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Schumann Resonance Measurement Based on Nonlinear Interaction

Cao Bingxia [1, a], Qiao Xiaolin [2,b]

[1]School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin, China

[2] School of Information Engineering, Harbin Institute of Technology at Weihai, Weihai, China

[a] jchdd1980@163.com, [b] paulqiao@sohu.com

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Abstract. Schumann Resonance relates with global temperature variations, new geophysics phenomena in the low ionosphere and short-term earthquake prediction etc. In this paper based on the nonlinear modulation model of high frequency and extreme-low frequency electromagnetic waves in low ionosphere, the Schumann Resonance observing is researched. Taking the fair weather electric field in account, the cross modulation index was 4.2×10^{-4}. At the first Schumann Resonance observatory of China, the first 4 peaks of Schumann Resonance respectively at 7, 14, 20, 26Hz were obtained in demodulation spectra of the high frequency time service signals. The parameter characteristics of Schumann Resonance in the low ionosphere were analyzed under the geographical condition of middle latitude area. The feasibility of Schumann Resonance measurement by demodulating the spectra of HF has been verified. The non-linearity between Schumann Resonance and very low frequency signals also was discussed.

Introduction

The earth and ionosphere construct a resonator cavity. Its resonance frequency is defined by the size of the earth [1]. The global thunderstorm and lightning provides the excitation of low frequency radiation so that the Schumann Resonance (SR) which can propagate round the earth is generated. Balser and Wagner made measurements to extract the spectrum peaks at 7.8, 14.2, 19.6, 25.9 and 32Hz from the background noise in 1962. Owing to the connection between lightning activity and the Earth's climate it has been suggested that SR may also be used to monitor global temperature variations [2] and variations of water vapor in the upper troposphere. Schumann resonance has been used to study the lower ionosphere on Earth and it has been suggested as one way to explore the lower ionosphere on celestial bodies. Effects on Schumann resonance has been reported following geomagnetic and ionospheric disturbances [3, 4]. More recently, discrete Schumann resonance excitations have been linked to transient luminous events – sprites, elves, jets, and other upper-atmospheric lightning. A new field of interest using Schumann resonance is related to short-term earthquake prediction [5-10].

In 1972, Alpert [11] proposed that the natural electromagnetic wave produced by the thunderstorm is strong enough for the nonlinear effect in D layer ionosphere. That is where the Schumann Resonance generates. Y M. Yampolski et.al.[12]proved the validity of this theory. The large antenna arrays of the radio telescope UTR-2 in Ukraine were used to receive RWS (round-the world signals) from the time and frequency service radio station near Moscow.

Y M. Yampolski operated the experiment in high latitude. As we know, the earth-ionosphere waveguide cavity is complicated and has obvious day and night transition and latitude effect. Its height behaves significant even sharp spatial variation. Under the influence of the geomagnetic field, its electrical characteristics become anisotropic [13]. So we need to observe the phenomena in different latitudes. It is helpful to research the propagation characteristics of ELF (extra low frequency) in the earth-ionosphere waveguide and to reveal new geophysical phenomena.

Based on the research value of SR we have found, Harbin Institute of Technology has founded the first special SR observatory was in eastern coastal area in China. There are ground based induction magnetometers and high frequency receiving and demodulation system. Using the observing data from the observatory, the non-linear interaction between HF and SR signals in middle latitude is analyzed in this paper.

Nonlinear Interaction Model between HF and SR

According to the theory of non-linear interaction in ionosphere, the non-linearity is due to the electron heating which leads to the increase of the electron temperature. The electron temperature T_e subtracts the neutron and molecule temperature T to get the increase of electron temperature ΔT. According to Gruevich [14], under the elementary theory condition, the heating efficiency depends on the energy of heating field, that is:

$$\Delta T \approx T \frac{E_h^2}{E_p^2} \tag{1}$$

In(1), E_h is the amplitude of heating field; E_p is that of the so-called plasma field[14], and the following is its definition

$$E_p = \left[3kT \frac{m}{e^2} \delta \left(\omega^2 + v^2 \right) \right]^{1/2} \tag{2}$$

Where $k = 1.43 \times 10^{-23} \mathrm{J/K}$ is Boltzmann's constant, m, e are respectively the electron mass and charge, $\delta \approx 2m/M$ is the fraction of energy given by electrons to heavy particles through collisions, ω is the heating field frequency, and v is the effective collision frequency of electrons. Equation (2) shows that E_p depends on the height distributions of $T(z), \delta(z)$ and $v(z)$.

To estimate the interaction level between SR and HF signals, the amplitude of plasma field is obtained $E_p \approx 0.3\mathrm{V/m}$ provided by Gurevich [14]. And at the altitude of D layer ionosphere, there is fair weather electric field $E_0 \approx 0.3\mathrm{V/m}$. And near the ground the value of E_S is about $3 \times 10^{-4}\ \mathrm{V/m}$. So taking into account the influence of fair weather electric field, $E_h = E_0 + E_S$. So we can get $E_h^2 = (E_0 + E_S)^2 \approx E_0^2 + 2E_0E_S$, where E_0^2 is DC component which stands for the average heating of electrons. And the term $2E_0E_S$ determines the effect which we are interested in, the modulation of T_e by the SR field. So (1) can be written as the following:

$$\Delta T_s \approx T \frac{2E_0E_S}{E_p^2}. \tag{3}$$

In (3) there is a linear relation between ΔT_s and E_S. So the spectra peaks in the spectrum of $T_e(\omega)$ will repeat those in $E_S(\omega)$.

At the height of nonlinear interaction between SR and HF, collision frequency v attributes to the collision between air molecule and electrons, $v \propto T_e^{1/2}$ [14]. So v has the form of $v \approx v_0 (T_e/T)^{1/2}$, where v_0 is the collision frequency under $T_e = T$. So substituted into (3), we obtain:

$$\begin{aligned} v\left[T_e(t)\right] &= v\left[T+\Delta T_S(t)\right] \approx v_0\left(\frac{T+\Delta T_S}{T}\right)^{1/2} \\ &\approx v_0\left(1+\frac{E_0 E_S(t)}{E_p^2}\right) \end{aligned} . \tag{4}$$

Then let us represent an HF wave in the form $E_H = E_{H0} e^{j(kr-\omega t)}$ in the region of main attenuation, where wave number $k = k_0 + jk_1$. In the D layer of ionosphere, the electron density $N_e \approx 10^8 \mathrm{m}^{-3}$, and so we can get the plasma frequency $\omega_p = \left(N_e e^2 / \varepsilon_0 m\right)^{1/2} \approx 6\times10^5 \mathrm{s}^{-1}$, thus $\omega_0 \sim v \gg \omega_p$. Using the approximate equations $k_0 \approx \omega_0 / c$, $k_1 \approx v\cdot\omega_p^2 \Big/ \left(2c\left(\omega_0^2+v^2\right)\right)$, such result can be obtained:

$$\begin{aligned} k_1 = k_{10} + k_{11}(t) &= \frac{v\cdot\omega_p^2}{2c\left(\omega_0^2+v_0^2\right)} \\ &\approx \frac{v_0\cdot\omega_p^2}{2c\left(\omega_0^2+v_0^2\right)}\left(1+\frac{E_0 E_S(t)}{E_p^2}\right). \\ &= k_{10} + k_{10}\frac{E_0 E_S(t)}{E_p^2} \end{aligned} \tag{5}$$

Here, $k_{10} = \dfrac{v_0\cdot\omega_p^2}{2c\left(\omega_0^2+v_0^2\right)}$, $k_{11}(t) = k_{10}\dfrac{E_0 E_S(t)}{E_p^2}$.

As we know that the attenuation factor is nearly equal to 1, which depends on t as $e^{-k_{11}(t)L}$. And L here is the equivalent length traveling in the attenuation region. We can get the following result:

$$E_H = E_{H0}\cdot e^{j(k_0 r-\omega_0 t)} e^{-k_{10}L}\left(1-k_{10}L\frac{E_0 E_S(t)}{E_p^2}\right). \tag{6}$$

Here we can get the cross modulation index of the HF signal by SR $\mu = v_0\cdot\omega_p^2\cdot L\cdot E_0\cdot E_S(t) \Big/ \left(2c\left(\omega_0^2+v_0^2\right)\cdot E_p^2\right)$. Obviously, we can get conclusion that SR signals $E_S(t)$ modulate the amplitude of the HF radio waves. And the modulation depth is proportional to the electric field intensity $E_S(t)$. The spectrum of $E_S(\omega)$ can be obtained analyzing the frequency spectrum of received HF signals.

Measurement and Analysis

The system in this paper received the time service signals called BPM from the National Time Service Center in PuCheng, Shanxi province. The carrier frequency is 10MHz. BPM transmits 5 minutes continuous wave (CW) after 25 minutes time service signals. The CW signals were used to do spectrum analysis. The cross dipole antenna of the receiving system is shown in Figure 1.

Fig.1 The HF receiving antenna

As we know, 1F mode plays the main role in the shortwave communication link within 2000km. In the 1F mode, the ionospheric virtual height can be assumed about 150km. The distance from PuCheng to the receiving station is about 1160km and the depth of SR in the ionosphere is 10km. according to triangle computation, we can get $L \approx 74$ km. For $\omega_0 \approx 10 \times 2 \times \pi \times 10^6 \mathrm{s}^{-1}$, the cross modulation depth μ is 4.2×10^{-4}. Taking other propagation mode existing into account, the modulation depth μ should slightly larger than this value. It is consistent with the result of Y M. Yampolski et.al.

Spectrum Analysis

The output of the receiver is based-band signal $U(t)$ with the bandwidth of 100Hz. The amplitude spectrum of $U(t)$ is analyzed as the following:

$$A(\omega) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left|F(\omega, t_i)\right|^2}\,. \tag{7}$$

Here, $F(\omega, t_i) = \frac{2}{T}\int_{t_i}^{t_i+T} U(t) \cdot e^{j\omega t} \mathrm{d}t$ is the spectrum of the signal $U(t)$. And $A(\omega)$ is the averaging over N realization, and $t_i = t_0 + (i-1)T$, $i = 1, 2, ..., N$. t_0 is the start time of observation and T is the time length of switching. During the data processing T and N were varied from 10 to 1s and 15 to 300, respectively, to search the best result. Figure 2 is one of the spectrums of demodulated BPM.

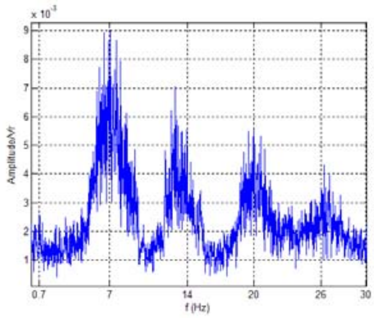

Fig.2 The SR Spectrum of demodulated BPM

In Fig. 2 peaks to the first 4 eigen-frequency at 7, 14, 20, 26Hz, respectively, are very clear in the spectrum of demodulated BPM. But the exact frequencies and amplitudes are obscured by the burrs. So the mean smoothing processing was carried out to the above frequency domain data. $A'(1) = A(1)$, $A'(i) = 0.5*(A(i) + A(i-1))$, $i = 2, 3, ..., n$. Here, $n = \mathrm{B} \bullet \mathrm{N}/f_s$, B is the bandwidth we are interested in. N is the length of A. f_s is the sampling frequency. After reduplicate smoothing the result was obtained as Figure 3.

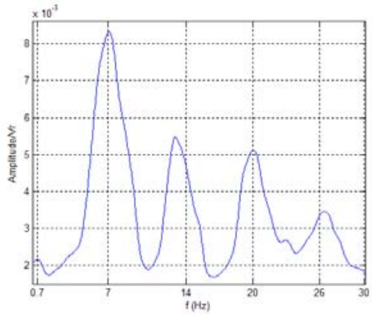

Fig.3 The SR Spectrum of demodulation BPM

The spectrum peaks of SR by smoothing processing have clearer frequency and amplitude characteristics. According the model of interaction between HF and SR signals, the electron heating is induced by the electric field component E_{SR}. Based on (6) the peaks on demodulated spectrum is corresponding to those of E_{SR}. And by the ground based measurement the electric and magnetic field components of SR near the ground can both be obtained. So maybe it is an effective method to do quantitative analysis by the both ways to research the ELF wave propagation characteristics in the earth-ionosphere wave-guide.

Conclusion and Discussion

In the paper, the physics model of the nonlinear interaction between SR and HF in the D layer of ionosphere is deduced. And the model is validated by the experiment in middle latitude. In the demodulated spectrum of HF, the peaks of the foregoing 4 eigen-frequencies of SR were observed. The frequency and amplitude characteristics were obtained.

Very low frequency electromagnetic waves travel in the earth-ionosphere wave-guide. So it can be concluded that the cross modulation between VLF and SR also exits. As known $\omega_0 \sim v \gg \omega_p$, $\omega_{VLF} \ll \omega_{HF}$ and $\mu \propto 1/\left(\omega_0^2 + v_0^2\right)$, it can be concluded that this interaction may be stronger than that between HF and SR. So it is an important content to research the non-linear phenomena between VLF and natural oscillations in ELF next step.

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