Theoretical Investigation on HF-VHF Electromagnetic Emissions from Sprites

Etude Théorique des Émissions Électromagnétiques HF-VHF des Sprites

***M.B. Garnung*[1,2], *S. Celestin*[1], *and T. Farges*[2]**

[1] *LPC2E, University of Orleans, CNRS, matthieu.garnung@cnrs-orleans.fr*
[2] *CEA, DAM, DIF, 91297 Arpajon, France*

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Abstract:
Sprites are complex discharges that consist of many plasma filaments named streamers. They are produced high above thunderstorms (40 km to 90 km altitude), usually in association with positive cloud-to-ground lightning. It is known that sprites produce electromagnetic radiation observed typically in the extremely low (ELF) to ultra low (ULF) frequency bands [e.g., Cummer et al., GRL, 25, 1281, 1998]. More recently, sprites have been found to be associated with LF emissions in the range 50 to 350 kHz [Fullekrug et al., JGR, 115, A00E09, 2010], which emissions have later been proposed to be related to streamer expansion processes [Qin, et al., GRL, 39, L22803, 2012]. In a different context, Ihaddadene and Celestin [JGR, 122, 1000, 2017] have shown that collisions between streamers with opposite polarities would lead to strong electric field variation on the order of a few picoseconds in air at ground-level. The future space mission TARANIS funded by CNES will measure electromagnetic emissions associated with sprites. In this work, we present an effort on modeling relevant sprite streamer processes generating characteristic electromagnetic radiation with a focus on the possibility for streamer collisions to generate HF-VHF emissions (3 MHz to 300 MHz).

Résumé:
Les sprites sont des décharges complexes composées de filaments de plasma appelés streamers. Ils sont produits au dessus de cellules orageuses et s'étendent entre 40 km et 90 km d'altitude, et généralement associés à un éclair positif nuage-sol. Les sprites sont connus pour produire des émissions électromagnétiques habituellement observées dans la bande ELF-ULF [e.g., Cummer et al., GRL, 25, 1281, 1998]. Plus récemment, il a été découvert que les sprites ont également une émission dans la bande LF (50 Hz-350 kHz) [Fullekrug et al., JGR, 115, A00E09, 2010], laquelle a été proposée comme étant en lien avec le processus d'expansion des streamers [Qin, et al., GRL, 39, L22803, 2012]. Dans un contexte différent, Ihaddadene et Celestin [JGR, 122, 1000, 2017] ont montré que les collisions de streamers avec des polarités opposées devraient conduire à une forte variation du champ électrique de l'ordre de quelques picosecondes dans l'air à pression atmosphérique. La prochaine mission spatiale TARANIS financée par le CNES mesurera les émissions électromagnétiques associées aux sprites. Dans cette étude, nous présentons nos efforts sur la modélisation des processus producteurs de rayonnements électromagnétiques caractéristiques des streamers de sprites. Nous nous concentrons plus spécifiquement sur la possibilité que les collisions de streamers produisent un rayonnement dans la bande HF-VHF (3 MHz-300 MHz).

1 Introduction

Sprites are complex discharges that consist of many filaments named streamers. They are produced high above thunderstorms, typically between 40 km to 90 km and, usually associated with a positive cloud-to-ground lightning. Streamers are ionization waves that turn the medium in which there are propagating into filamentary plasma. They are known to have a strong electric field near their heads, which is able to ionize the air locally. This ionization process allows streamers to propagate step by step. We know that sprites produce electromagnetic radiation observed typically from the Extreme Low Frequency (ELF) to Ultra Low Frequency (ULF) [1]. More recently, sprites have been found to be associated with LF emissions in the range 50 to 350 kHz [2], which emissions have later been proposed to be related to streamer expansion processes [3]. Ihaddadene and Celestin [4] showed that collisions between streamers with opposite polarities would lead to strong electric field variation on the order of a few picoseconds in air at ground-level. In addition, these collisions between streamers are very common within sprites. The future space mission TARANIS [5] funded by CNES will measure electromagnetic emissions associated with sprite events in a band spreading from DC to 30 MHz. The quantification of this possible electromagnetic emission as well as related spectral signatures is therefore of prime importance for the preparation of TARANIS. In this work, we present an effort on sprite streamer electromagnetic radiation produced by a collision between two streamers at an altitude of 60 km and a spacecraft observing the event at $\sim$ 600 km of altitude.

2 Method

2.1 Model for streamers

The dynamics of a streamer can be described using drift diffusion equations for electrons, positive and negative ions, coupled with Poisson's equation in a cylindrical coordinate system [6]. In our model, the fluid equation is solved using an upwind scheme while Poisson's equation is iteratively solved via the Successive Over Relation (SOR) approach [7] [8]. The photoionization process is reduced to an uniform free electron background of $10^8\,\mathrm{m}^{-3}$ and we neglect the production of negative ions. The electric field is produced by two remote electrodes put at the opposite ends of the domain such that a uniform Laplacian field of $E_0 = 1130\,\mathrm{V\,m^{-1}}$ is established. The characteristic of the simulation domain is essentially based on [9] except that the size of the domain along the radial direction is twice larger to avoid streamer interaction with boundaries, and the system is set at 60 km altitude rather than at ground level. The initiation of streamers is done by placing two neutral Gaussian plasma clouds with a peak density of $5.5 \times 10^{12}\,\mathrm{m}^{-3}$ and a characteristic spatial decay scale of 0.8 m in the simulation domain at 6.8 m from the left and the right with respect to the center of the domain.

2.2 Model for electromagnetic emission

The analytical time domain solution for the azimuthal magnetic component of the electromagnetic field from a finite antenna of length $H = H_2 - H_1$ is given by [10] :

$$B_\theta(t) = \frac{\mu_0}{4\pi}\int_{H_1}^{H_2} \frac{\sin(\theta)}{R^2} i(z, t - \frac{R}{c})\ dz + \frac{\mu_0}{4\pi}\int_{H_1}^{H_2} \frac{\sin(\theta)}{cR}\frac{\partial i(z, t - \frac{R}{c})}{\partial t}\ dz \tag{1}$$

where $i(z,t)$ is the current flowing through the antenna, θ is the polar angle of the receiver with respect to the source location, R is the distance between the antenna and the receiver, c is the speed of light in vacuum and μ the permeability in vacuum. Figure 1 shows the situation studied. We consider a collision of two streamers occurring at 60 km of altitude, and a spacecraft flying at a distance $R = 600$ km. We also set the polar angle $\theta = 90°$. The first term of equation (1) is the induction part, second term is the radiative part. The length of the antenna is assimilated to the length of the streamer, so that $H = 50$ m. Since H is several order of magnitude lower than R, we neglect the induction part in (1) [3].

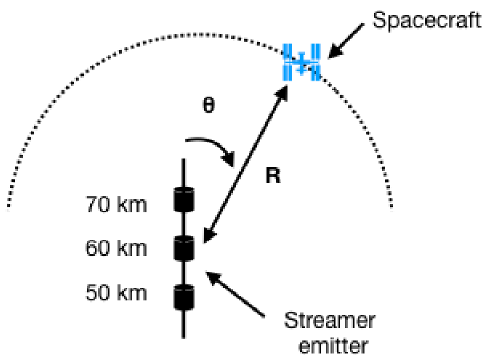

Figure 1 – Geometry of the electromagnetic radiation from a sprite at 60 km *altitude observed by spacecraft flying at* 600 km.

The current used in the simulation is the vertical current $I_z(z,t)$ flowing in the streamer body. It is calculated by integrating the current density along the radial direction.

3 Result

Figure 2 shows a cross-sectional view of the electric field at the time of the collision between two streamers. We observe in the bottom part of Figure 2, a peak in the electric field reaching about $7\,\mathrm{kV\,m^{-1}}$ in the colliding region. At the next moment, the electric field will suddenly collapse due to the large increase of the conductivity in this area [11]. After the propagation of an electrostatic wave, the streamer will have the same behavior as a double-headed streamer [12].

Figure 3 shows the azimuthal component of the magnetic field radiated by the streamer system. We notice that before the collision of streamers (before $t = 4.5\,\mu\mathrm{s}$), there is the lack of significant electromagnetic emission due to a weak variation of the current in time. On the other hand, around $4.5\,\mu\mathrm{s}$ we notice a strong peak of

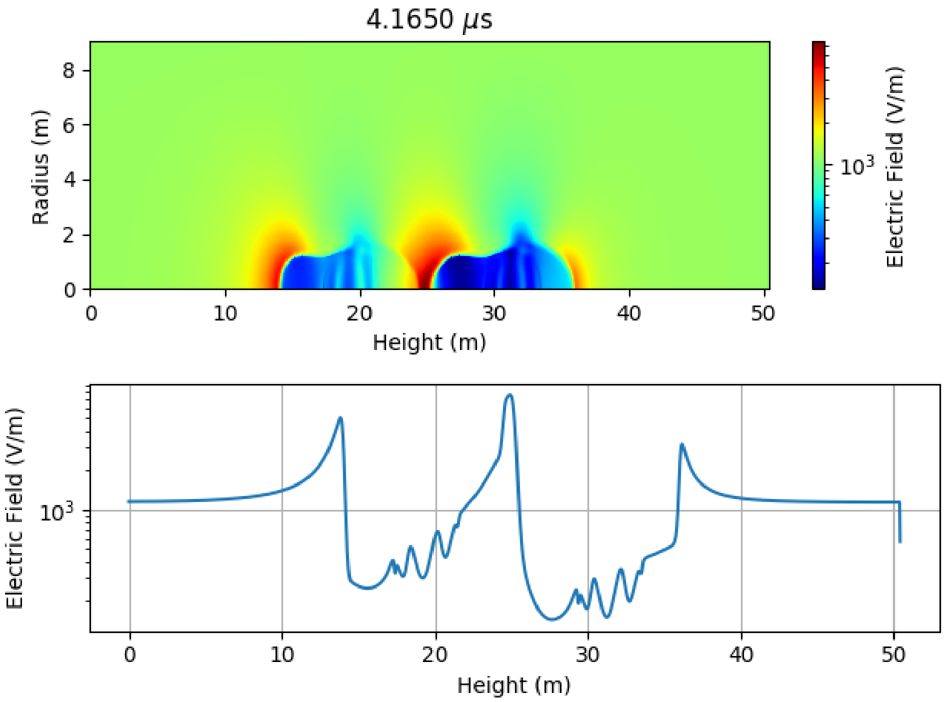

Figure 2 – Collision between two streamers of different polarity at an altitude of 60 km*. Top: Electric field in the simulation domain at the moment of the collision. The collision is occurring in the reddest region. We also observe that the highest electric field area is located in the vicinity of streamer heads. Bottom : Electric field along the height.*

the azimuthal magnetic component reaching almost 0.4 pT. This peak is the result of the collision of streamers which has led to a significant variation of the current in time.

4 Conclusion

The strong and rapid variation of the electric field in few nanoseconds is associated with a strong variation of the current. According to equation (1), this variation of the current in time will result in an electromagnetic radiation during the collision at streamers. On the other hand, during the propagation of streamers, no significant electromagnetic emission is observed, especially in the HF-VHF range. From these results, we will calculate specific signatures associated with streamer collisions taking place in sprites.

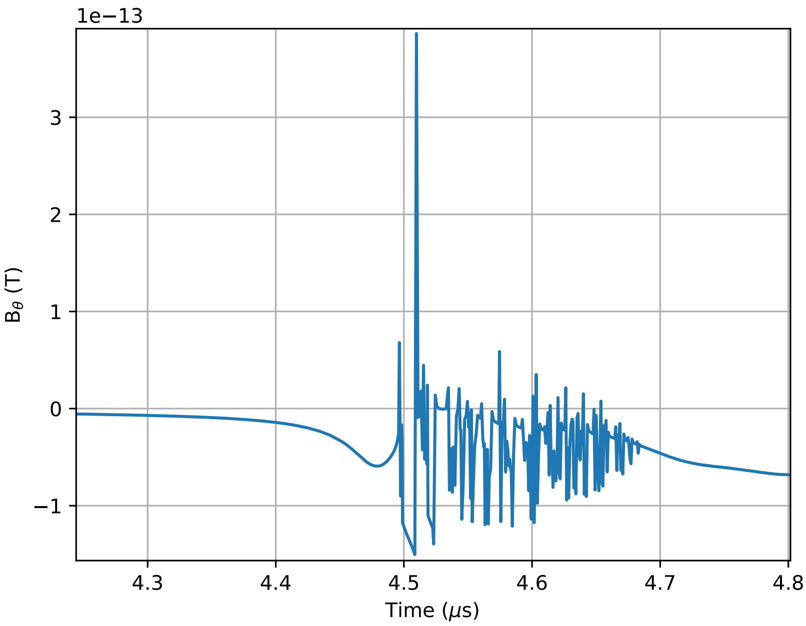

Figure 3 – Azimutal magnetic field component computed by using equation (1) *observed horizontally. We note the strong variation of the current around* 4.5 µs *as related to the collision of streamers.*

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