Propagation of ELF Radiation from RS-LC System and Red Sprites in Earth-Ionosphere Waveguide

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Abstract

In this paper, two different mechanisms return stroke-lateral corona (RS-LC) system and red sprites which excite Earth-ionosphere waveguide have been discussed. The electric and magnetic fields from RS-LC system and red sprites in the Earth-ionosphere waveguide have been calculated. It has been found that red sprites contribute to the Schumann resonances (SR) greatly as compared to the RS-LC system.

1. Introduction

Lightning discharge is primarily considered as the source of radio frequencies ranging from a few Hertz to microwaves. Return stroke is the most intense form of cloud-to-ground lightning. The maximum radiated power from lightning lies in the extremely low frequency (ELF) to very low frequency (VLF) region. Earth and ionosphere having good electrical conductivities at ELF and VLF form a natural cavity which is commonly known as Earth-ionosphere waveguide [1]. UHF generated from lightning discharge can penetrate the ionosphere but the ELF and VLF waves are reflected from the ionospheric boundary and propagate within the Earth-ionosphere waveguide. The Earth-ionosphere waveguide behaves like a resonator at ELF frequencies and amplifies the signals from lightning at the resonance frequencies. Schumann (1952) first studied theoretically about the global resonance of the Earth-ionosphere waveguide system known today as the Schumann resonances (SR). The resonant frequency of nth mode f_n for an ideal Earth-ionosphere waveguide is given by [2]

$$f_n = \frac{c}{2\pi R_e}\sqrt{n(n+1)} \tag{1}$$

where, n is an integer; c is the velocity of light; and R_e is the Earth's radius.

According to equation (1), the first five resonance frequencies are 10.6, 18.4, 26.0, 35.5, and 41.1 Hz. In the above calculation (equation 1), the ionosphere is considered as the perfect conductor, but in reality it has some finite conductivity. The SR frequencies "ω" can be calculated using the ionospheric parameters by following relation [3]

$$\omega = \frac{c\sqrt{n(n+1)}}{R_e}\cdot\frac{1}{\sqrt{1-\frac{2h_s}{a}\left[\gamma + \ln\left(\frac{\omega_{02}h_s}{c}\sqrt{\frac{i\omega}{\nu_{e2}}}\right)\right]}} \tag{2}$$

n=1,2,3,……, where, γ=0.577 is Euler's constant; "a" is height of the base of ionospheric D region; "h_s" is the scale height; $\omega_{02} = N_2 e^2/m_e\varepsilon_0$ is the plasma frequency (N_2 is the electron density at "a"), m_e and e are the mass and charge of electron respectively, ε_0 is the permittivity of free space and ν_{e2} is the electron collision frequency at "a".

They [3] calculated first three SR frequencies to be f_1=(7.71+0.43i), f_2=(13.62+0.78i) and f_3=(19.51+1.15i) Hz using ionospheric parameters a=55 km, h_s=7 km, N_2=4×10^7 m^-3, ν_{e2}=10^7 s^-1. Madden and Thompson [4] obtained the SR frequencies to be 7.8, 14.1, 20.3, 26.3 and 32.5 Hz. The shifting of the SR to lower frequencies from its ideal values (equation 1) is because of energy loss due to the finite ionospheric conductivity. The maximum power in the ELF and VLF range is radiated from return strokes. Paras and Rai [5,6] found that the red sprites are also the source of strong ELF radiation. However, we do not know as which one contributes to the Schumann resonances. The purpose of the present paper is to have a comparative study of electromagnetic wave propagation from RS-LC system and red sprites in the Earth-ionosphere waveguide contributing to Schumann resonances.

2. Theory

ELF radiation having frequency 3-60 Hz can propagate within the Earth-ionosphere waveguide without significant attenuation. Using the spherical polar coordinates (r,θ,φ) with the Earth's center as the origin, the electric and magnetic fields associated with these ELF in Earth-ionosphere waveguide are given by [7]

$$E_r(\omega) = -\frac{M_c(\omega)i\nu(\nu+1)}{4\pi\varepsilon_0 hR_e^2\omega}\sum_{n=0}^{\infty}\frac{(2n+1)P_n(\cos\theta)}{n(n+1)-\nu(\nu+1)} \tag{3}$$

$$H_\phi(\omega) = \frac{M_c(\omega)}{4\pi hR_e}\sum_{n=1}^{\infty}\frac{(2n+1)P_n^1(\cos\theta)}{n(n+1)-\nu(\nu+1)} \tag{4}$$

where, $M_c(\omega)$ is the current moment of the source in frequency domain; R_e=6400 km is the Earth's radius; h=90 km is the ionosphere height; the field source is positioned on the ground surface at the pole (θ=0), so that θ is the angular source-observer distance; ω=2πf is the angular frequency; ε_0 is the permittivity of free space; $P_n(\cos\theta)$ and $P_n^1(\cos\theta)$ are the Legendre and associated Legendre polynomials of the

order n; and $\upsilon(f)$ is the propagation parameter of ELF radio waves.

The parameter "$\upsilon(f)$" is given by [7]

$$\nu(f) = \sqrt{\frac{1}{4} + (kR_e)^2 S_v^2} - \frac{1}{2}$$ (5)

where,

$$S_v = \frac{c}{V} - i(5.49)\frac{\chi}{f}$$ (6)

$$\frac{c}{V} = 1.64 - 0.1759 \log f + 0.01791 (\log f)^2$$ (7)

"c" and "V" are the velocity of light and phase velocity of wave in Earth-ionosphere waveguide respectively; and the wave attenuation factor "χ" is given by

$$\chi = 0.063 f^{0.64}$$ (8)

The schematic diagram of calculation model and coordinate system has been shown in Fig. 1.
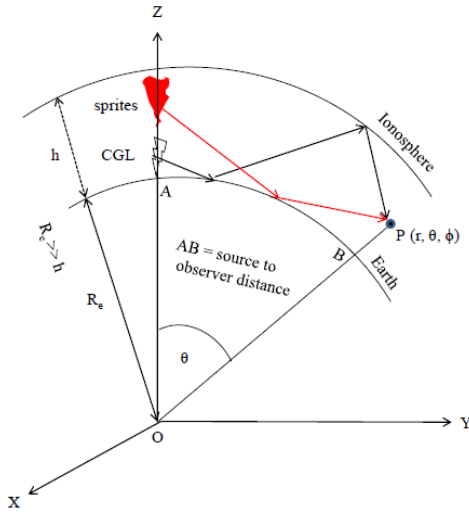

Figure 1: Schematic diagram of calculation model and coordinate system. The ELF radiation from red sprites and cloud-to-ground lightning (CGL) travel in the Earth-ionosphere waveguide and observed at point $P(r,\theta,\phi)$. Here, the observation point is on the surface of earth i.e. $r=R_e$.

3. Return Stroke-Lateral Corona System

Cloud-to-ground lightning contains two different types of current. The first one and most intense is the return stroke current. It can ranges from 10-100 kA with duration of 100-200 μs [8]. Typical length of return stroke ranges from 5-10 km. Return stroke is the response of stepped leader which is formed at the base of the thundercloud and carry charge towards the ground. The propagation of stepped leaders and return strokes has been successfully described by considering the potential gradient waves [9,10]. The velocity and current expressions for return strokes are given by [5,10]

$$V_{rs}(t) = V_0 \left(e^{-at} - e^{-bt} \right)$$ (9)

$$I_{rs}(t) = I_0 \left(e^{-\alpha t} - e^{-\beta t} \right)$$ (10)

where, $V_0 = 9 \times 10^7$ m/s; $a = 3 \times 10^4$ s^{-1}; $b = 7 \times 10^5$ s^{-1}; $I_0 = 22$ kA; $\alpha = 1.6 \times 10^4$ s^{-1}; $\beta = 5 \times 10^5$ s^{-1}.
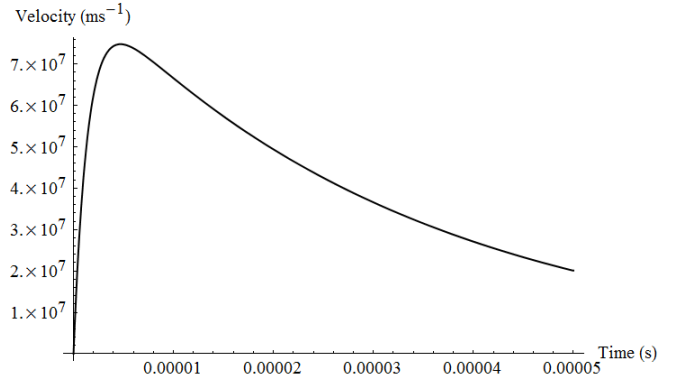

Figure 2: Velocity of RS-LC system with time.

Below the tip of the return stroke, the whole channel up to ground surface is at high potential than the surrounding medium left by stepped leader. The negative ions and electrons along the entire channel from tip to the ground move towards the highly conducting return stroke core and constitute a current which immediately flows to the ground through this channel. Since this current is developed due to the radial movement of negative ions and electrons, it is known as "lateral corona current". The mathematical expression is given by [11]

$$I_{lc}(t) = \frac{KV^2 V_0}{ab}\left[(b - a)\ \exp\left(\frac{-2t}{CR}\right) \right.$$

$$\left. - b\ \exp\left[-\left(a + \frac{2}{CR}\right)t\right] + a\ \exp\left[-\left(b + \frac{2}{CR}\right)t\right] \right]$$ (11)

where, K=Corona constant (10^{-16} AV^{-2} m^{-1}s^{-1}); V=Potential difference between the return stroke and the leader sheath in volts and can be taken as 10^8 Volts; C=Distributed capacity of the leader sheath-return stroke core in farads/m; R=Distributed resistance of the above configuration (CR=5.3865 ms for I_0=22 kA).

Since both the currents flow simultaneously in the cloud-to-ground lightning channel and they are not separable. So, the total current is written by

$$I_{tot}(t) = I_{rs}(t) + I_{lc}(t)$$ (12)

The current moment M_c associated with a current source is defined as the multiplication of the current in the channel of the source body and the distance travelled by it. The mathematical expression for M_c is given by

$$M_c(t) = 2I(t)\int_0^t V(t)\ dt$$ (13)

where, I(t) and V(t) are the current and velocity of the system respectively. The velocity and current associated

with RS-LC system have been shown in Fig. 2 and Fig. 3 respectively. Further, the current moment in time domain also has been shown in Fig. 4. The peak value of M_c comes out to be around55 kA.km for the defined parameters of RS-LC system.

Using the Fourier transformation technique, we calculated $M_c(\omega)$ the Fourier component of $M_c(t)$ for RS-LC system. Electric and magnetic fields associated with the ELF waves propagating within the Earth-ionosphere waveguide from RS-LC system have been calculated with the help of equations (3), (4) and (13). Fig. 5 and Fig. 6 show the electric field at distances of 1000 and 5000 km respectively from the current source. Similarly, magnetic field has been also calculated and shown in Fig. 7 and Fig. 8. The electric and magnetic fields due to RS-LC system come out to be of the order of 10^{-5} Vm^{-1} and 10^{-8}Am^{-1} respectively, and get peak at SR frequencies.
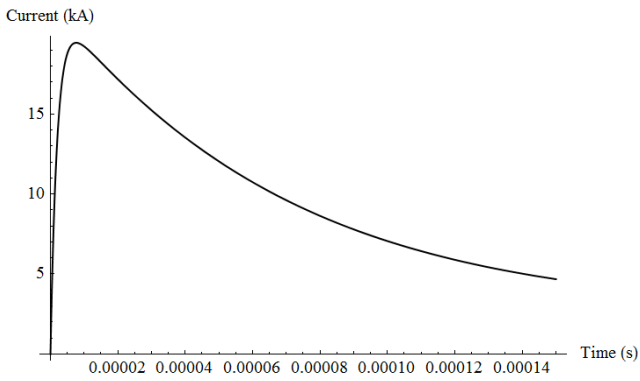

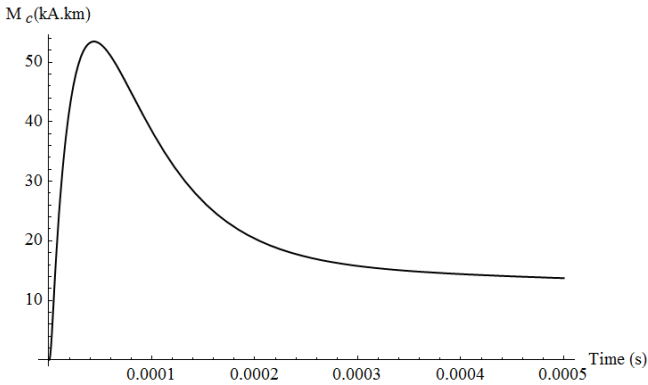Figure 3: Current of RS-LC system with time.

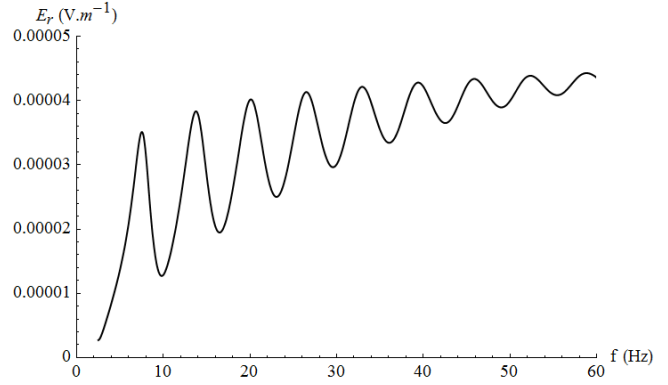Figure 4: Current moment of RS-LC system with time.

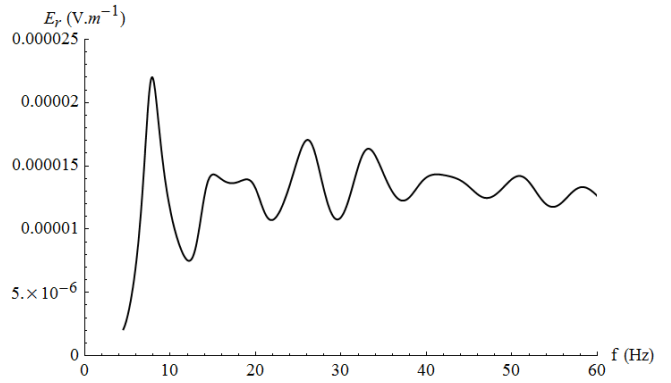Figure 5: Electric field versus frequency at a distance of 1000 km from the source.

Figure 6: Electric field versus frequency at a distance of 5000 km from the source.
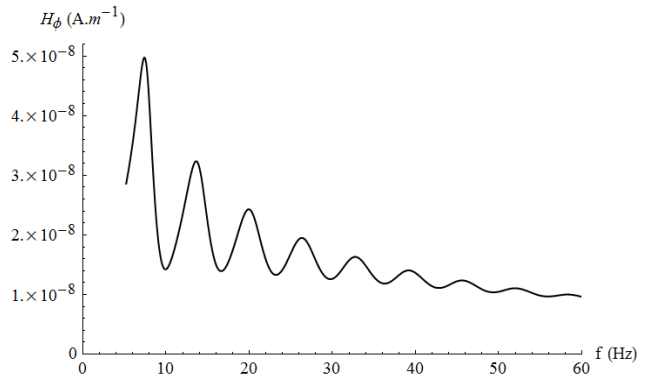

Figure 7: Magnetic field versus frequency at a distance of 1000 km from the source.
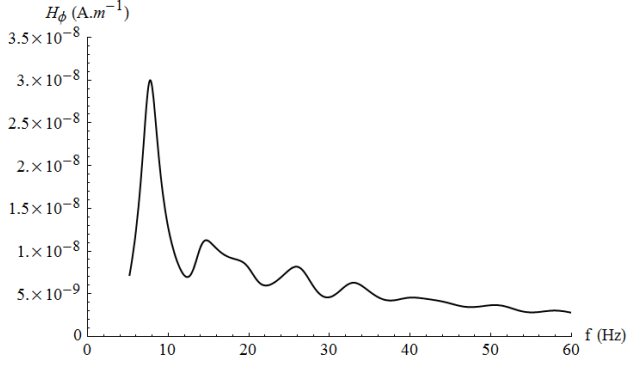
Figure 8: Magnetic field versus frequency at a distance of 5000 km from the source.

4. Red Sprites

Red sprites are the optical emissions in the upper atmosphere. Wilson (1925) first predicted about the ionization and breakdown of upper atmosphere. He recognized that the thundercloud electric field decreases with altitude z as $\sim z^{-3}$ and the critical breakdown electric field which decreases even much faster (proportional to the exponentially decreasing atmospheric density) leads to the result that there will be a height at which cloud electric field will exceeds the sparkling limit to produce upper atmospheric lightning discharges[12]. Latter, Franz et al. [13] reported the low-light-level TV images of these high altitude lightning discharges. Red sprites, blue jets and elves are some forms of high altitude lightning discharges which are categorized according to their shape, color and altitude of occurrence. Red sprites are the most frequent candidates among them. Sprites are luminous red structures that typically span the altitude ranges from 60-90 km, often with faint bluish tendrils dangling below [14]. The lateral extent of sprites can ranges from 10-50 km. Sprites are associated with the strong positive cloud-to-ground lightning and occur in the dying stage of the thunderstorm [15]. The mechanism for the generation of sprites is the "runaway breakdown" model, which describes that the large quasi-electrostatic fields developed in the upper atmosphere due to the strong positive cloud-to-ground lightning produce an upward traveling beam of ~1 MeV runaway electrons to produce optical emissions called red sprites. Sprites can propagate upwards or downwards from their point of origination. Downwards sprites can propagate with a maximum velocity of 3-10% of the speed of light [16]. The peak vertical current in the body of sprites can ranges from 1.6-3.3 kA [17]. Rycroft and Odzimek [18] have reported the values 5-10 kA.

The velocity and current expressions for red sprites are given by [5,6]

$$V_{sp}(t) = V_1 \exp\left[-\xi\left(t-\eta\right)^2\right] \tag{14}$$

$$I_{sp}(t) = I_1\left(e^{-\gamma t} - e^{-\delta t}\right) \tag{15}$$

where, $V_1=1.16\times10^7$ ms^{-1}; $\xi=4.13\times10^5$ s^{-2}; $\eta=3.83\times10^{-3}$ s; $I_1=8.35\times10^3$ A; $\gamma=1.10\times10^2$ s^{-1}; and $\delta=7.00\times10^2$ s^{-1}.

The value of V_1 has been chosen such that the maximum value of sprite velocity is about 4% of the velocity of light. Similarly, the value of I_1 corresponds to a peak current of 5 kA. These values are in accordance with the experimental observations [16,17,18]. The time variation of velocity and current of red sprites have been shown in Fig. 9 and Fig. 10 respectively.
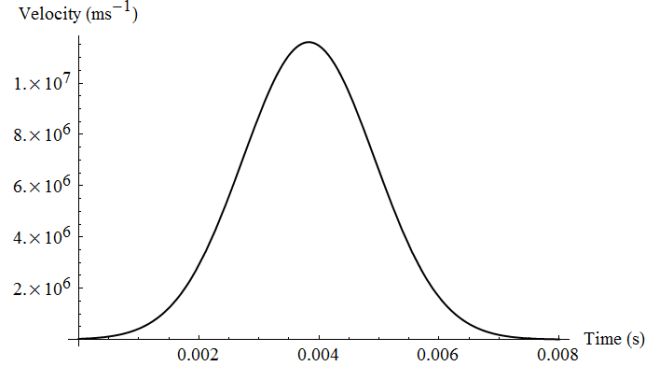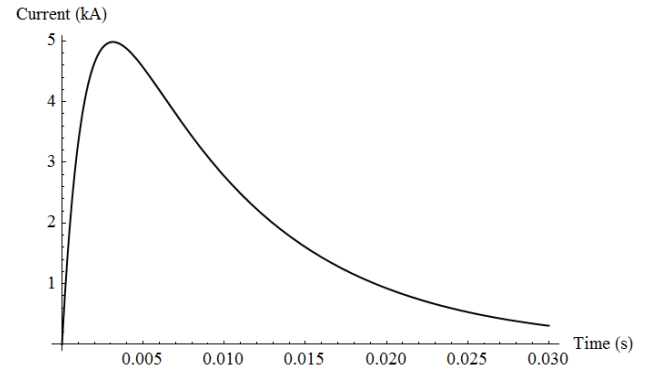

Figure 9: Velocity of red sprites with time.

Figure 10: Sprite current with time.

$M_c(\omega)$ for red sprites has been calculated using equations (13), (14) and (15), consequently electric and magnetic fields can be calculated using equations (3) and (4) respectively. The current moment of red sprites in time domain has been shown in Fig. 11. The peak value of M_c for red sprites comes out to be around 260 kA.km. Cummer at al. [17] measured the current moment of three sprites and reported peak values range from 150 to 240 kA.km. So, the calculated peak value of M_c is well in conformity with the experimental results.

The calculated electric and magnetic fields associated with red sprites in Earth-ionosphere waveguide have been shown in Fig. (12-13) and Fig. (14-15) respectively. The electric and magnetic fields get peak at the SR frequencies. The calculated electric and magnetic fields have been found to be of the order of 10^{-3} Vm^{-1} and 10^{-6} Am^{-1} respectively. Magnitudes of sprites electromagnetic fields are much larger than RS-LC system.
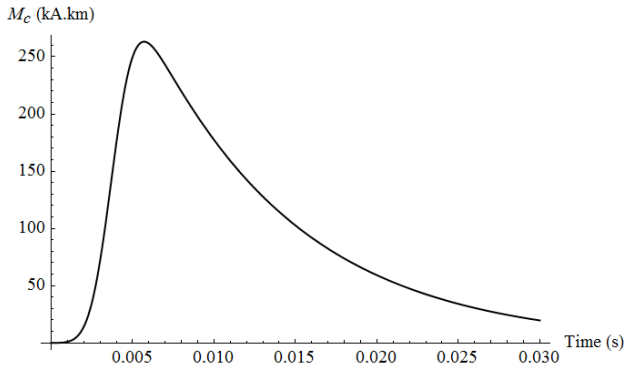
Figure 11: Current moment of red sprite with time.

One may notice that the average electric field of red sprites (Fig. 12) at a distance of 1000 km remains almost constant with frequency while that due to RS-LC system increase with frequency. The source electric field due to RS-LC system peaks at around 5 kHz [5] and that due to sprites has maximum in the ELF range having a broad maximum in the frequency range 0-100 Hz [5] and then decreases sharply. These variations at the source spectrum make the field in Fig. 5 to rise with frequency while that in Fig. 12 to remain almost constant.

Further, one can notice that the electric field at a distance of 5000 km (Fig. 13) does not have clear peak in second harmonic while for magnetic field (Fig. 15) the second harmonic has sharp peak. Nickolaenko et al. [7] also obtained in their calculation that the electric field for a transient event has a clear peak of second harmonic in magnetic field component at 5000 km while the electric field component at the same distance the second harmonic is diffused.
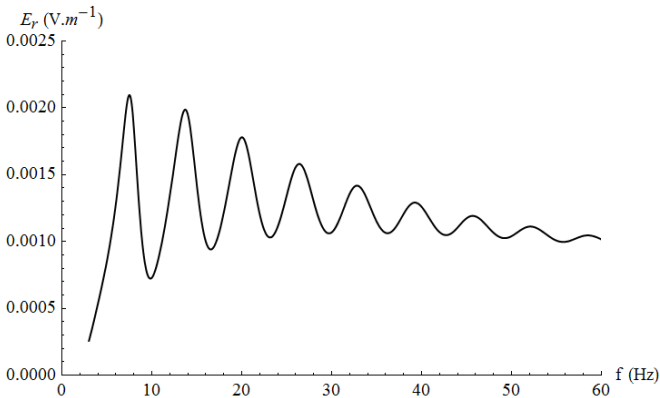

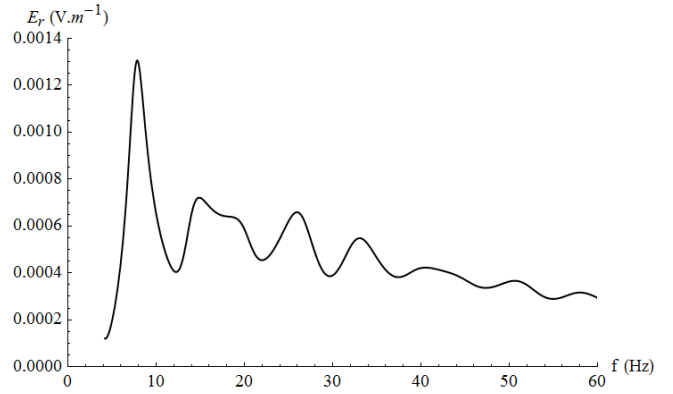Figure 12: Electric field versus frequency at a distance of 1000 km from the source.

Figure 13: Electric field versus frequency at a distance of 5000 km from the source.
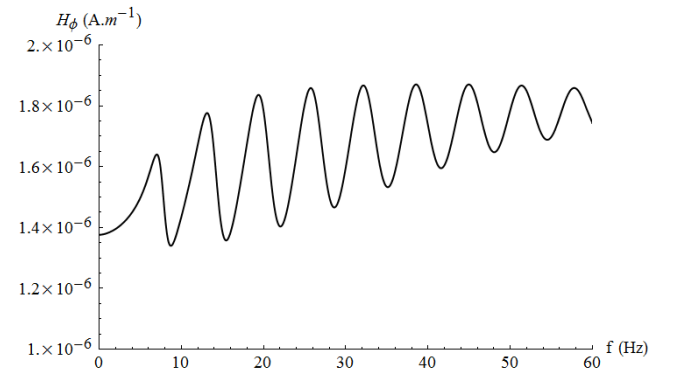
Figure 14: Magnetic field versus frequency at a distance of 1000 km from the source.
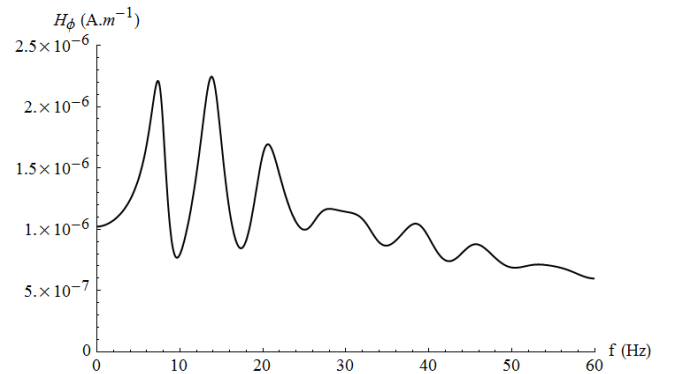
Figure 15: Magnetic field versus frequency at a distance of 5000 km from the source.

5. Results Discussion and Conclusion

Electric and magnetic fields from RS-LC system and red sprites in Earth-ionosphere waveguide have been calculated. Calculations have been made at distances of 1000 km and 5000 km from the source. The ionospheric reflection from red sprites as per our estimates becomes effective beyond a distance of about 700 km. Nickolaenko et al. [7] have made calculations at 2, 5, 10 and 15 thousand kilometers. Ando et al. [19] also synthesized the observed Schumann resonance

at distance ranging from 5000 to 13000 km. In our representative calculations, we have taken the distances of 1000 km and 5000 km. Both the electric and magnetic fields contribute to SR and get peak at around 7.7, 14.0, 20.0, 26.0, 32.2 Hz and so on. Madden and Thompson [4] obtained the SR frequencies to be 7.8, 14.1, 20.3, 26.3 and 32.5 Hz. The daily variation in SR frequencies can be around +0.5/-0.5 Hz. Recently, Chand et al. [3] reported the experimental results of electric and magnetic fields associated with the first three SR frequencies 7.8, 14.0 and 20.0 Hz. They observed diurnal variation in the SR frequencies associated with magnetic field components, the maximum frequency variation of about 0.3, 0.4 and 0.7 Hz was observed in the first, second and third mode respectively. The variation in first and second mode SR frequency occurred during the intense solar X-ray bursts by ~ 0.2 Hz and 0.3 Hz respectively [20]. Our theoretical calculations of SR frequencies are in good agreement with the experimental observations [3,4].

Polk [21] reported the vertical electric field range as 0.22×10^{-3}-1.2×10^{-3} Vm^{-1} by considering the first three resonance peaks. König [22] reported the typical electric and magnetic fields strength as 1×10^{-3} Vm^{-1} and 10^{-5} Am^{-1} respectively. Williams [23] reports 5 years of SR magnetic field intensity measurements from Rhode Island with monthly mean 8Hz mode intensities in the range 1.03×10^{-6} to 5×10^{-6} Am^{-1}. The calculated SR electric and magnetic fields strength from RS-LC system has been found of the order of 10^{-5} Vm^{-1} and 10^{-8} Am^{-1} respectively at 1000 and 5000 km from the source. Similarly, the calculated electric and magnetic fields strength from the red sprites has been found to be of the order of 10^{-3} Vm^{-1} and 10^{-6} Am^{-1} respectively at both 1000 and 5000 km from the source. If we compare our results with the experimental observations reported above [21,22,23], the electromagnetic fields strength associated with red sprites are of the same order, however the strength of electromagnetic fields associated with RS-LC system is very low.

One finds that the current of the RS-LC system is many times larger than the red sprite current. However, because of the large channel length of sprites, its current moment becomes much larger than the current moment of RS-LC system. A large current moment gives rise to large electric field. The spectrum also depends upon the rate of change of current moment which is larger for red sprites. As mentioned above the field strengths calculated for the first few resonant peaks of Schumann resonances are comparable to various experimental observations [21, 22, 23]. The calculations for RS-LC system for the same distance are about two orders of magnitude smaller than that due to red sprites. Thus the red sprites are more likely to generate Schumann resonances.

SR can be used to study the global lightning activity by tracking changes in the SR field intensities. Williams [23] suggested that SR may provide the useful information to monitor the global temperature. The SR frequency variation can be used to determine the daily variation of electron density N_2.

Electromagnetic fields from RS-LC system and red sprites get very sharp peaks at smaller distances like 1000 km, but peaks become fader as the distance of observation increases. The electric field component of fundamental SR frequency at 1000 Km is 1.59 times to that at 5000 Km. This ratio is increased to 2.85 for the first harmonic. Similarly, the ratio of field strength of fundamental SR frequency at a distance of 1000 Km to that at 5000 Km for red sprites is 1.69 while for the first harmonic it is 3.3. In the calculations of Nickolaenko et al. [7], the peaks at resonance frequencies at 2000 km are sharp while those at 5000, 10000 and 15000 km are faded. The results are similar in the magnetic field component. In our calculation, the magnetic field component (Fig. 14) due to red sprites at a distance of 1000 km on average increases with frequency. The same trend has been obtained in the electric field due to RS-LC system at a distance of 1000 km. Nickolaenko et al. [7] also for ELF transient events (Q-bursts) found that the average electric field was increasing with frequency in the magnetic field component at a distance of 5000 km. Positive CG lightning associated with red sprites excite the Earth-ionosphere waveguide [24]. Cummer et al. [17] have observed that the total current moment associated with sprite-producing lightning has two distinct peaks. They described that the second peak having slow tail corresponds the current flowing in the sprite body itself. Slow tails of sprite-associated lightning flashes have been observed in the ELF range [25, 26], in the lower ELF range, [15] and in the ULF/ELF transition range [27].

A question arises whether SR are related to sprites. Earlier it was thought that the return stroke is the only source to excite earth-ionospheric waveguide producing Schumann resonances. However, we have found that the field strengths calculated for red sprites is in excellent agreement with the experimental observations of field strength of Schumann resonances observed by various workers [21, 22, 23]. The field strength due to RS-LC system is about two orders of magnitude lower than that due to red sprites. Therefore it is concluded that the red sprites may contribute to SR occurring in the earth-ionosphere waveguide significantly.

Acknowledgements

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