

The amplitude loss and phase delay are related to the collision frequency of electrons with ions and neutral particles. The collision frequency of the space position z determined by the height when longitude and latitude have been determined:

$$v_{et}(z) = v_{ei}(z) + v_{em}(z) \tag{1}$$

where, v_{ei} is the collision frequency of electron and neutral particle, and v_{em} is the collision frequency of electron and ion, which are related to the concentration of each ion n_i and neutral particle n_m, and space temperature T, which expression are shown below.

$$v_{em}(z) = 1.7\times10^{11}\frac{n_m(z)}{2.7\times10^{19}}\sqrt{\frac{T}{300}} \tag{2}$$

$$v_{ei}(z) = \frac{5.5n_i(z)}{T^{\frac{3}{2}}}\ln\left(220\frac{T}{n_i(z)^{\frac{1}{3}}}\right) \tag{3}$$

According teo the collision frequency $v_{et}(z)$, the amplitude loss factor $\alpha(z,\omega)$ and phase constant $\beta(z,\omega)$ of each frequency in the space can be calculated below.

$$\alpha(z,\omega) = \frac{\omega}{\sqrt{2}c}\sqrt{\sqrt{\left[1-\frac{\omega_p^2(z)}{\omega^2+v_{et}^2(z)}\right]^2+\frac{\omega_{\mathrm{p}}^4(z)v_{et}^2(z)}{\omega^2(\omega^2+v_{et}^2(z))^2}}-\left[1-\frac{\omega_p^2(z)}{\omega^2+v_{et}^2(z)}\right]^2} \tag{4}$$

$$\beta(z,\omega) = \frac{\omega}{\sqrt{2}c}\sqrt{\sqrt{\left[1-\frac{\omega_p^2(z)}{\omega^2+v_{et}^2(z)}\right]^2+\frac{\omega_{\mathrm{p}}^4(z)v_{et}^2(z)}{\omega^2(\omega^2+v_{et}^2(z))^2}}+\left[1-\frac{\omega_p^2(z)}{\omega^2+v_{et}^2(z)}\right]^2} \tag{5}$$

where, c is the speed of light, ω is the angular frequency of the incident wave, and $\omega_p(z)$ is the angular frequency of the plasma in the space, which formula is:

$$\omega_p(z) = \sqrt{\frac{N(z)e^2}{m_e\varepsilon_0}} \tag{6}$$

where, m_e is the electron mass, e is the electron charge, $N(z)$ is the number of electrons per unit volume, ε_0 is the vacuum dielectric constant.

After calculating the amplitude loss and phase delay of the single-layer homogeneous medium according to the relevant parameters of the ionospheric model, the frequency response of the amplitude loss and phase delay of the whole ionosphere can be calculated by:

$$H(\omega) = \exp\left(-\int_0^L \alpha(z,\omega)dz\right)\cdot\exp\left(-j\cdot\int_0^L \beta(z,\omega)dz\right) \tag{7}$$

where, j is the imaginary part.

This paper assumes that the ionosphere is composed of several layers of homogeneous medium approximately, and the pulse signal passes via ionosphere channel by vertical incidence.Therefore, the integral of dz can be approximated as the summation of a uniform height distance d_n. $E(\omega)$ is the value of the angular frequency via ionosphere channel, and L is the logarithmic formula for free space loss calculation.

$$E(\omega) = E_0(\omega)\exp\left(-\sum_{n=1}^{N}\alpha_n(n,\omega)d_n + j\omega t - j\sum_{n=1}^{N}\beta_n(n,\omega)d_n\right) \tag{8}$$

$$L(f) = 32.45 + 20\lg f + 20\lg D \tag{9}$$

Table 1 Pulse energy loss via ionospheric transmission at different time.

Time	0:00	6:00	12:00	18:00
Maximum loss (dB)	197	206	224	218
Mean loss (dB)	192	201	219	212

Table 2 Pulse energy loss via ionospheric transmission on different region.

Region	Beijing	Hongkong	Wellington	Hawaii	Lhasa	Rio	Moscow	Jakarta
Maximum loss (dB)	212	216	209	215	214	213	208	215
Mean loss (dB)	219	224	215	223	222	220	214	223

where, f is the frequency (unit: MHz), D is the distance (unit: km), $E_0(\omega)$ is the initial amplitude.

Finally, the ionospheric channel frequency response model is calculated below:

$$E(\omega)=E_0(\omega)\exp\left(\begin{array}{l} j\omega t+\frac{\ln 10}{20}L(\omega) \\ +\sum_{n=1}^{N}\left(\alpha_n(n,\omega)d_n-j\beta_n(n,\omega)d_n\right)\end{array}\right) \quad (10)$$

After that, the waveform estimation of spaceborne lightning pulse can be calculated.

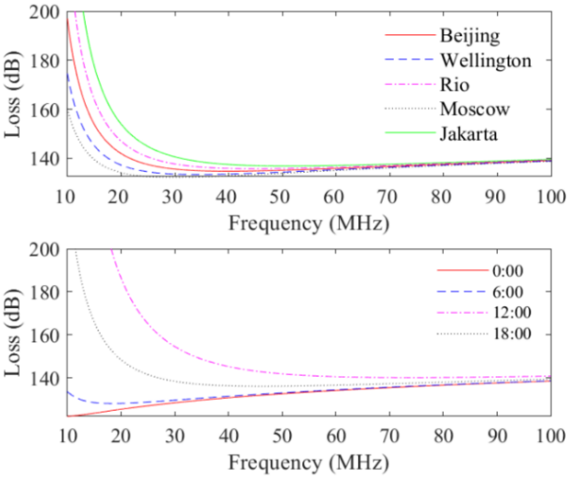

Fig.3 Mean loss via ionosphere channel within 10-100MHz.

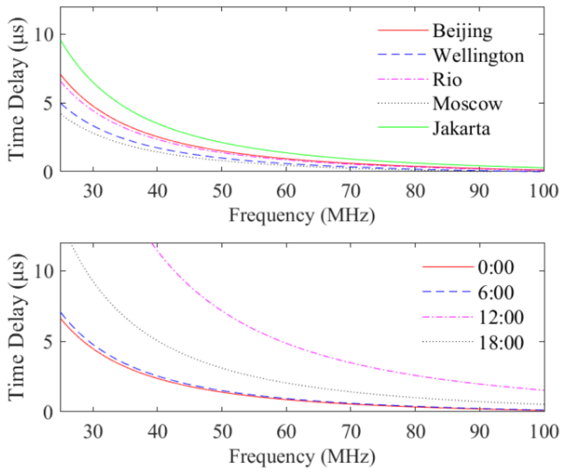

Fig.4 Time delay via ionosphere channel within 25-100MHz.

4. SIMULATION ANALYZING

According to multiple sample data of IRI-2016 and NRLMSISE-00 model, the channel is modeled. Assume that the altitude of the satellite receiver is 2000km. **Fig.3** is the amplitude transmission loss comparison of frequency response within 10MHz-100MHz established by different ionospheric sample.

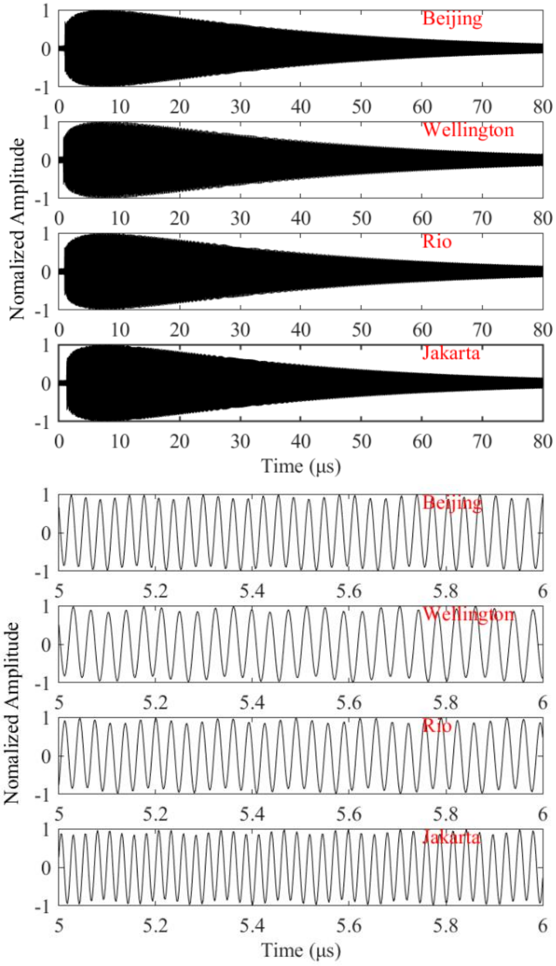

Fig.5 Normalized estimated waveform via ionospheric channel in different region (The top is the overall envelope, and the bottom is the partial enlargement).

According to the amplitude loss, we can get the penetration rate of each frequency in different ionosphere. The high frequency component has lower loss and stronger penetration in ionosphere, but the loss is higher in free space. Both the loss and the band width of penetrating ionosphere at daytime are larger than those at night.

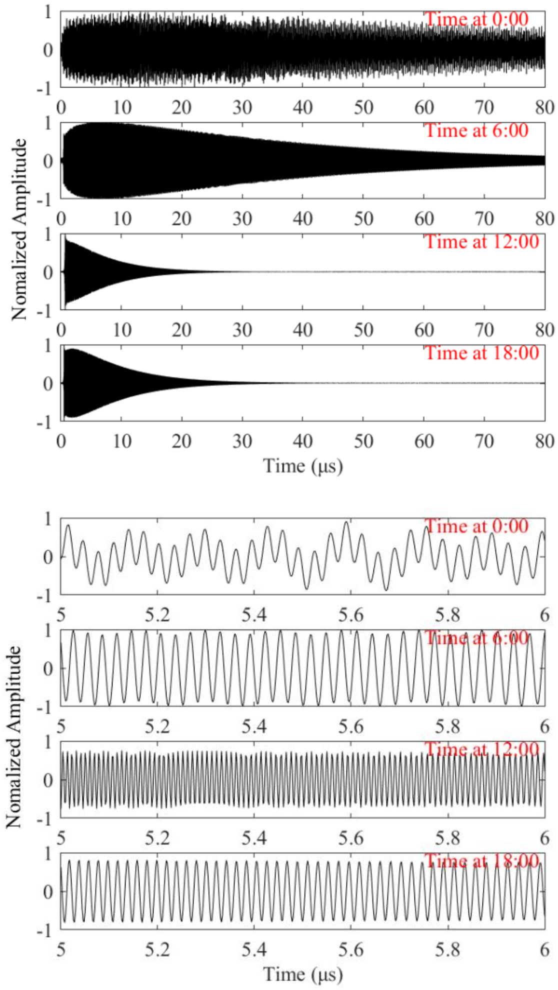

Fig.6 Normalized estimated waveform via ionospheric channel at different time (The top is the overall envelope, and the bottom is the partial enlargement).

In addition, it can be found that the time delay of each sample in the ionospheric channel is also different as shown in **Fig.3**. The time delay of high frequency component is shorter than that of low frequency component and the time delay in daytime is larger than that in night within 25MHz-100MHz.

After modeling ionospheric channel, the pulse signal via ionosphere channel can be estimated. This paper chooses some estimated waveforms at typical time and region as shown in **Fig.5** and **Fig.6**.

It can be found that the estimated waveforms occur time delay which is related to the time via ionosphere channel. It is clear to find that the time delay at night is generally more than that during the day, but there is little difference among regions at the same local time.

The statistical data of energy attenuation are shown in **Table 1** and **Table 2**. It can be found that there is a huge energy loss in the transmission process, which is mainly because the low-frequency components of signal energy are unable to penetrate the ionosphere.

Fig.7 shows that the normalized amplitude spectrum of pulse signal via different ionospheric channels, which can find that the energy is mainly concentrated within the band of 5MHz to 50MHz.

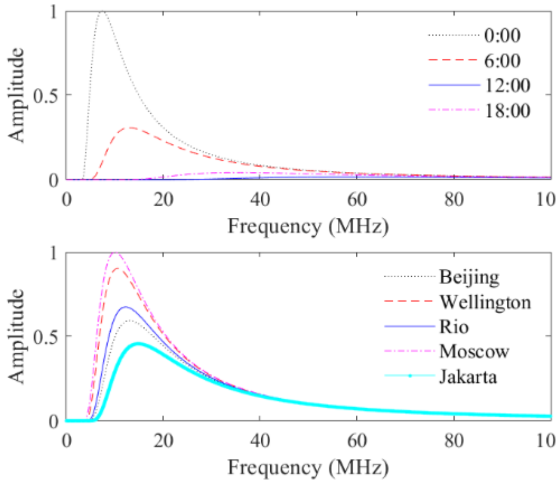

Fig.7 Normalized amplitude spectrum via ionospheric channel.

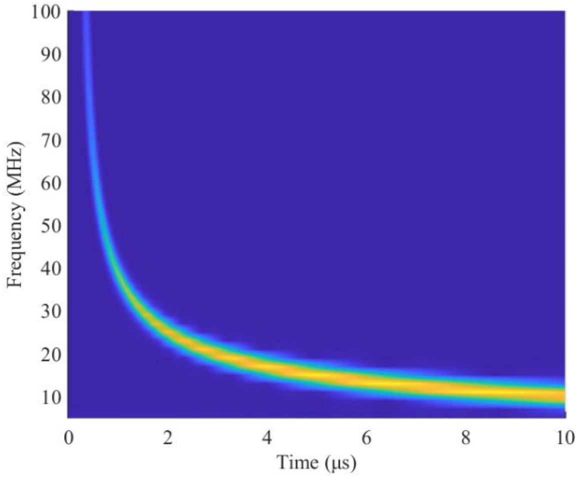

Fig.8 Time-frequency diagram of typical estimation waveform.

However, according to **Fig.3**, the spaceborne lightning pulse is not a time-invariant signal, and the delay of its low-frequency component is greater than that of its high-frequency component from samples. Therefore, the waveform of partial enlargement in **Fig.5** and **Fig.6** is only the instantaneous frequency which cannot reflect the band completely.

To find more characteristics, the time-frequency analysis of estimated waveform by Short-time Fourier Transform (STFT) is performed as shown in **Fig.8**. It can be found that the low-frequency component of the estimated waveform of lightning pulse signal has different degrees of tailing in different frequency components via ionosphere channel. The time-varying characteristics of the estimated waveform are obvious that the overall time-frequency distribution is approximate to the inverse proportional function. Its time-frequency characteristics should be considered to detect spaceborne lightning pulse or estimate its parameters.

According to the above analysis, the low-frequency with high energy when the pulse passes via ionosphere channel hardly, and the high-frequency can reach the ionosphere. But with the increase of frequency, the lower the pulse energy is, the greater the free space loss is. Therefore, the suitable frequency range for ground observation of this pulse signal is VHF.

5. CONCLUSION

In this paper, using the ionospheric sample data of several regions and typical periods, a frequency response calculation method is used to obtain the attenuation and dispersion model of the long-distance transmission via ionosphere channel. When the pulse signal passes through different ionospheric propagation channels, the time delay and attenuation of each frequency are very different, so different estimation waveform models are obtained. After analyzing the characteristic of estimated waveform in time domain, frequency domain and time-frequency domain, the suggestion of receiving and studying spaceborne lightning pulse has been proposed, which lays a foundation for subsequent pulse detection and recognition.

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