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# HF-VHF Electromagnetic Emissions from Collisions of Sprite Streamers

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## Key Points:

- EM emissions produced by a collision between two sprite streamers with opposite polarities are predicted using streamer and antenna models.
- Calculated radiated power from these EM emissions is compared to DEMETER, TARANIS, and FORTE radio instruments sensitivities.
- Sensitive ground-based instruments such as radiotelescopes (e.g., NenuFAR) may detect these emissions.

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**Abstract**

Sprites are complex transient plasma discharges that consist of many plasma filaments named streamers. They are produced high above thunderstorms. Sprites are known to produce electromagnetic radiation observed typically in the extremely low (ELF), ultra low (ULF), to as high as medium frequency (MF) radio bands. Recent research work showed that head-on streamer collisions lead to a reinforcement of the electric field over a short time scale, typically a few picoseconds at ground-level. The use of the similarity laws leads to a corresponding time scale on the order of a fraction of a microsecond at 50 km altitude, which opens the eventuality for HF-VHF emissions from sprites. In this paper, using a multifluid streamer model paired with an antenna model assimilating the streamer as a straight segment. We simulate head-on collision between two streamers with opposite polarities in order to evaluate their electromagnetic emissions. We report numerical prediction of the electromagnetic signature for 50, 60, 70, and 80 km altitudes. The magnetic field radiated varies over 4 orders of magnitude, between less than 0.1 fT to 7 pT. Comparing the spectral density from the head-on collision between two streamers with IME-HF (TARANIS), ICE (DEMETER), and FORTE RF payload, we find that IME-HF and ICE could detect these signatures. We compare these results with sensitive ground-based instruments like the radiotelescope NenuFAR, and show that detections of such events might be possible with this type of fast and sensitive radiotelescopes.

**1 Introduction**

Sprites are sudden and bright luminous events occurring above thunderclouds between 40 km and 90 km altitude. They have been observed for the first time in 1989 (Franz et al., 1990) during the test of a TV camera in low light condition. Sprites are composed of many plasma filaments named streamers, which radiate electromagnetic emissions. Cummer et al. (1998) observed electromagnetic emission in the extremely low frequency (ELF) to ultra low frequency (ULF) range due to electric currents flowing in the body of sprites. They evaluated that the electromagnetic energy in the ELF range is comparable to that of the parent cloud-to-ground (CG) lightning discharge. Füllekrug et al. (2001) confirmed these observations with radio and optical records of sprites with long-time delays relative to their parent lightning discharges. Füllekrug et al. (2010) recorded emissions in the low frequency (LF) range, which are temporally coincident with the sprite light emission. Farges and Blanc (2011) reported electromagnetic radiation in the medium frequency

45 (MF) range during sprites events. Qin et al. (2012) demonstrated the importance of the  
46 local air density on the emission frequency for a single-headed streamer and proposed  
47 that LF emissions are associated with streamer expansion processes.

48 In a different context, Ihaddadene and Celestin (2015) showed that collisions be-  
49 tween streamer discharges at air at ground-level with opposite polarities would lead to  
50 strong electric field variations over a duration on the order of a dozen of picoseconds un-  
51 der high electric fields. This was later confirmed through the use of different models (e.g.,  
52 Köhn et al., 2017; Babich & Bochkov, 2017; Luque, 2017; Shi et al., 2019). Luque (2017)  
53 and Shi et al. (2019) reported that such streamer collisions at ground-level should pro-  
54 duce electromagnetic emission in the ultra high frequency (UHF i.e., 300 MHz-3 GHz)  
55 range. Using similarity laws (e.g., Pasko et al., 1998; Pasko, 2006; Qin & Pasko, 2015)  
56 to scale this typical duration of  $\sim 10$  ps at an altitude of 60 km, one finds a typical time  
57 scale on the order of a few tens of nanoseconds suggesting that electromagnetic emission  
58 in the high frequency (HF) and very high frequency (VHF) bands (respectively 3 MHz-  
59 30 MHz and 30 MHz-300 MHz) might be produced. These emissions would be observ-  
60 able from space for frequencies above the ionospheric cutoff. It is worth mentioning that  
61 collisions between streamers seem common in sprites as it can be seen on pictures reported  
62 in (e.g., Gerken et al., 2000; Cummer et al., 2006). Indeed, one can also observe a change  
63 in the filament shape and brightness in the vicinity of intersections, indicative of actual  
64 collisions. We cite an observation, which is striking regarding the importance and fre-  
65 quency of streamer collisions in sprites: this result was first presented at the AGU Fall  
66 Meeting 2019 in San Francisco (McHarg et al., 2019).

67 The original idea of using streamers with opposite polarities came from the scal-  
68 ing at timescales found by (Ihaddadene & Celestin, 2015) to sprite altitudes. It is clear  
69 from high-speed video observations that a great number of collisions between stream-  
70 ers of opposite polarities do occur, despite the fact that the occurrence frequency is not  
71 quantified yet (e.g., McHarg et al., 2019). Other kinds of collisional geometries leading  
72 to rapid changes in the electric current can be envisioned, such as the collision of stream-  
73 ers with inhomogeneities (Luque & Gordillo-Vázquez, 2011; Ihaddadene et al., 2019) or  
74 the connection of a streamer with the oppositely charged tail of another streamer (Luque  
75 & Ebert, 2010).

76 TARANIS (Lefeuvre et al., 2008) was a satellite mission funded by the French space  
77 agency (CNES) dedicated to the study of impulsive transfers of energy between the tro-  
78 posphere and the near-Earth environment, which are manifested by Transient Luminous  
79 Events (TLEs) and Terrestrial Gamma rays Flashes (TGFs) produced by thunderstorm  
80 activity. TARANIS had several types of sensors to observe TLEs and TGFs. In this pa-  
81 per, we are particularly interested in the electric field instrument named *Instrument de*  
82 *Mesure du champ Electrique* (IME), and the magnetic field instrument named *Instru-*  
83 *ment de Mesure du champ Magnétique* (IMM). IME includes two antennas, IME-BF for  
84 the low frequencies from DC up to 1 MHz and IME-HF for the high frequencies from  
85 100 kHz up to 35 MHz. IMM is a tri-axis magnetometer, so-called search-coil, designed  
86 to measure the magnetic field variation between 5 Hz and 1 MHz. In addition, the in-  
87 strument MCP (MicroCameras and Photometers) is made up of 2 cameras and 4 pho-  
88 tometers designed to detect and characterize TLEs (Farges et al., 2018).

89 Unfortunately, TARANIS has never reached its orbit due to launch failure on Novem-  
90 ber 17th, 2020. We hence to compare with previous radio instruments from other mis-  
91 sions dedicated to lightning observations in order to evaluate the possibility to use pre-  
92 vious work and possibly future work to conduct such studies. We then use the radio in-  
93 strument ICE from the DEMETER mission (Berthelier et al., 2006) and the FORTE's  
94 radio payload (Jacobson et al., 1999). These two missions have the advantage to have  
95 a similar orbit trajectory to that TARANIS would have had.

96 The DEMETER mission was to provide a nearly continuous survey of natural elec-  
97 trostatic, electromagnetic emissions, and ionospheric irregularities that can be related  
98 to seismic activity (Parrot et al., 2006). In this paper, we focus on the radio instrument  
99 ICE (Berthelier et al., 2006), which relies on four spherical sensors mounted at the ends  
100 of four antenna arms. It operates over a wide frequency range from DC to 3.175 MHz.  
101 Note that the DEMETER mission had also a magnetic instrument named IMSC that  
102 we do not consider in the present study because of a weak sensitivity.

103 The FORTE mission was dedicated to the study of lightning from space with op-  
104 tical and radio payloads (Jacobson et al., 1999). As for the DEMETER mission, we fo-  
105 cus on the RF payload that is composed of two tunable receivers in the frequency range  
106 20-300 MHz.

107 The purpose of this work is to characterize the electromagnetic radiation expected  
 108 to be produced by collisions of streamers with opposite polarities, and to study its de-  
 109 tectability by TARANIS, DEMETER, FORTE, and ground-based instruments such as  
 110 the radiotelescope NenuFAR (Zarka et al., 2012, 2015).

## 111 2 Methods

112 In this work, we use a streamer model based on a 3-D axisymmetric fluid approach  
 113 (e.g., Liu & Pasko, 2004). It consists in solving Poisson's equation (1) coupled with drift-  
 114 diffusion equations (2)-(4). Poisson's equation is written as:

$$\nabla^2 \phi = -\frac{q_e}{\epsilon_0} (n_p - n_e - n_n) \quad (1)$$

115 where  $\phi$  is the electric potential,  $q_e$  is the elementary charge,  $\epsilon_0$  is the vacuum permit-  
 116 tivity, and  $n_p$ ,  $n_e$ , and  $n_n$  are the positive ion, electron, and negative ion densities, re-  
 117 spectively. Equation (1) is numerically solved using a Successive Over-Relaxation (SOR)  
 118 method (Press et al., 2007) coupled with Chebyshev's acceleration method (Golub & Van Loan,  
 119 1996). Drift-diffusion equations (2), (3), and (4) describe the fluid motion and the lo-  
 120 cal evolution of the electron, positive ion, and negative ion populations, respectively:

$$\frac{\partial n_e}{\partial t} + \vec{\nabla} \cdot (n_e \vec{v}_e - D_e \vec{\nabla} n_e) = (\nu_i - \nu_a) n_e + S_{ph} \quad (2)$$

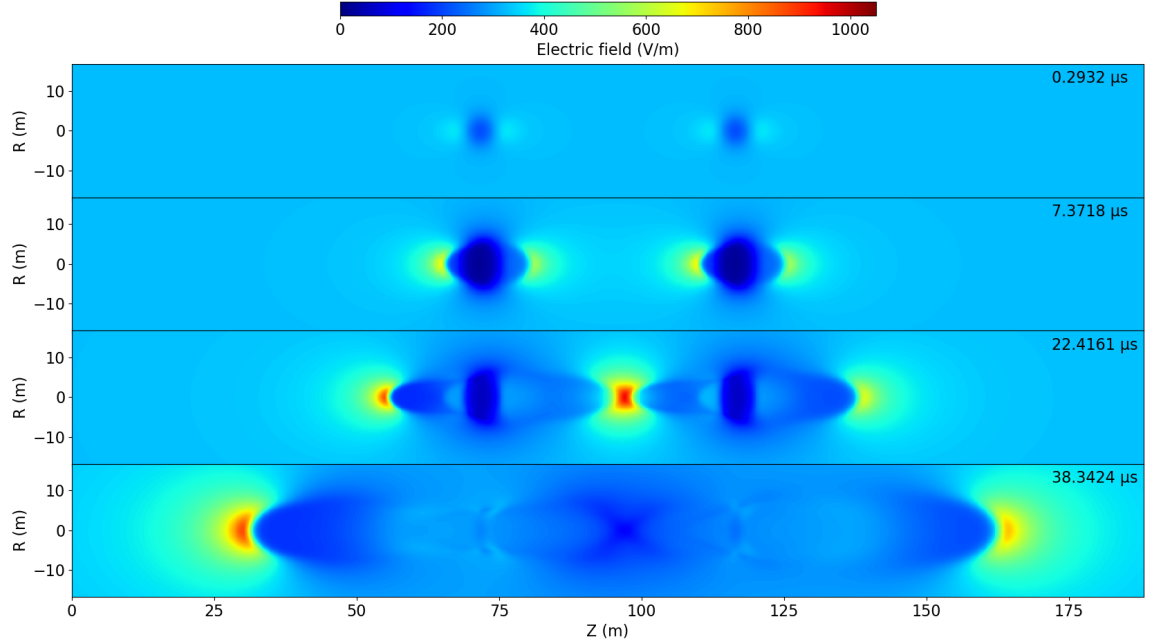
$$\frac{\partial n_p}{\partial t} + \vec{\nabla} \cdot (n_p \vec{v}_p - D_p \vec{\nabla} n_p) = \nu_i n_e + S_{ph} \quad (3)$$

$$\frac{\partial n_n}{\partial t} = \nu_a n_e \quad (4)$$

121 where  $n_k$  is the density,  $v_k$  is the velocity,  $D_k$  is the diffusion coefficient, and  $k$  is  $e$  for  
 122 electrons,  $p$  for positive ions, and  $n$  for negative ions.  $\nu_i$  is the ionization frequency while  
 123  $\nu_a$  is the the sum of the two- and three-body electron attachment frequencies. These fre-  
 124 quencies are calculated from Morrow and Lowke (1997).  $S_{ph}$  is the rate of electron-ion  
 125 pair production due to photoionization processes evaluated using the three-group SP<sub>3</sub>  
 126 model (Bourdon et al., 2007). Drift-diffusion equations are computed numerically through  
 127 a basic upwind scheme (low-order) combined with an 8<sup>th</sup> high-order scheme using the  
 128 Flux Corrected Transport technique (Zalesak, 1979).

129 The numerical grid has a size of  $151 \times 1681$  for a resolution  $8 \frac{N}{N_0} \mu\text{m}$ , where  $N$  is  
 130 the local neutral density of air and  $N_0$  is the air density at ground level. The simulation  
 131 is conducted at an altitude of 70 km under a homogeneous electric field of  $40 \frac{N}{N_0} \text{kV/cm}$ .  
 132 As the length of the simulated domain along the  $z$ -direction is small ( $< 200$  m), we ne-

133 glect the variation of the air density as function of the altitude. Two gaussian neutral  
 134 plasma seeds with a characteristic radius  $\sigma = 3$  m are placed at 75.6 m and 122.8 m away  
 135 from the right border so as to produce two double-headed streamers, such that at 99 m  
 136 (i.e., in the middle of the simulation domain) a head-on collision occurs between a neg-  
 ative and a positive streamer as shown in Figure 1. The initial density distribution is



**Figure 1.** Four 2-D cross-sectional views of the absolute value of the axial component of the electric field for two double-headed streamers at an altitude of 70 km under a Laplacian electric field of  $40 \frac{N}{N_0}$  kV/cm. The time for each snapshot is given at the top-right corner of each panel while the electric field is encoded with the colorbar. The head-on collision between the two double-headed streamers (identified as the moment of time the electric field reaches its maximum) occurs at  $22.12 \mu s$ .

137

138

written as:

$$n_{i,j} = A \left[ \exp \left( -\frac{r_i^2 + (z_j - z_0)^2}{\sigma^2} \right) + \exp \left( -\frac{r_i^2 + (z_j - z_1)^2}{\sigma^2} \right) \right] \quad (5)$$

139

140

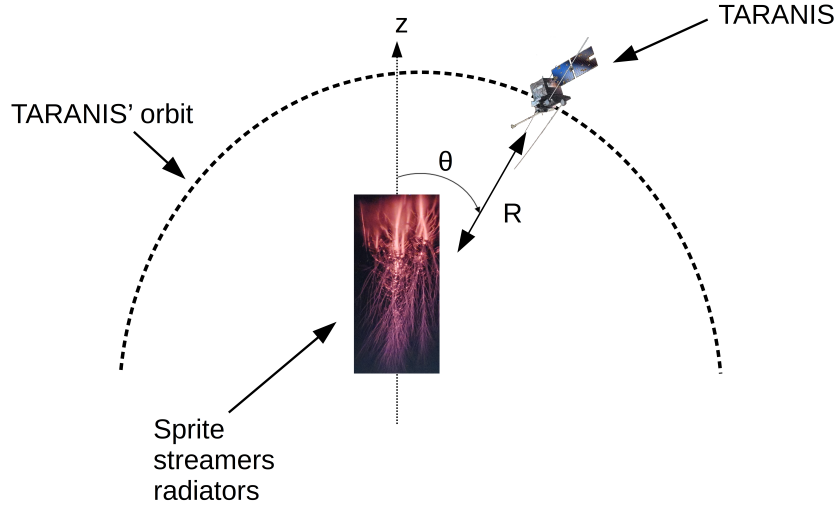
141

where  $A$  is the peak electron density,  $z_0$  and  $z_1$  are the positions of the maximum density of the seeds. In this work, at 70 km altitude,  $A = 4.6 \times 10^{11} \text{ m}^{-3}$ ,  $z_0 = 75.6$  m, and  $z_1 = 122.8$  m.

142 The magnetic field radiated by the streamers is evaluated through the model of Uman  
 143 et al. (1975) considering the cylindrical simulation domain as a straight antenna. The  
 144 magnetic field  $B_\phi$  produced by this antenna is given by:

$$B_\phi(t) = \frac{\mu_0}{4\pi} \int_{H_1}^{H_2} \frac{\sin \theta}{R^2} i(z, t - \frac{R}{c}) dz + \frac{\mu_0}{4\pi} \int_{H_1}^{H_2} \frac{\sin \theta}{cR} \frac{\partial i(z, t - \frac{R}{c})}{\partial t} dz \quad (6)$$

145 where  $H_1$  and  $H_2$  are the lower and upper edges of the simulation domain so that the  
 146 length of the antenna is given by  $H_2 - H_1$ . The variable  $\theta$  is the polar angle between  
 147 the observer (the spacecraft) and the streamers system (see Figure 2). As a sprite event  
 148 occurs over a short timescale, we consider that  $\theta$  is constant, and for the sake of simplic-  
 149 ity and to maximize the produced magnetic field, we set it to  $90^\circ$ . The variable  $R$  is the  
 150 distance between the spacecraft and the streamers system. In this study, we consider the  
 151 case of spacecraft orbiting at an altitude of 600 km. The quantity  $i(z, t)$  is the total cur-  
 152 rent resulting from the summation of the fluid current produced by ions and electrons,  
 153 and the displacement current created by the temporal variation of the electric field. The  
 observational geometry is sketched in Figure 2.



**Figure 2.** Observational geometry used in our model. Streamers are considered as straight antennas. The spacecraft is at a distance  $R$  from the streamers system, which is localized at a given altitude, and making an angle  $\theta$  with respect to the spacecraft. Credits for the sprite picture: Stéphane Vetter (2019).

154  
 155 Furthermore, the timestep varies dynamically to capture fast processes in the sim-  
 156 ulation. We resample the obtained radiated magnetic field at the lowest timestep used



157 during the numerical simulation in a regular fashion through a cubic interpolation. For  
 158 a simulation at 70 km altitude, this lowest timestep is 2.5 ns.

159 The electric field radiated by the antenna is evaluated using the approximation  $E =$   
 160  $cB$  as the receiver is far away from the source. Indeed, a sprite streamer can be found  
 161 between 40 km and 90 km altitude while typical satellites in low Earth orbit are at  $\sim 600$   
 162 km altitude. Furthermore, we neglect the first term in equation (6) giving that the re-  
 163 ceiver is far away from the source. This assumption is verified if both terms in the equa-  
 164 tion (6) compare such that:

$$\frac{1}{R}i(z, t - \frac{R}{c}) \ll \frac{1}{c} \frac{\partial i(z, t - \frac{R}{c})}{\partial t} \quad (7)$$

165 after straightforward manipulation, we obtain:

$$R \gg c \frac{i(z, t - \frac{R}{c})}{\frac{\partial i(z, t - \frac{R}{c})}{\partial t}} \quad (8)$$

166 and through a dimensional analysis, one obtains:

$$R \gg c\Delta t \quad (9)$$

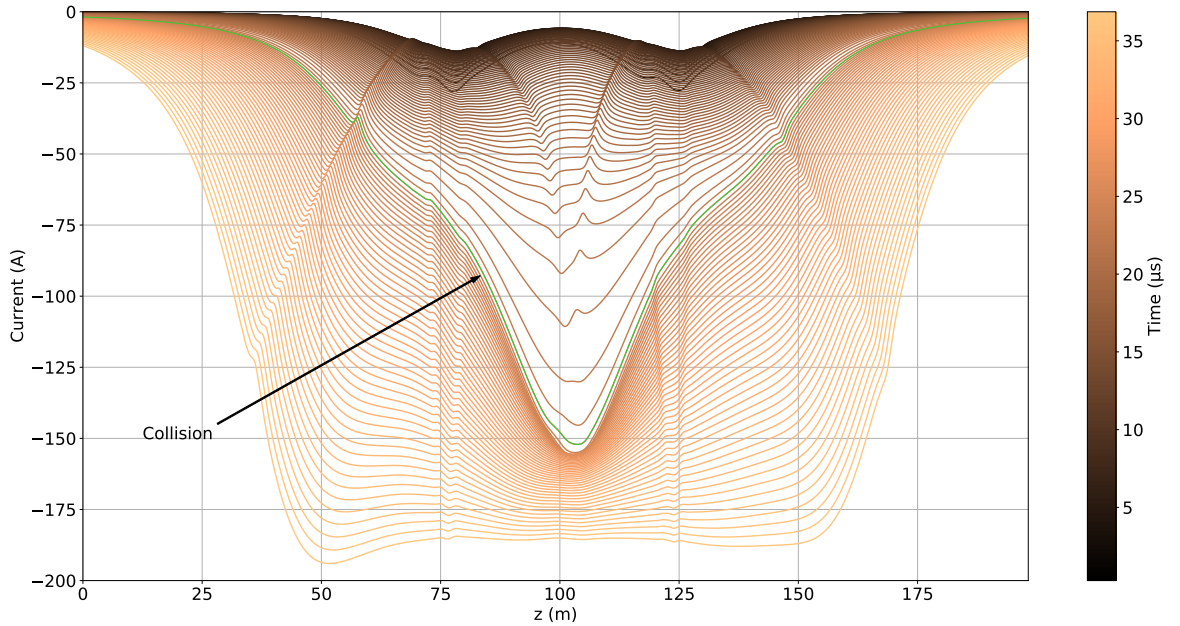
167 The typical duration of the entire simulation, including propagation of double-headed  
 168 streamers and their head-on collision at 70 km is around 20  $\mu s$ . We hence get  $c\Delta t \sim$   
 169 6 km, which is about 100 times lower than the streamer-receiver distance ( $\sim 600$  km) con-  
 170 sidered in the study. The assumption neglecting the first term of the equation (6) is there-  
 171 fore deemed valid in the present study.

172 Gerken et al. (2000) show that streamers can have transverse extents of about 150  
 173 m above 60 km altitude. Such streamers are therefore much wider than those usually  
 174 obtained in simulations and presumably would carry much stronger electric currents. In-  
 175 deed, the radius of the streamers shown in Figure 1 is  $\sim 5$  m. We hence consider a fac-  
 176 tor of  $\sim 30$  between such simulated sprite streamers and those in reality above 60 km.  
 177 This difference in the streamer radius needs to be accompanied by an increase in the elec-  
 178 tric current proportional to the increase in the transverse area ( $30^2 = 900$ ). As part  
 179 of a preliminary work, through numerical simulations we have verified that such scaling  
 180 is physical and that the corresponding streamers do follow the dynamics of smaller ones.  
 181 However, those simulations are extremely resources- and time-consuming if to be pur-  
 182 sued with a high grid resolution. In this work, we therefore choose to use this simple fac-  
 183 tor of  $30^2$  to obtain the current carried by high-altitude sprite streamers. Note that the

184 difference in size between real sprite streamers and simulated ones is also confirmed by  
 185 Liu et al. (2009) who found 4 orders of magnitudes between simulated and observed streamer  
 186 brightnesses (brightness should be proportional to the streamer volume ( $\sim 30^3$ )) and  
 187 McHarg et al. (2010) showed that a typical sprite streamer tip is 193 m, but found much  
 188 greater radii for splitting streamers.

### 189 3 Results and Discussion

190 Figure 1 shows a 2-D cross-sectional view of the electric field at the moment of the  
 191 head-on collision between two double-headed streamers at 70 km. The collision occurs  
 192 at  $z \sim 100$  m. The simulation domain is scaled at other altitudes using similarity laws.  
 193 As part of preliminary work for the present study, we have verified the validity of this  
 scaling-based method by realizing simulations at various altitudes. Figure 3 shows the



**Figure 3.** Total electric current along the axis of the domain as a function of position (lines are separated by a step of  $0.29 \mu\text{s}$ ) for the collision between two double-headed streamers illustrated in Figure 1. The time associated with the collision is defined as the time at which the electric field reaches its maximum.

194  
 195 temporal evolution of the total current  $i(z, t)$  (Equation (6)) before, during, and after  
 196 the collision at 70 km (Figure 1). It illustrates the increase of the current during the ex-

197 pansion of the two double-headed streamers before the collision (above the green curve),  
 198 the strong variation of the current during the collision (green curve), and the increase  
 199 of the current after the collision (below the green curve).

200 Figure 4a shows the magnetic field waveform radiated by streamers for collisions  
 201 occurring at different altitudes as it would be observed by satellite when ignoring the dis-  
 202 persion of the signal through the ionosphere. We can separate each colored curve in three  
 203 parts. The first part is before the collision. During that stage, the increase of the mag-  
 204 netic field is due to an increase of the current in time resulting from the expansion of the  
 205 two double-headed streamer, as first reported by Qin et al. (2012). The second stage cor-  
 206 responds to the interaction between streamers. During the interaction, the electric field  
 207 reaches up to  $271 \frac{N}{N_0}$  kV/cm leading to a strong increase in the electron density over a  
 208 few nanoseconds, and then a strong variation of the current moment over a short time  
 209 scale leading to a significant increase of the magnetic field illustrated by peaks in Fig-  
 210 ure 4a. The increase of the electron density involves an increase of conductivity, which  
 211 then leads to a sudden decrease of the electric field. Following the collision, we obtain  
 212 a single double-headed streamer resulting from the merging of the two double-headed  
 213 streamers. In the third stage, the total current is still increasing because of the expan-  
 214 sion of the single double-headed streamer (Qin et al., 2012), as during the first stage. This  
 215 expansion is due to the presence of a homogeneous electric field above the stability field  
 216 for streamer propagation (e.g., Liu et al., 2009).

217 We conducted a simulation using the same setup with a single double-headed streamer  
 218 in the aim to make a control experiment. Comparison with this no-collision case is shown  
 219 in Figure 4a. In this figure the magnetic field in the control simulation (no-collision case)  
 220 is multiplied by two to represent the magnetic field radiated by two non-interacting stream-  
 221 ers. This comparison reveals that in the absence of a collision, the radiated magnetic field  
 222 is around 1 pT at the position of the satellite, while in the case with collision we found  
 223 7 pT at 70 km altitude. The results for 50 km, 60 km, and 80 km are scaled using sim-  
 224 ilarity laws. The sprite-observer distance stays at 600 km for all cases.

225 In Figure 4b, we show the spectral density of electric fields radiated by two streamer  
 226 systems with and without collisions scaled at different altitudes. For each spectral den-  
 227 sity shown in Figure 4b, we observe three spectral regions for the case with collisions (plain  
 228 curves). The first region corresponds to the linearly decreasing part of the spectral den-

229 sity and stops before the first significant decrease in the spectral density of the electric  
 230 field in Figure 4b. The frequency range for this region starts from  $\sim 630$  kHz up to  $\sim 1.2$   
 231 MHz for an altitude of 50 km. For an altitude of 60 km, the frequency range spreads from  
 232  $\sim 190$  kHz up to  $\sim 360$  kHz. At 70 km altitude, the first region is located between  $\sim 53$   
 233 kHz and  $\sim 103$  kHz, and for 80 km altitude it starts from  $\sim 12$  kHz to  $\sim 23$  kHz. Note that  
 234 these low frequencies depend on the duration of the magnetic field signal therefore they  
 235 don't have a straightforward physical signification. The second region starts from the  
 236 previous point to the first bump. At 50 km altitude, this region reaches up to  $\sim 30$  MHz,  
 237 for 60 km altitude it is 9 MHz, for 70 km altitude it is  $\sim 3$  MHz, and for 80 km altitude  
 238 it is  $\sim 600$  kHz. The last region is filled with numerical noise. For the cases without col-  
 239 lisions, the three regions turn into only two regions. The first region is defined by a power  
 240 law decrease of the spectral density followed by the second region, which is similar to the  
 241 third region mentioned above. For 50 km altitude the steep decrease is in the range 648  
 242 kHz to 30 MHz, for 60 km altitude it is from 193 kHz to 9 MHz, for 70 kilometer alti-  
 243 tude it begins at 55 kHz and it finishes at 2.6 MHz, and for 80 altitude it is between 12  
 244 kHz and 570 kHz. For all these altitudes, the spectral density decreases by about a fac-  
 245 tor of approximately 75000. Note that the frequency associated with the first region is  
 246 similar to the frequency for the case with collision.

247 To investigate the capability for radio instruments to detect these electromagnetic  
 248 signatures, we compare our simulation results to the sensitivity threshold of the instru-  
 249 ments IME-HF (dotted black line), FORTE RF payload (dotted dark blue), and ICE (dot-  
 250 ted goldenrod) in Figure 4b. In order to make comparison, we use the spectral density  
 251 but we do not normalize it with respect to a specific antenna length. The sensitivity of  
 252 IME-HF is slightly dependent on the frequency staying almost constant at  $\sim 2 \times 10^{-8}$   
 253  $\text{V/m}/\sqrt{\text{Hz}}$  from 50 kHz to 30 MHz, which is significantly below the signal level associ-  
 254 ated with streamer collisions occurring between 50 km and 80 km altitude. On the other  
 255 hand, the sensitivity for both ICE (30 kHz - 30 MHz) and FORTE RF (20-320 MHz)  
 256 payload are constant in their own frequency range at respectively  $10^{-7} \text{V/m}/\sqrt{\text{Hz}}$  and  
 257  $5.6 \times 10^{-8} \text{V/m}/\sqrt{\text{Hz}}$ . The sensitivity threshold of FORTE is obtained from the upper  
 258 panel of Plate 1 in Jacobson et al. (1999) indicated to be  $\sim 10^{-8.5} \text{V}^2/\text{m}^2/\text{MHz}$  in their  
 259 figure caption. Note that this is an overestimation of the real sensitivity threshold of FORTE  
 260 (e.g., see Lehtinen et al. (2004), Section 5). The frequency range covered by ICE matches  
 261 within the frequency range covered by a head-on collision occurring between 50 and 80

262 km altitude. However, its sensitivity threshold is slightly above the two cases at 70 km  
263 and 80 km altitude. Concerning the FORTE RF payload, its frequency range allows it  
264 to observe in the noisy part of the signal where its sensitivity threshold is not sufficient  
265 to detect a potential signature of a head-on collision between two streamers. The sen-  
266 sitivity of the two magnetic instruments is not reported because their maximum of sen-  
267 sitivity (which is reached at 1 MHz for IMM and 5 kHz for IMSC) is about 10 times lower  
268 than the maximum of the spectral density for a collision-case at 70 km altitude.

269 The specific spectral signature depends on the altitude of streamers at the time of  
270 the collision (as time scales up with altitude, frequency scales down according to sim-  
271 ilarity laws (e.g., Pasko, 2006)), thus creating a selective filter. Additionally, note that  
272 in this frequency range, the propagation through the ionosphere should reflect a signif-  
273 icant part of the VLF-LF signal. We observe in Figure 4b that the sensitivity thresh-  
274 old for IME-HF allows to measure a significant part of the signal associated with a sin-  
275 gle collision while this proportion is significantly lower for ICE. We hence conclude that  
276 for a single head-on collision of double-headed streamers, IMM and IMSC could not de-  
277 tect the signal, while IME-HF and ICE might. Figure 4b shows that the neutral den-  
278 sity dependence of streamer collision timescales would make altitude discrimination of  
279 events possible, and hence could play a complementary role in the exploitation of pho-  
280 tometric measurements. However, note that the cases studied here are under the strong  
281 assumption that the effect of the ionosphere is negligible and that the noise context is  
282 favorable. If we consider that the nighttime cutoff frequency of the ionosphere is 5 MHz  
283 (Davies, 1989), one could conclude that HF signals coming from streamer collisions should  
284 not be measurable by the instruments considered in the present study. However, that  
285 the ionosphere cutoff frequency depends on the state of the ionosphere, which can be strongly  
286 disturbed during thunderstorms, and even ULF-LF radio emissions are known to be ob-  
287 servable from space during thunderstorm activity (e.g. Parrot et al., 2008). Moreover,  
288 the sensitivity of IME-HF is evaluated from ground based measurements, therefore the  
289 true sensitivity in space would only be known in flight.

290 However, as previously mentioned, sprites are composed of many streamers mov-  
291 ing up and down, and often interacting. It is expected that, TARANIS and other ground-  
292 based radio instruments will observe an incoherent signal resulting from the complex in-  
293 teractions of many sprite streamers. It is also possible that multiple collisions occurring  
294 at the same time would strengthen the radio signal predicted for one single collision in

295 the present paper. Furthermore, the radio emission produced by lightning discharges will  
 296 tend to contaminate data. Extracting relevant information might require to use statis-  
 297 tical or machine learning techniques. The observation of the electromagnetic energy re-  
 298 leased by sprites might help evaluate the number of streamers within sprites , and the  
 299 importance of their interactions, for example following the study of Liu et al. (2019).

300 Another parameter having an importance is the angle  $\theta$ . As previously mentioned,  
 301 we set it to 90 to maximize the radiated magnetic field (see Equation (6)). We evalu-  
 302 ate its influence on the spectral density with respect to sensitivity thresholds of the three  
 303 instruments. The result is shown in Figure 5.

304 We note that IME-HF would have been able to detect electromagnetic emissions  
 305 at 50 km altitude for  $\theta \geq 13^\circ$ , at 60 km altitude it becomes  $\theta \geq 8^\circ$ , at 70 km altitude  
 306  $\theta \geq 4^\circ$ , and it drops to  $2^\circ$  for 80 km altitude. In the case of ICE due to its sensitivity  
 307 threshold (see Figure 4), it can only detect a streamer collision at 70 km altitude with  
 308  $\theta \geq 29^\circ$  and 80 km altitude for  $\theta \geq 13^\circ$ . It appears that for the case considered here,  
 309 observations from spacecraft is possible for a broad range of polar angles.

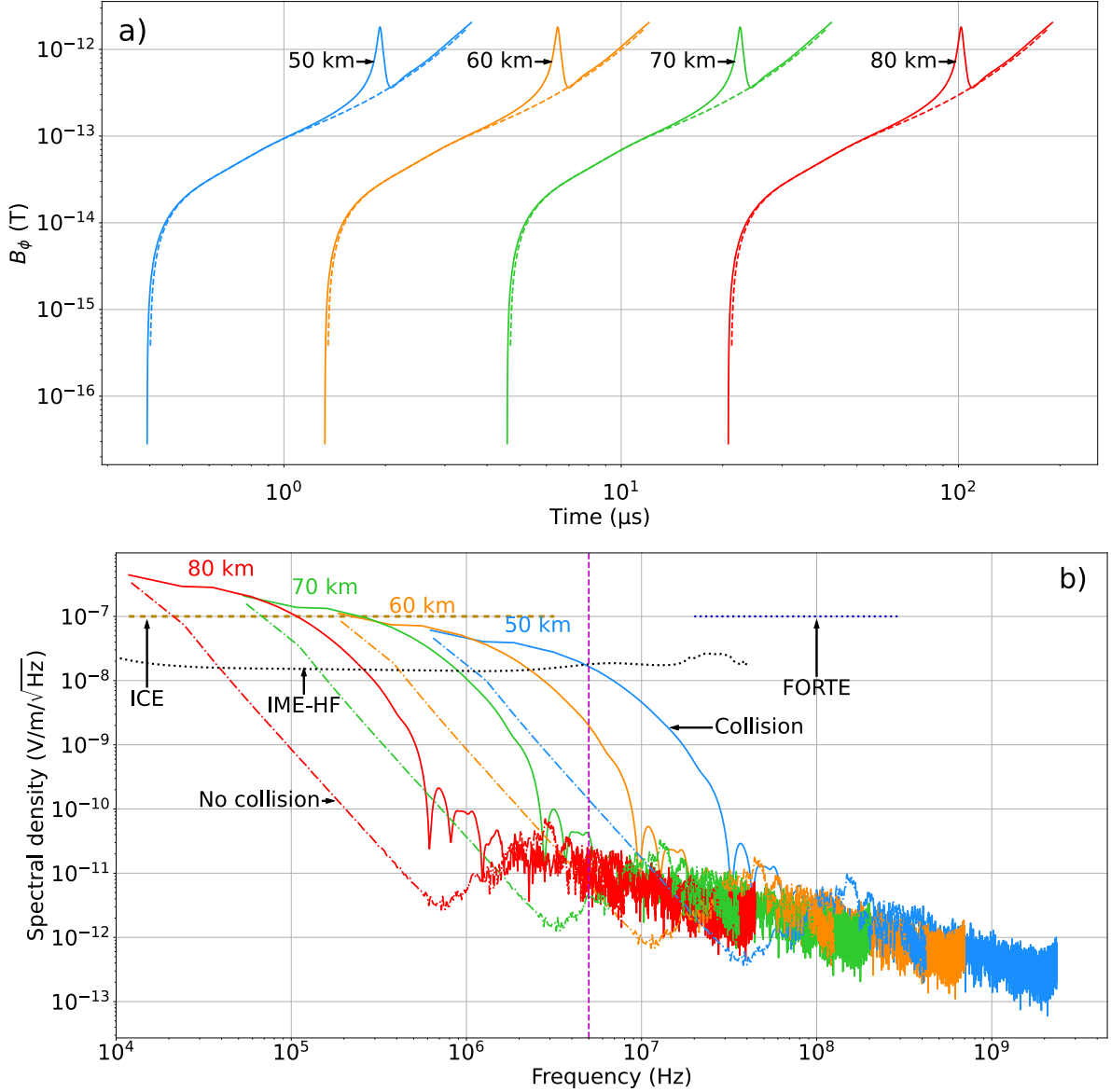
310 We also evaluate the possibility to observe such events from ground-based telescopes.  
 311 As an example, the radio telescope NenuFAR performs observations between 10 MHz  
 312 and 85 MHz (Zarka et al., 2012, 2015). The main scientific objectives regarding Nenu-  
 313 FAR are the detection and study of exoplanets in radio, detection of the radio signal of  
 314 the ‘‘Cosmic Dawn’’ (epoch of formation of the first stars and galaxies), and the study  
 315 of pulsars (hyperdense and strongly magnetized dead stars in rapid rotation). The typ-  
 316 ical distance between the radiotelescope and the sprite event is assumed to be similar  
 317 to that of a satellite observation, such as sketched in Figure 2. In the field of radioas-  
 318 tronomy, the Jansky unit ( $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ ), corresponding to the electromag-  
 319 netic spectral flux density, is commonly used to compare the sensitivity of the instru-  
 320 ment with sources. Computing the spectral flux density is done through the norm of the  
 321 Poynting vector  $S$  given by:

$$S = \frac{cB^2}{\mu_0} \quad (10)$$

322 followed by a Fourier transform. Calculations show that the spectral density flux pro-  
 323 duced by a sprite streamer collision in the NenuFAR range is of  $\sim 2 \text{ GJy}$  which is six  
 324 orders of magnitude larger than the sensitivity of NenuFAR over a timescale of a dozen

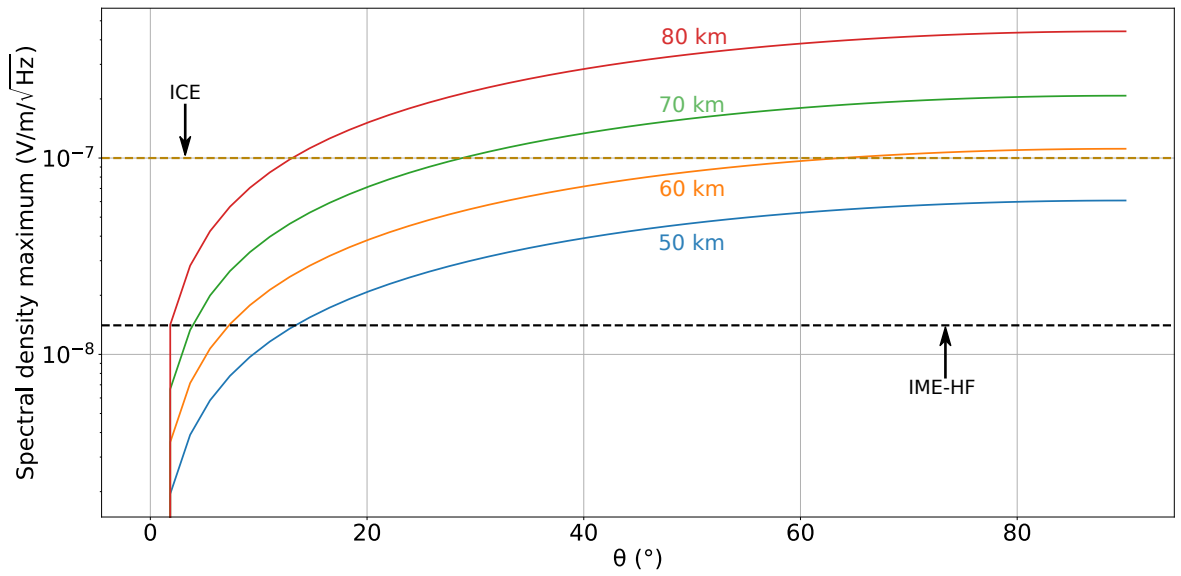
325 of microseconds, which demonstrates the high potential of radiotelescopes in the study  
326 of TLEs.

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**Figure 4.** a) Magnetic field radiated by two double-headed streamers evolving at an altitude of 50 km (blue), 60 km (orange), 70 km (green), and 80 km (red). The peak of each curve appears when the head-on collision between two streamers occurs. b) Spectral density of the electric field radiated by two double-headed streamers experiencing a collision (solid lines) and two, non-interacting streamers (dash-dotted lines) immersed in a homogeneous electric field of  $40 \frac{N}{N_0}$  kV/cm at 50 km, 60 km, 70 km, and 80 km altitude. The dotted black line is for the sensitivity of the electric field instrument (IME-HF) on board TARANIS, while the blue one is for the FORTE RF payload sensitivity and the goldenrod is for the DEMETER radio instrument (ICE). The sensitivity of the magnetic field instrument (IMM) is not shown because its sensitivity is too low (high sensitivity threshold). The dashed vertical magenta line corresponds to the typical ionospheric cutoff nighttime.





**Figure 5.** Variation of the maximum of the spectral density as function of the polar angle  $\theta$  for a head-on collision at 50 (blue), 60 (orange), 70 (green), and 80 (red) km altitudes. The dotted goldenrod line corresponds to the sensitivity of ICE while the dotted black line is the minimum of the IME-HF sensitivity.

## 4 Conclusions

In this paper, we investigate the production of electromagnetic radio emissions associated with the interaction of plasma filaments in sprite discharges using a streamer fluid model. We show that the collision between two streamers produces a strong variation of the electric current over a short time scale. The short time scale is caused by the increase of the electron density leading to a high conductivity in the plasma, which then briefly collapses the electric field and produces a strong current variation over this short time scale. We compare the resulting signal with the sensitivity of two radiowave instruments of TARANIS, along with DEMETER and FORTE radio instruments.

For a single collision, we find that the electric field exceeds IME-HF (electric antenna), ICE, and FORTE sensitivity thresholds. However, we conclude that IMM (magnetic antenna) and IMSC sensitivities are too weak to detect such events. The challenge to analyze IME-HF data during thunderstorm where radio emission released by lightning discharges will also be mixing with the radio pattern associated with streamer collisions stays an open question. The results presented in this paper only concern a single head-on collision between two streamers with opposite polarities. This work has a strong implication for the scientific return of a possible revival of the TARANIS mission about the understanding of sprites.

A question remaining open concerns the impact of the ionosphere filtering on the propagation of the signal because in standard condition (i.e., without thunderstorms), the ionosphere tends to block all radio signal below or near its frequency cutoff. However, during a thunderstorm the ionosphere is strongly disturbed and some low-frequency emissions are known to become observable.

In addition to space observations, we find that ground-based instruments like NenuFAR should detect sprite filament collision events, and therefore open a new way to investigate the microphysics of sprites.

Finally, this method is not only applicable to sprite streamers. In principle, the method could be applied to streamers from gigantic jets. In particular, gigantic jets have jump step to the ionosphere at around 50 km altitude. During that stage, it is possible that descending streamers from the ionosphere collide with ascending streamers produced by the jet (Pasko et al., 2002; da Silva & Pasko, 2012).

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