The Estimation of Power Flux of Microwave Radiation from a Negative Narrow Bipolar Pulse at Low Earth Orbit Satellite Altitude

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***Abstract*— In this paper, we estimate power flux densities at two points in space within the orbiting range of low Earth orbit (LEO) satellite. One point located 200 km away from the narrow bipolar pulse (NBP) emission source with angle $\theta = 45°$ and the other point located 2000 km away from the NBP emission source with angle $\theta = 45°$. The sensitivity of the LEO satellite sensor must be larger than 10^{-8} W/m^2/Hz at distance 200 km and 10^{-10} W/m^2/Hz at distance 2000 km in order to be able to capture microwave radiation from NBP.**

***Index Terms*— Lightning electromagnetic, microwave radiation, narrow bipolar pulse.**

I. INTRODUCTION

For decades, remote sensing of electromagnetic (EM) fields from natural lightning either on ground or in space has been concentrated below the VHF band. Recently, as natural lightning has been found to produce not only EM emissions below VHF band but also gamma- and x-rays, the interest is very high to observe EM signatures at various frequencies spectrum.

Recent study in [1] has shown that close negative cloud-to-ground (-CG) natural lightning emitted microwave radiation. Further studies in [2-6] showed that microwave radiations from several types of natural lightning events (-CG and intra-cloud or IC) interfered significantly with wireless communication system at 2400 MHz. It has been found that narrow bipolar pulses (NBPs) have interfered severely with the wireless system. As all studies recorded the microwave radiation at ground level, in this paper we are motivated to determine required sensitivity level of a LEO satellite to detect microwave radiation from NBPs. In this paper, the sensitivity level is determined based on estimation of power flux density at space corresponding to the measured power flux density at ground assuming a perfectly conducting ground.

II. NARROW BIPOLAR PULSE

Narrow bipolar pulses (NBPs) are the electric fields produced by a distinct category of IC lightning. They were first reported by [7] and later described in more detail by [8-12]. Several researchers [13, 14] have proposed that in the source of NBPs a hot conductive channel exists through which currents of many kiloamperes in amplitude flow. The estimated speed of propagation of the current pulse is from 0.3×10^8 m/s to 1×10^8 m/s with an estimated channel length of about 1000 m or less. Considering such very fast propagation speeds in virgin air, it is not likely that the initial breakdown will be due to the electron drift speed in the ambient electric field. That in turn suggests that the initial breakdown propagation is either photon- or fast (runaway) electron-modulated. The fact that close NBP electric field signatures appear without any detectable initial breakdown processes (pre-leader activity) preceding the event, and that HF/VHF radiations can be detected almost simultaneously with the NBP onset, suggest that the initial breakdown processes and the formation of the hot conductive channel must occur instantaneously, i.e., at the propagation speed of light. Furthermore, frequent observations of gamma-ray glows [15] from thunderstorms suggest that the electric fields that are needed to produce runaway electron avalanches are common inside thunderstorms. As relativistic runaway electron avalanches (RREAs) come into the picture, the NBP electric field signature is believed to be generated from the propagation of RREAs alone rather than from current pulse propagation along a hot conductive channel [16,17]. The proposed simulation models fit very well with the electric field changes and HF/VHF radiation signatures. The estimated propagation speed is between 2–3 × 10^8 m/s with estimated lengths between 400 and 600 m.

III. ELECTRIC FIELD AT THE RECEIVING ANTENNA OVER A PERFECT CONDUCTING GROUND

Consider a receiving microwave system over a perfectly conducting ground with horizontal distance d from the NBP emission source as shown in Fig. 1. The height of the emission source from the ground is denoted as h. The monopole antenna tuned at 2400 MHz with 20 MHz bandwidth (B). The antenna gain (G_r) is 9 dBi. The antenna gain is related to the effective aperture of the antenna, A_e as such:

$$A_e = \frac{G_r \lambda^2}{4\pi} \tag{1}$$

where λ is related to the carrier frequency. The power flux density (Poynting vector, S) at distance r (equal to $\sqrt{d^2+h^2}$) from the radiation source is:

$$S = \frac{E^2}{\eta} \text{ [Watt/m}^2\text{]} \tag{2}$$

where E is the incident electric field and η is the intrinsic impedance of free space. The power received at distance r, $P(r)$ is given by the power flux density times the effective aperture of the receiver antenna and can be related to the electric field using Equations 1 and 2:

$$P(r) = SA_e = \frac{E^2}{\eta}\left(\frac{G_r \lambda^2}{4\pi}\right) \text{ [Watt]} \tag{3}$$

The receiving system consists of only a transmission line, a low noise amplifier (LNA) and a band pass filer (BPF) and connected directly to a digitizer. The receiver system gain (G_s) is 11.6 dB. The incident electric field can be related to the measured voltage at the digitizer (V_m) using Equation 3:

$$\frac{E^2}{\eta}\frac{G_r \lambda^2}{4\pi} = \frac{V_r^{\,2}}{R} = \frac{V_m^{\,2}}{G_s^{\,2} R} \tag{4}$$

where V_r and R are the voltage at the input terminal of the receiving system and the resistance of the antenna, respectively. Re-arranging Equation 4 gives:

$$E^2 = \frac{\eta 4\pi}{R G_r G_s^{\,2} \lambda^2} V_m^{\,2} \tag{5}$$

Let us consider the fact that the microwave sensor at 2400 MHz detects only radiation field component in the Fraunhofer region (see Appendix for details).

The radiation component of the vertical electric field at ground level at a horizontal distance d from the axis of the current element is then given by Equation 6, as such:

$$\begin{aligned} &E_{z,rad}(t) = \\ &-\frac{L}{2\pi\varepsilon_0}\frac{\cos^2\phi}{c^2\sqrt{d^2+h^2}}\left[\frac{d}{dt}I(t-\sqrt{d^2+h^2}/c)\right] \\ &= E \end{aligned} \tag{6}$$

Re-arranging Equation 6 to represent the current source gives us:

$$\begin{aligned} &\left[\frac{d}{dt}I(t-\sqrt{d^2+h^2}/c)\right] \\ &= -E(t)\frac{2\pi\varepsilon_0}{L}\frac{c^2\sqrt{d^2+h^2}}{\cos^2\phi} \end{aligned} \tag{7}$$

IV. POWER FLUX DENSITY AT A DISTANCE R AT ANY POINT IN SPACE

The radiation component of the electric field at any point in space from the NBP emission source is given by Equation A8 (Refer to Appendix). Rearranging Equation A8 in term of the current source gives:

$$\left[\frac{d}{dt}I(t-\sqrt{r}/c)\right] = E_{\theta,rad}(t)\frac{4\pi\varepsilon_0 c^2 r}{L\sin\theta} \tag{8}$$

The relationship between the radiated electric field at any point in space and the radiated electric field measured close to the conducting ground is given by the common current source at retarded time governed by Equation 7 and 8:

$$E_{\theta,rad}(t) = -\frac{1}{2}\frac{\sqrt{d^2+h^2}\sin\theta}{r\cos^2\phi}E(t) \tag{9}$$

As expected for a vertical current source the nulls found to be in the vertical axis when θ = 0° and θ = 180°. The power flux density at any point in space can be estimated as:

$$\begin{aligned} S_\theta &= \frac{E^2{}_{\theta,rad}}{\eta}\frac{1}{B} \\ &= \frac{\sin^2\theta}{4r^2}\frac{d^2+h^2}{\cos^4\phi}\frac{E^2(t)}{\eta}\frac{1}{B} \end{aligned} \tag{10}$$

and by substituting Equation 5 into Equation 10, we obtain the relation between the flux and the measured voltage V_m as:

$$S_\theta = \frac{\sin^2\theta}{r^2}\frac{d^2+h^2}{\cos^4\phi}\frac{\pi}{G_r G_s^{\,2}\lambda^2}\frac{V_m^{\,2}}{R}\frac{1}{B} \tag{11}$$

where $\cos\phi = \frac{d}{\sqrt{d^2+h^2}}$.

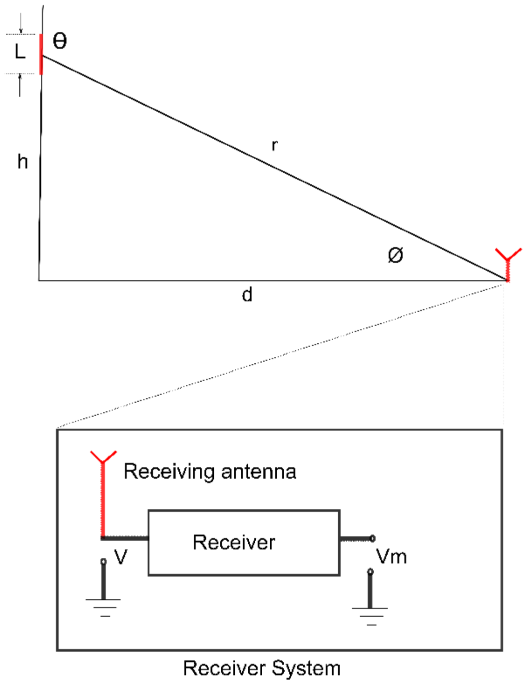

Figure 1: Geometry relevant to derivation of equations pertinent to radiation component of electric field emitted by narrow bipolar pulse (NBP) source at altitude h from conducting ground. The range and horizontal distance to the point of observation are r and d, respectively. A detail description of the receiver system is given by the bottom diagram where V_m is the measured voltage by digitizer.

Table 1
Parameters

Parameter	Value
Horizontal distance to the observation point on the ground, d	10 km
Range of LEO orbit, r	200 km and 2000 km
The height of the NBP source from the ground, h	15 km
The receiving antenna gain, G_r	9 dBi
The receiving system gain, G_s	11.6 dB
Wavelength, λ	12.5 cm
Antenna resistance, R	36.5 Ω
System bandwidth, B	20 MHz
Elevation angle, θ	45°

An example of the measured voltage V_m of microwave radiation used to obtain the result in Section IV is shown in Figure 2.

V. RESULTS AND ANALYSIS

Power flux densities at two points in space are plotted. One point located 200 km away from the NBP emission source with angle $\theta = 45°$ and the power flux density is shown in Figure 3. The other point located 2000 km away from the NBP emission source with angle $\theta = 45°$ and the power flux density is shown in Figure 4. The sensitivity of the LEO satellite sensor must be larger than 10^{-8} W/m^2/Hz at distance 200 km and 10^{-10} W/m^2/Hz at distance 2000 km in order to be able to capture microwave radiation from NBP.

VI. CONCLUSION

Theoretically, we have estimated sensitivity levels of a microwave sensor aboard LEO satellite, which is determined based on estimation of power flux density at space corresponding to the measured power flux density at ground assuming a perfectly conducting ground. It has been found that the sensitivity of the LEO satellite sensor must be larger than 10^{-8} W/m^2/Hz at distance 200 km and 10^{-10} W/m^2/Hz at distance 2000 km in order to be able to capture microwave radiation from NBP.

APPENDIX: RADIATION COMPONENT OF THE ELECTRIC FIELD AT ANY POINT IN SPACE EMITTED BY A SHORT CURRENT ELEMENT OVER A PERFECTLY CONDUCTING GROUND

Let us consider a short current element (a simple way to model the flow of electrons during electron avalanches). The direction of the current oppose the direction of the electrons flow) with a length of L and let it be directed in the positive z-direction with its center at the origin as shown in Figure 1. The current flowing in the current element is given by:

$$I(t) = I_0 e^{jwt}. \qquad \text{(A1)}$$

The current transports charge from one end of the channel element to the other end. The electric fields at any point in space generated by the current element can be calculated using scalar and vector potentials. At first, we treat the analysis in frequency domain and later we will provide the corresponding time domain field. The electric fields are given by:

$$E_r = \frac{I_0 e^{jwt} e^{-jwr/c}}{2\pi\varepsilon_0} L\cos\theta \left[\frac{1}{cr^2} + \frac{1}{jwr^3}\right] \qquad \text{(A2)}$$

and

$$E_\theta = \frac{I_0 e^{jwt} e^{-jwr/c}}{4\pi\varepsilon_0} L\sin\theta \left[\frac{jw}{c^2 r} + \frac{1}{cr^2} + \frac{1}{jwr^3}\right] \qquad \text{(A3)}$$

where r is the distance to the point of observation.

Let us consider the fact that the microwave sensor at 2400 MHz only detects radiation field component in Fraunhofer region when $r > 2L^2/\lambda$ (the length of the current element L due to the electron avalanches is in order of several millimeters and the wavelength λ at 2400 MHz is 12.5 cm). The radiation component of the electric field at any point in space is:

$$E_{\theta,rad} = \frac{I_0 e^{jw(t-r/c)}}{4\pi\varepsilon_0} L\sin\theta \left[\frac{jw}{c^2 r}\right] \qquad \text{(A4)}$$

and the field varies inversely with distance r.

Let us now consider a short current element over a perfectly conducting ground plane. The electric field at any point over the conducting plane can be calculated by replacing the conducting plane with an image current element with the same height *h* from the conducting plane and the distance to the point of observation r_i. The radiation component of the vertical electric field at ground level (the horizontal electric field is zero) at a horizontal distance *d* from the axis of the current element is then can be calculated as such:

$$E_{z,rad} = -\frac{I_0 e^{jw(t-\sqrt{d^2+h^2}/c)}}{2\pi\varepsilon_0} L\cos^2\phi\left[\frac{jw}{c^2\sqrt{d^2+h^2}}\right] \qquad \text{(A5)}$$

In time domain;

$$E_{z,rad}(t) = -\frac{L}{2\pi\varepsilon_0}\frac{\cos^2\phi}{c^2\sqrt{d^2+h^2}}\left[\frac{d}{dt}I(t-\sqrt{d^2+h^2}/c)\right] \qquad \text{(A6)}$$

where $\cos\phi = \frac{d}{\sqrt{d^2+h^2}}$.

Now, consider a case where the observation point is at any point in space while the radiation source is close to the conducting plane. When $r >> h$ and $r_i >> h$, then we can approximate $r\hat{k} \approx r_i\hat{k}$ using paraxial approximation and consequently $\theta = \theta_i$. In this case, the total radiation component of the electric field is contributed only by the source at the origin as such:

$$E_{\theta,rad} = \frac{I_0 e^{jw(t-r/c)}}{4\pi\varepsilon_0} L\sin\theta\left[\frac{jw}{c^2 r}\right] \qquad \text{(A7)}$$

In time domain;

$$E_{\theta,rad}(t) = \frac{L\sin\theta}{4\pi\varepsilon_0 c^2 r}\left[\frac{d}{dt}I(t-\sqrt{r}/c)\right] \qquad \text{(A8)}$$

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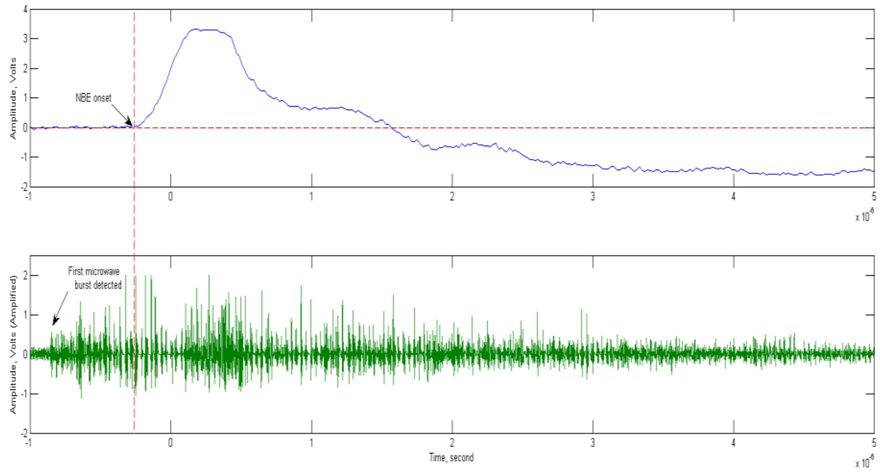

Figure 2: A NBP emission (top) and its associated microwave radiation (bottom) recorded at horizontal distance d = 10 km on the ground. The y-axis of the bottom plot represents the measured voltage V_m

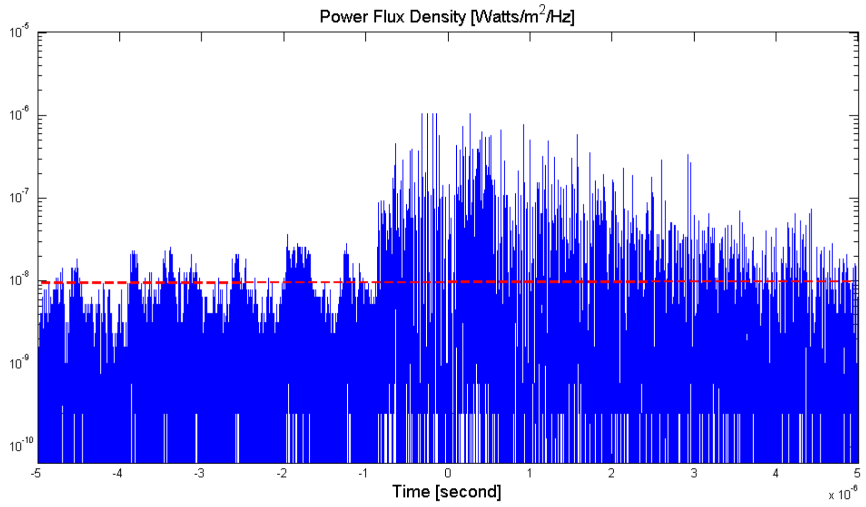

Figure 3: Power flux density at r = 200 km from the NBP emission source with angle θ = 45°.

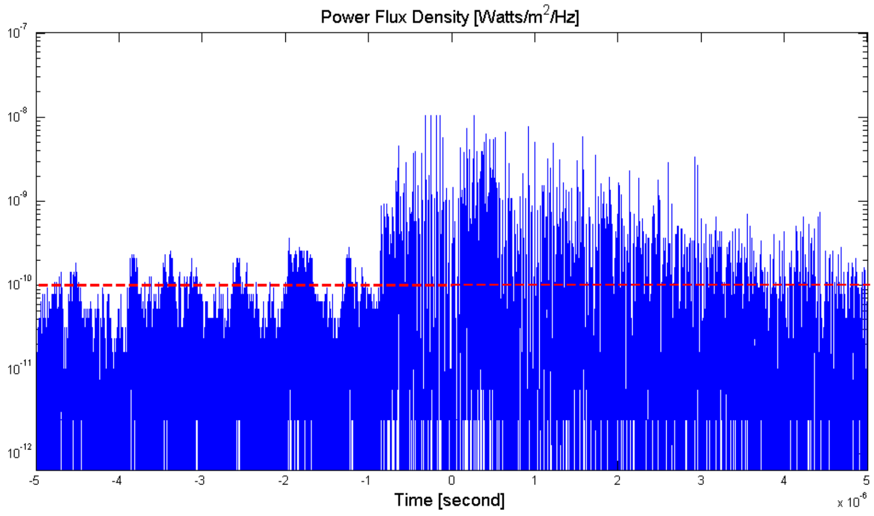

Figure 4: Power flux density at r = 2000 km from the NBP emission source with elevation angle θ = 45°