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Propagation and plasmas: new challenges, new applications

Lightning and TLE electric fields and their impact on the ionosphere

Champs électriques induits par les éclairs et les événements lumineux transitoires et leur effet sur l'ionosphère

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ABSTRACT

This article presents a review of broad band electric field measurements recently performed near thunderstorm areas. It is shown that large lightning pulses propagate up to the upper ionosphere, where they are reflected, producing natural ionograms. Lightning and sprite electric fields are characterised in different frequency bands and localised. The distance between sprite and parent lightning reaches ten kilometres. Transient MF signals are recorded simultaneously with some sprites. In addition short term fading of MF radio link signals are observed after lightning due to an increased absorption in the lower ionosphere induced by thermal electron heating. Their horizontal extension is larger than 200 km which is comparable with the extension of elves which are the luminous counterpart of the effects of lightning in the ionosphere.

RÉSUMÉ

Cet article présente des mesures large bande du champ électrique récemment réalisées à proximité d'orages. Nous montrons que de fortes impulsions des éclairs se propagent vers la haute ionosphère en produisant des ionogrammes naturels. Les champs électriques des éclairs et des sprites sont décrits en détail dans différentes bandes de fréquence et localisés. La distance entre un sprite et son éclair parent atteint dix kilomètres. De plus, une atténuation d'émissions radio MF de très courte durée est observée après un éclair, due à l'accroissement de l'absorption dans la basse ionosphère induite par le chauffage thermique électronique. Leur extension horizontale dépasse 200 km ce qui est comparable à l'extension des elves qui sont la contrepartie lumineuse des effets des éclairs dans l'ionosphere.

1. Introduction

The impact of lightning in the atmosphere and ionosphere has been observed and investigated for many decades with an increased interest since the discovery of Transient Luminous Events and Terrestrial Gamma-ray Flashes in the Earth's atmosphere [see special issues: J. Atmos. Solar-Terr. Phys. 2003; and J. Geophys. Res. Space 2009 and 2010 on the Chapman

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Conference "Effects of Thunderstorms and Lightning in the Upper Atmosphere"]. Electric field measurements are intensively performed for better understanding these phenomena. Most of observations are performed in the ELF and VLF frequency range at very large distances, up to 10,000 km or more [1]. VLF sensors can provide a real-time image of the thunderstorm areas. Recent observations linked one to one specific VLF emissions to TLE observations. Differentiations of different kinds of narrow-band VLF emission perturbations provide indications about implied mechanisms. Sprites, triggered by positive Cloud to Ground lightning, are related to "early fast" VLF perturbations while "Trimpi" VLF perturbations with longer on-set duration of $\sim$2 s are representative of Lightning-induced Electron Precipitations, that is heating and ionisation of the lower ionosphere [2]. In parallel, measurements of ELF emissions are used to determine the current moment of lightning and sprites [3]. Measurements in the HF frequency range are rare because signals at frequencies higher than the plasma frequency are not reflected by the ionosphere, and are more difficult to observe at ground. They were observed by the DEMETER satellite at 700 km altitude, the propagation up to the satellite being favoured by local ionospheric heating due to high thunderstorm activities [4]. Observations in the vicinity of thunderstorms are rare. They are interesting to determine source mechanisms. For example, VLF signals recorded at several hundreds of kilometres showed in cloud discharges at the time of sprite initiation, never observed at large distances [5].

The purpose of the present article is to present original broad band electric field measurements performed near thunderstorm areas. They concern direct observations of lightning pulses reflected from the ionosphere and forming ionograms, lightning being used as natural transmitters. A comparison with ionograms obtained from a ionospheric sounder validates this interpretation. In a second part direct emissions from lightning and sprites were characterised and located simultaneously in ELF and VLF frequency range. The third part shows transient disturbances of MF radio links during strong lightning, representative of the heating of the lower ionosphere. The MF disturbances can be the counterpart of the optical emissions produced by the interaction of the lightning EMP (ElectroMagnetic Pulse) with the lower ionosphere, called elves.

2. Experimental principle

Main objectives of the experiments performed by CEA since 2000, are the study of: (i) lightning flashes, more particularly their detection, their localisation and their characterisation from the analysis of the electric field waveform in different frequency ranges; (ii) similar studies of TLEs; and (iii) the effects of lightning and TLEs on MF radio links.

Several measurement campaigns have been organised. From 2003 to 2006, all measurements were performed in collaboration with European laboratories during the EuroSprite campaigns [7,2]. The basic principle is to measure the vertical electric field from lightning and TLE in the vicinity of the source (i.e. within distances lower than 1000 km). Depending on the campaign objectives, one or several measurement stations were deployed. Each station is equipped with a vertical electric field antenna mounted on a mast, and a computer used for data digitalisation and archiving. Two types of antenna were used: (i) a wide-band (10 kHz–80 MHz) rod antenna manufactured by Rohde & Schwarz or (ii) a dipole antenna designed and manufactured by CEA. The pass-band of the latter antenna ranges from less than few hundreds of Hz to 10 MHz. The response inside this band is flat and the antenna factor well known. The performances of the digitalisation cards inside the computer have been improved from a campaign to another. For instance, in 2009, 14 bit resolution and 100 MHz sampling frequency were available together with high memory storage (several tens of milliseconds). Data are GPS stamped.

For some campaigns, additional equipment has been used according to the campaign objectives. For example, goniometers were used for localisation studies using direction finding methods.

Finally, the location of lightning, studied in this article, is provided by Météorage, which is the French lightning location network. It locates more than 90% of the cloud to ground (CG) flashes in France. It gives for each event its time, with an accuracy of less than few microseconds, its location, with accuracy of less than 1 km, and its peak current. With this high time resolution, each lightning detected by our system can be associated one to one, without ambiguity, to the corresponding lightning flash detected by Météorage.

3. Are lightning natural ionosondes?

During the 2000 campaign, an additional HF antenna has been coupled to the dipole antenna. This HF antenna is a horizontal passive wire with a broad radiation diagram directed vertically. Its frequency band ranges from 1 MHz to 30 MHz. When a signal was detected by the dipole antenna, the signal measured by the HF antenna was simultaneously acquired.

The objective of this experience was to measure the lightning-induced electric field in the HF band, the VLF-LF part being filtered. Usually, the HF signal lasts 100 to 200 µs after the return stroke (i.e. when the lightning channel reaches ground). In some rare occasions (less than 1% of all recorded events), long duration electric field, that is more than 1 ms, has been measured after the return stroke. Two events occurring in 3 minutes interval at 16:51:43 and 16:54:01 UT on August 30th 2000 are shown in Fig. 1. The figure shows successively from top to bottom: (i) the HF signal, (ii) five narrow band (0.6 MHz) signals, in spectral bands not disturbed by radio transmissions, (iii) the triggering electric field measured with the dipole antenna and (iv) the spectrogram of the HF signal.

In the spectrogram, the horizontal continuous lines are due to radio transmissions. The return stroke signal arrives at $t = 0.1$ ms. The broadband HF signal is very noisy but the narrow band signals reveal a structure. The HF lightning signal lasts from 2 to 3 ms. HF bursts are measured in all bands simultaneously with the return stroke arrival. Additional pulses arrive after this first one, with a delay increasing with the frequency. This feature is found also in the spectrogram. The

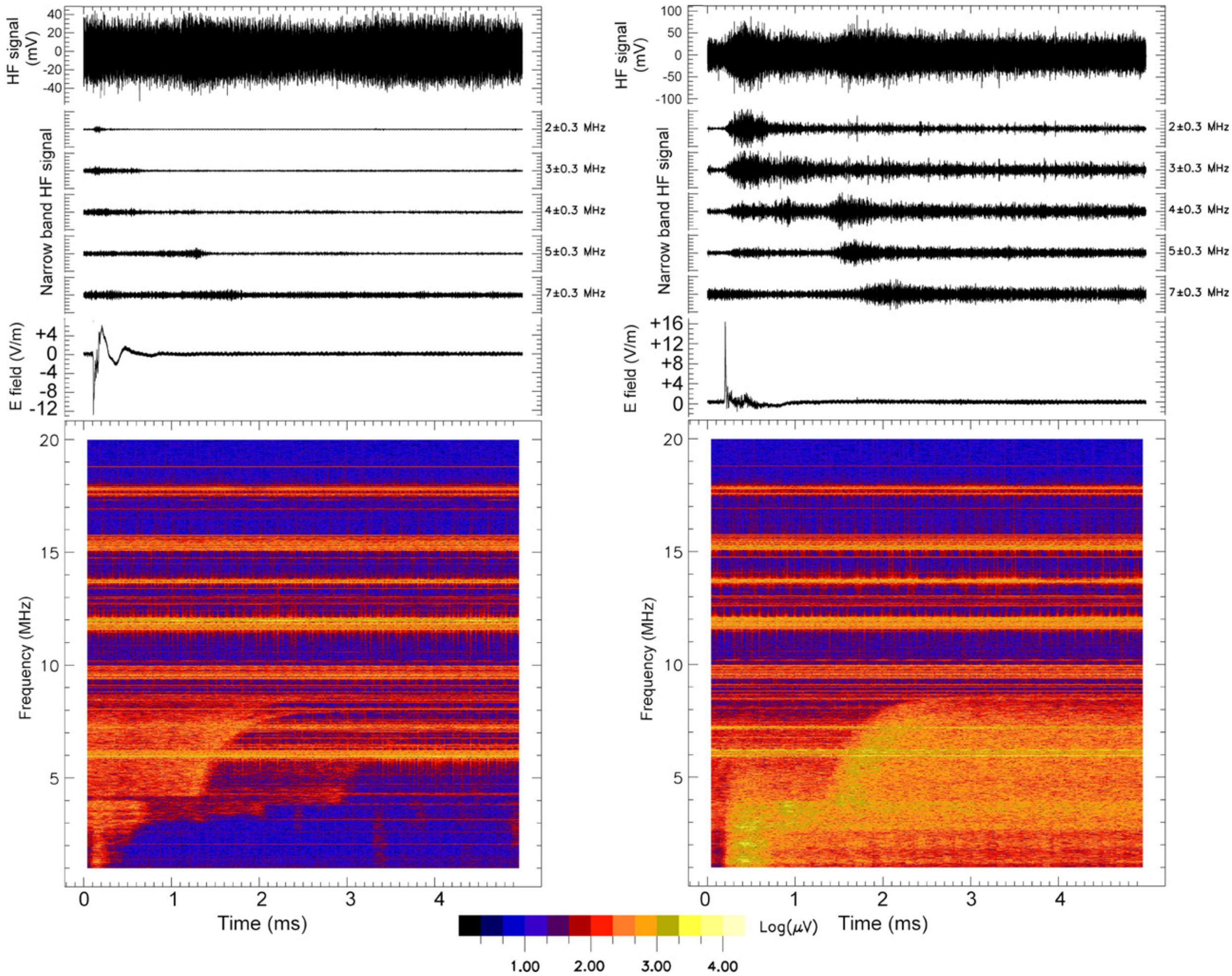

Fig. 1. Measurements recorded on August 30th 2000 at 16:51.43 (left) and 16:54:01 UT (right). (Top): Broad band HF signal and narrow-band HF signals, numerically extracted from HF signal. (Middle): lightning electric field measured with the vertical dipole antenna. (Bottom): Spectrogram of the HF signal.

Fig. 1. Mesures d'événements enregistrés le 30 août 2000 à 16:51:43 (gauche) et 16:54:01 TU (droite). (Haut) : Signal HF large bande et signaux bande étroite, extraits numériquement du signal HF. (Milieu) : Champ électrique de l'éclair mesuré par l'antenne dipolaire verticale. (Bas) : Spectrogramme du signal HF.

time variations with frequencies of the different pulses are similar to vertical ionograms, dedicated to ionosphere electron density measurements [8].

A ionosonde launches a sequence of HF pulses at increasing frequencies to penetrate more and more deeply into the ionosphere. This technology is based on the propagation property of electromagnetic waves inside plasma: they are reflected when their frequency is equal to the local plasma frequency. The feature observed in lightning spectrograms is due to the propagation time increase with frequency, due to reflections at increasing altitudes in the ionosphere. These reflections are observed at frequencies from ∼3 MHz to ∼8 MHz. Below 3 MHz, the absorption by the D region, induces very intense damping. Above the plasma frequency of about 8 MHz, the electromagnetic waves are not reflected by the ionosphere, they are transmitted to space. The increase of the propagation time around 8 MHz is very typical of what it is observed in ionograms around the critical plasma frequency of the F2 region (foF2).

The time delay Δt between first arrival (ground wave) and subsequent arrivals (sky waves) is consistent with ionospheric reflections. In a first approximation, mainly valid in the E region where the wave velocity is the speed of light c, the reflection altitude h can be deduced from the lightning distance d and the time delay Δt by the following equation:

$$h = 1/2\sqrt{(\Delta t.c)^2 + 2.\Delta t.c.d} \tag{1}$$

Table 1 gives the time, the distance and the peak current of the 7 events detected by the system on August 30th, 2000. For E region critical plasma frequencies (foE) ranging from 2 to 4 MHz [8], Δt varies from 250 μs to 400 μs. For the two examples of Fig. 1, the E region reflection heights range from 95 to 125 km, which is in good agreement with the usual

Table 1
Characteristics of the lightning providing ionograms from Météorage database. The last column gives the plasma frequency of the F2 region deduced from the lightning spectrograms.

Tableau 1
Caractéristiques données par Météorage pour les éclairs ayant fourni les ionogrammes. La dernière colonne donne la fréquence plasma de la région F2 déduite des spectrogrammes des éclairs.

Time (UT)	Distance (km)	Peak current (kA)	FoF2 (MHz) measured on spectrogram
04:52:31.423	190.8	−55.4	4.5
08:50:35.200	246.7	−130.6	6.5
09:44:07.555	177.8	141.8	7.0
12:03:12.769	228.6	81.9	8.0
12:24:01.652	151.1	−72.3	8.5
16:51:43.059	212.4	−77.9	8.0
16:54:01.461	208.4	82.4	8.0

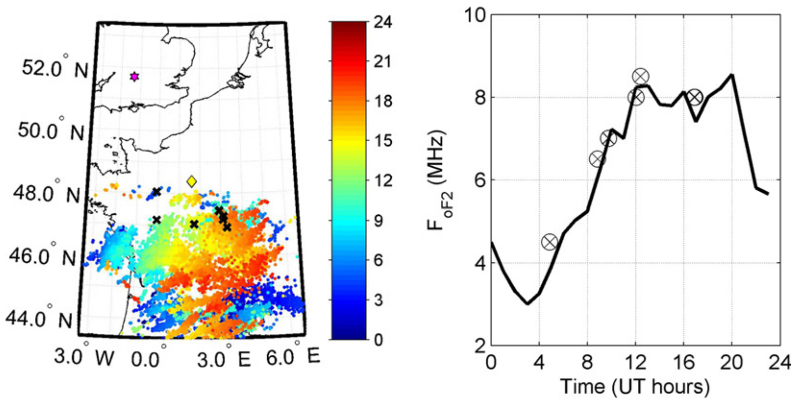

Fig. 2. (Left): Map of the lightning activity on August 30th, 2000 around CEA station (yellow diamond). Colour indicates the impact time (UT). Seven events with spectrograms looking like ionograms have been detected; locations of triggering lightning are shown with black crosses. (Right): Plasma frequency of the F2 region (FoF2) vs. time deduced from spectrograms (circled crosses) and compared to Chilton ionosonde measurements (continuous line).

Fig. 2. (Gauche) : Carte de l'activité orageuse le 30 août 2000 autour du site de mesure du CEA (losange jaune). La couleur code l'heure de l'impact de l'éclair (TU). Sept événements, dont le spectrogramme ressemble à un ionogramme, ont été identifiés ; la localisation des éclairs ayant généré ces signaux est représentée par des croix noires. (Droite) : Fréquence plasma de la région F2 (foF2) en fonction du temps déduite des spectrogrammes (croix cerclées) et comparée aux mesures de l'ionosonde de Chilton (ligne continue).

E region altitude [8]. The gap around 4 MHz, with a time increase from 0.3 ms to 1.1 ms, is due to a reflection at higher altitudes in the F region of the ionosphere, were this simple model is no more valid.

The left part of Fig. 2 shows the lightning activity map on August 30th, 2000. The location of lightning flashes, which produced ionograms, is highlighted with black crosses. They are located at 150 to 250 km from the CEA station (yellow diamond). Table 1 shows that these lightning have indiscriminately positive or negative polarity. However, all are characterised by high peak current (more than 50 kA). On the right part of this figure, the foF2 measured on the spectrograms are compared with foF2 measured by the Chilton (UK) ionosonde. The comparison shows a very good agreement confirming that intense lightning flashes can really act as natural ionosonde.

This kind of measurements, never shown before at the knowledge of the authors, may have a limited interest for ionospheric studies (weak resolution, hazardous aspect of lightning, etc.). However, these measurements show that the amplitude of lightning HF radiation is sufficient to go through the ionosphere. A satellite can then measure them. The location of lightning from space using HF signals may be easier than using VLF signals because their propagation through the ionosphere is less complex [9]. These measurements could be compared to the lightning-induced HF powerful signals recorded by DEMETER satellite [4]. One of the questions asked in this paper was the rarity of this phenomenon. Our measurements clearly show that only few lightning flashes (less than 1% of the considered lightning) can produce such powerful HF signals. This HF activity could be due to processes, which occur after the return stroke, as continuing currents and K processes [10]. Continuing currents refer to the charges which continue to flow, typically from 1 to 10 ms after the return stroke, from the cloud to the ground. Large continuing currents occur mainly after positive cloud-to-ground discharges [10] and appear as specific ELF signals [3,1,11]. Differently, K processes could better explain the present observations. Such processes refer to small discharges inside the cloud, producing rapid electric field variations [10]. The HF measurements, planned to be performed on board of the TARANIS satellite [12,13], are well adapted to characterise the cloud activity after a return stroke by using such HF measurements.

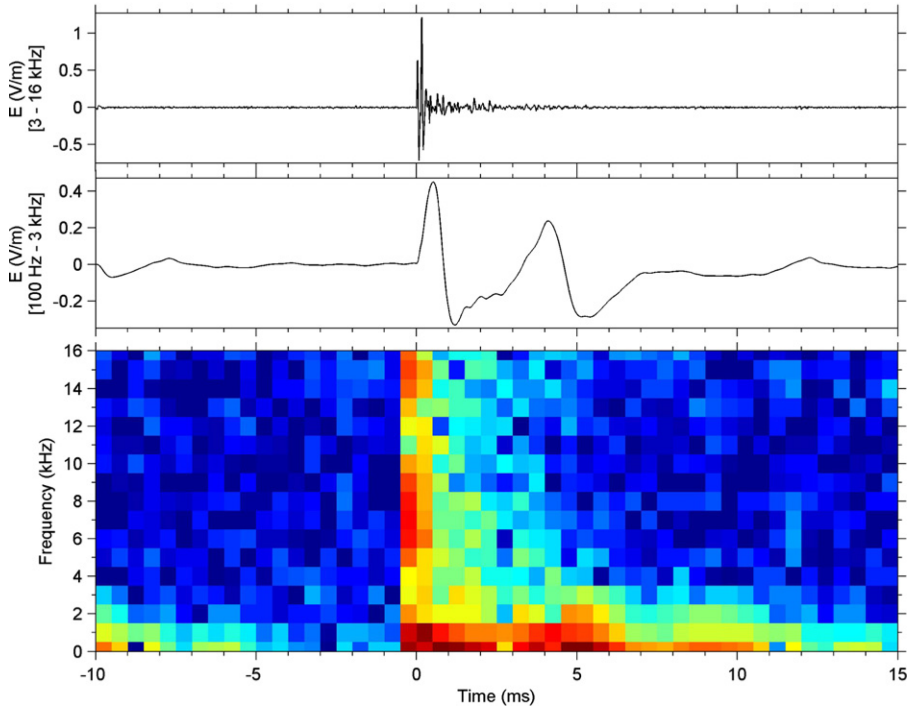

Fig. 3. Vertical electric field measurement for a sprite occurring on September 2nd, 2009 at 02:41:17.204 UT over the Gulf of Lions at about 500 km from the station. (Top): VLF component of the electric field (3–16 kHz). (Middle): ELF component of the electric field (100 Hz–3 kHz). (Bottom): Spectrogram of the measured electric field.

Fig. 3. Mesure du champ électrique verticale lors de la mesure d'un sprite le 2 septembre 2009 à 02:41:17.204 TU au dessus du Golfe du Lion à environ 500 km de la station. (Haut) : Composante TBF du champ électrique (3–16 kHz). (Milieu) : Composante EBF du champ électrique (100 Hz–3 kHz). (Bas) : Spectrogramme du champ électrique mesuré.

4. ELF and MF radiations from sprite

It has been shown very quickly after the discovery of sprites that the optical observations of sprites are very well correlated to electromagnetic field radiation in the ELF band [3,14]. Two peaks can be observed in ELF signals when a sprite occurs. The first one is due to the radiation of the sprite parent-lightning and the second one appears just when the sprite occurs. For long delayed sprites, that is sprites which appear more than few milliseconds after the parent-lightning (typically 30 ms), the second ELF pulse appears also simultaneously to sprites [15]. These ELF waves are the signatures of significant charge transfer and current flow inside the sprites themselves at high altitude [1,15]. It has been also suggested at the very beginning of sprite studies, that sprites radiations in the MF and HF bands can be the signature of runaway breakdown process triggered by cosmic radiations [16,6]. Theoretical studies predict strong electric fields in the frequency range from 1 to 10 MHz [17]. It is now widely accepted that the majority of sprites are due to streamer discharges and not to runaway breakdown process. However, this runaway process could be involved for some rare sprites [18].

In 2009, a dipole antenna was installed in the centre of France (2.63°E; 47.27°N) to measure the ELF radiation from sprites. Several ELF waveforms were recorded during summer and fall in relation to sprite producing thunderstorms. The ELF waveform shown in Fig. 3 has been related to a very big group of sprites on September 2nd at ∼500 km away from the station [19]. In the absence of photometric measurements, these observations were the only one inferring that the sprite occurred only 4 ms after the lightning and lasted 2 ms. This station was also the closest from the first gigantic jet associated to sprites, which was observed in Europe (more precisely near Corsica) [20].

Future analysis of this kind of waveforms will give the charge moment and some source details of the parent lightning which is the clue parameter for sprite triggering [21]. Usually, ELF wave measurements are realised with magnetic sensors very far from the source (up to 7000 km). The main interest to be located close to the source is the capability to study the dynamics of the current flowing inside the sprite. This is not possible at large distances because the small details disappear due to the high frequency damping during the propagation.

During the 2003 campaign, four stations, using the rod antenna, were deployed in France to measure vertical electric field in a large frequency range from 10 kHz to 10 MHz (Fig. 4). The measured radiations are correlated to CG discharges detected by Météorage and sprite observed from the Pic du Midi, in the French Pyrenees [7,2].

The system in AVF station (one of the four) was triggered for 44 of the 133 sprites measured in 2003. In many cases, low frequency (ELF-VLF) signals were identified within the sprite observation time interval. These emissions can be existed either by the sprite or by intracloud lightning, which has been associated to carrot sprites [22].

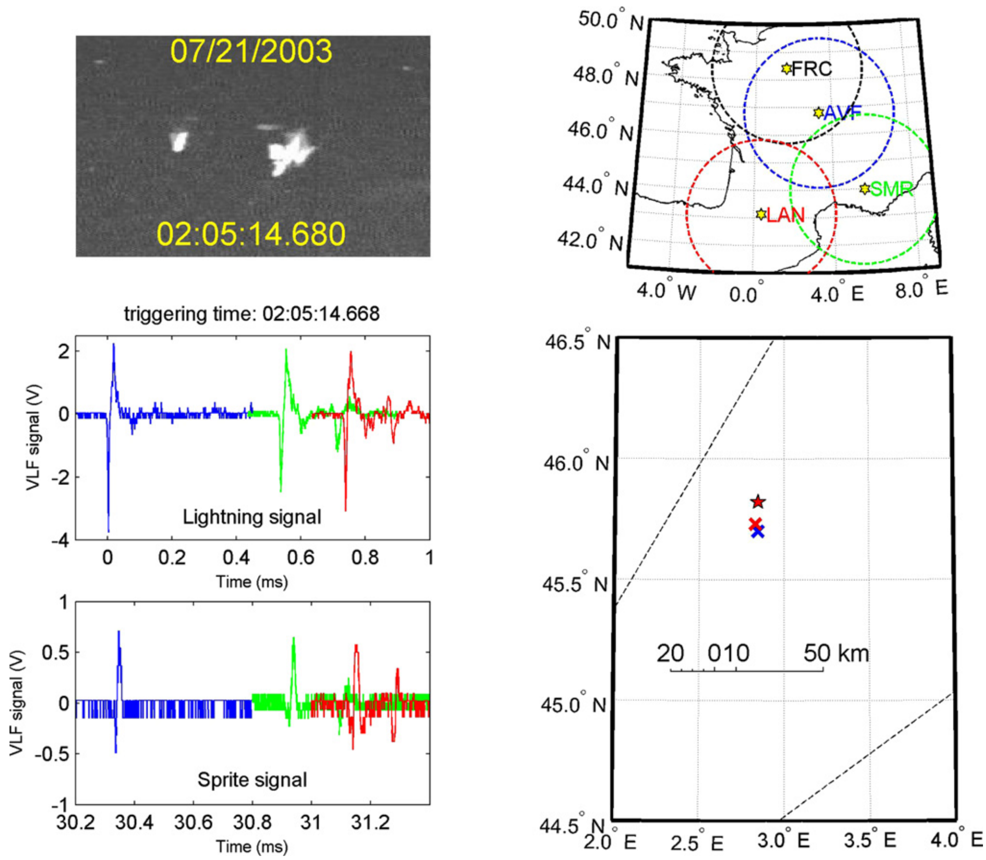

Fig. 4. VLF radiation from lightning and/or sprite. (Left, top): Sprite image at 02.05:14.668 UT 21st July 2003, (right, top) location of CEA sensors, (left, middle) waveforms of the lightning, observed at the station AVF in blue, at SMR in green and at LAN in red, (left, bottom) waveforms of the sprite with the same colour presentation, (right, bottom) lightning localisation by Météorage (blue cross), and lightning (red cross) and sprite (red star) localisations using CEA sensor data. The dashed lines represent the camera field of view (FOV), which was located at the Pic du Midi, close to LAN station.

Fig. 4. Emissions TBF d'éclairs et de sprites. (En haut à droite) : Emplacement des quatre stations CEA implantées en 2003. (En haut à gauche) : Image d'un sprite observe le 21 juillet 2003 à 02:05:14.668 TU. (Au milieu à gauche) : Signal associé à un éclair mesuré à la station AVF (bleu), SMR (en vert) et LAN (rouge). (En bas à gauche) : Signal associé au sprite donné en image par les trois mêmes stations avec la même code de couleur. (En bas à droite) : Localisation de l'éclair par Météorage (croix bleue) et à partir des données des stations (croix rouge). L'étoile rouge indique l'emplacement du sprite calculé avec les données des stations. Les lignes en tirets délimitent le champ de vue de la caméra située au Pic du Midi, près de la station LAN.

Fig. 4 shows a sprite image taken on July, 21st, 2003 at 02:05:14.680 UT. The frame is integrated from 12 to 32 ms after the parent lightning. The figure also shows the electric field signal of the parent lightning and a second signal 30 ms after the parent lightning, within the sprite camera exposure time. With three sensors detecting the same signal, it is possible to locate the source. The triangulation calculation provides the location of the lightning (red cross) which is 1 km away from the Météorage location (blue cross), which corresponds to the Météorage localisation precision. The location of the second event is 10 km away (red star) which is a separation distance often observed between sprite and its parent lightning. Recent triangulation of sprites using only camera observation shows that the distance between sprite and lightning is usually less than 50 km and mainly between 15 and 30 km [23]. The second signal is then attributed to the sprite itself. Such measurements, realised with a network of only few station in Western Europe, could then be used for direct localisation of sprite.

Weak MF emissions, i.e. enhancements of the signal from 0.5 to 3 MHz, were also measured during the sprite observation time interval, which corresponds to the 20 ms camera exposure time. To research radiations from sprites and to have no doubt on the origin of the VLF signal, we only select events (using the Météorage database) for which no CG discharge is observed inside the sprite observation time interval. Only 5 events over 44 were kept after this selection. Two examples are shown in Fig. 5 with the corresponding VLF measurements. The first case (top of Fig. 5) corresponds to Fig. 4 event; the sprite was located at about 130 km from the AVF station (see map of Fig. 4). The MF burst which arrives simultaneously to a VLF signal has a mean amplitude 3 dB over the noise level recorded before its arrival. The second case corresponds to a sprite observed in August 29th, 2003, at 02:41:10.658 UT at about 220 km from AVF station. This MF burst has an amplitude 5 dB higher than the MF noise. It is not associated to a VLF signal. However, this combination is not necessary for runaway processes [18]. The distance of observation is also compatible with the distances given by Gurevich's runaway

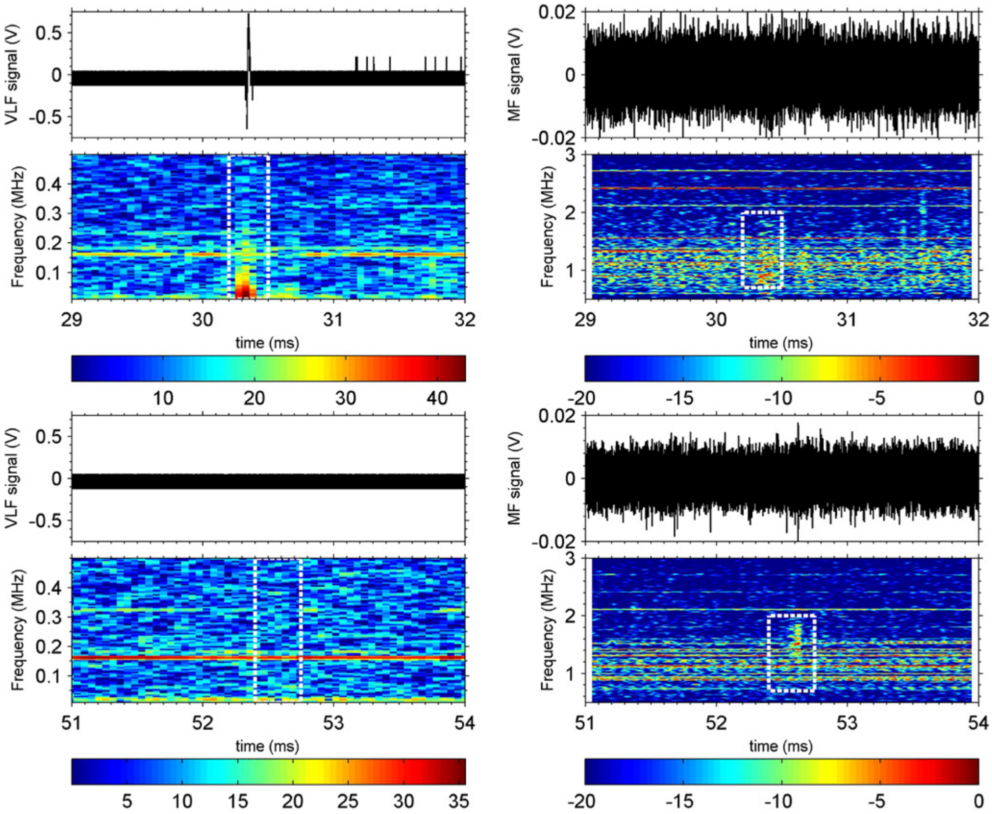

Fig. 5. Simultaneous VLF-LF and MF electric field measurements and spectrograms when sprites were observed on July 21st, 2003 at 02.05:14.668 UT (top) and on August 29th, 2003 at 02:41:10.658 UT (bottom). The origin of time axis is when the parent-lightning electric field arrives on the station and triggers the system.

Fig. 5. Mesures du champ électrique simultanément dans les bandes TBF-BF et MF et leur spectrogramme pour des sprites observées le 21 juillet 2003 à 02:05:14.668 TU et le 29 août 2003 à 02:41:10.658 TU. L'origine de l'axe des temps est situé quand le champ électrique de l'éclair parent arrive sur la station et déclenche le système.

models, which are between 100 and 300 km) [17]. Such emissions could be the signature of runaway processes. It is also interesting to note that these MF signals to the signals measured by DEMETER in the same frequency range [4].

5. Electron heating of the lower ionosphere due to lightning EMP

It has been shown that lightning EMP can modify significantly the electron density of the lower ionosphere. Such effect has been observed on narrow band VLF links at very large distances [1]. This chapter shows that broadband Medium Frequency (MF) measurements can also be used to study the perturbations of the lower ionosphere related to lightning activity. Such observations were never reported up to now, at the author's knowledge.

During the 2004 campaign, simultaneous measurements of the vertical electric field were performed in the VLF band and in the MF band in the AVF station (Fig. 4). A strong transient attenuation of the narrow-band MF radio signals was very frequently observed just after a return stroke, as shown in Fig. 6. This disturbance has been studied using ∼4000 return strokes on nine selected radio transmission signals [24]. The main characteristics of the perturbation are a mean peak attenuation of 12 dB, an onset time of less than 1 ms, and duration from 3 to 10 ms. Peak attenuations and durations are roughly proportional to the lightning-induced peak current. The perturbations have a circular structure, centred over the return stroke, and reaching distances as large as ∼250 km (Fig. 6). Almost all return strokes, whatever their polarity, having a peak current higher than 60 kA produce such disturbance on the MF links passing through the ionosphere D region at less than 250 km from the lightning.

The fading of the MF signals is consistent with impulsive heating of the electrons at ∼90 km altitude to 4–14 eV by the EMP from the discharges [25,26], followed by cooling of the electrons with a time constant (from 0.1 to 100 milliseconds) [27] that matches the recovery time of the MF signals. Differently, the absorption due to the enhanced EMP ionisation is very weak (Fig. 6) in comparison with the absorption due to heating (20 dB below). Moreover the recovery time for electron density enhancements is too long (from 1 to 100 s, typically 10 s [1]) in comparison with the observed MF signal recovery time. These perturbations are then the MF radio signature of the EMP effect on the lower ionosphere, just as

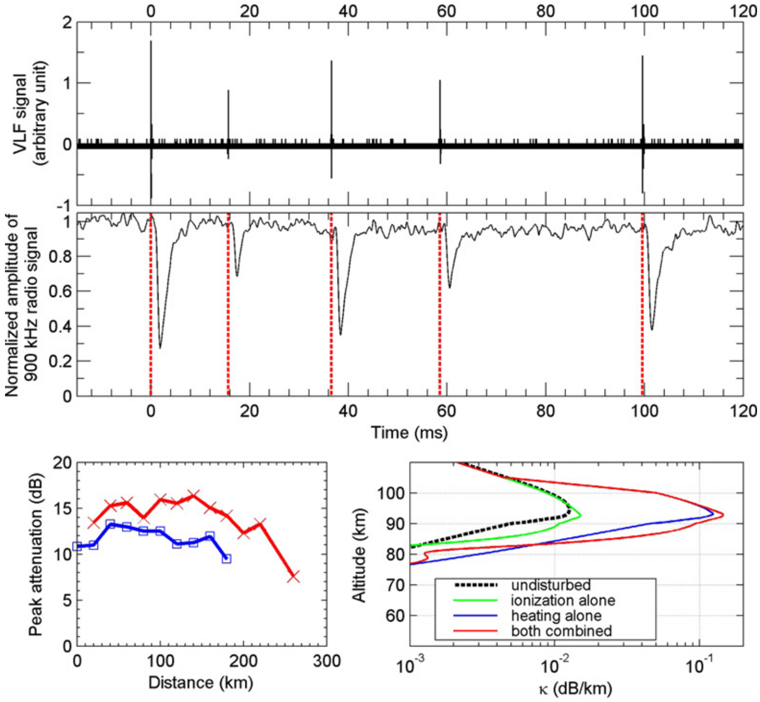

Fig. 6. (Top): Transient VLF emissions from successive lightning; (middle): 900 kHz radio wave absorption. A strong attenuation is observed after each lightning indicated with vertical red dashed lines – (bottom left): Maximal radio wave attenuation vs. lightning distance (in blue for lightning with peak current from 30 to 50 kA and in red for lightning with peak current from 60 to 80 kA) showing a perturbed zone within 200 km from lightning – (bottom right): Profile of the absorption coefficient κ of a MF radio link for different mechanisms.

Fig. 6. (Haut) : Emissions transitoires TBF d'éclairs successifs ; (milieu) : Absorption des ondes radio correspondant à 900 kHz ; une atténuation importante se produit après chaque éclair indiqué par un tiret vertical rouge – (bas gauche) : Atténuation maximale en fonction de la distance de l'éclair (en bleu pour les éclairs les plus faibles (30–50 kA) et en rouge pour les plus intenses (60–80 kA) montrant que la zone affectée atteint au moins 200 km autour de l'éclair – (bas droite) : Profil du coefficient d'absorption κ d'une onde radio MF pour différents mécanismes.

elves are their optical signature. This study shows the capability of this technique to monitor heating changes in the lower ionosphere, even for weak EMPs that do not lead to enhanced ionisation. Such observations complement VLF observations.

6. Conclusion

Different studies using broadband electric field measurements have been described in this paper. The first one shows the impact of large lightning discharges on the ionosphere, highlighting the similarity between lightning high frequency pulses which penetrate and are reflected in the upper ionosphere, and ionogram radio pulses. The second one details the broadband emissions of TLE and more particularly those in the MF range. Such MF signature could be related to runaway processes occurring during the TLE formation. Finally, lightning are the main contributor of the nighttime electron density D region change. Moreover, the lightning EMP electron heating of the lower ionosphere, underlined by transient MF radio link absorption, is probably the counterpart of the luminous emissions, elves, due to interaction of lightning EMP with lower ionosphere. These results emphasised the importance of measuring the electric field at high frequencies to study lightning and TLEs.

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References

[1] U.S. Inan, S.A. Cummer, R.A. Marshall, A survey of ELF and VLF research on lightning ionosphere interactions and causative discharges, J. Geophys. Res. 115 (2010) A00E36, doi:10.1029/2009JA014775.

[2] T. Neubert, M. Rycroft, T. Farges, E. Blanc, O. Chanrion, E. Arnone, A. Odzimek, N. Arnold, C.-F. Enell, E. Turunen, T. Bösinger, Á. Mika, C. Haldoupis, R.J. Steiner, O. van der Velde, S. Soula, O.P. Berg, F. Boberg, P. Thejll, B. Christiansen, M. Ignaccolo, M. Füllekrug, P.T. Verronen, J. Montanya, N. Crosby, Recent results from studies of electric discharges in the mesosphere, Surv. Geophys. (2008), doi:10.1007/s10712-008-9043-1.

[3] S.A. Cummer, U.S. Inan, T.F. Bell, C.P. Barring-Leigh, ELF radiation produced by electric currents in sprites, Geophys. Res. Lett. 25 (1998) 1281–1284.

[4] M. Parrot, U. Inan, N. Lehtinen, E. Blanc, J.L. Pinçon, HF signatures of powerful lightning recorded on DEMETER, J. Geophys. Res. 113 (2008) A11321, doi:10.1029/2008JA013323.
[5] A. Ohkubo, H. Fukunishi, Y. Takahashi, T. Adachi, VLF/ELF spheric evidence for in-cloud discharge activity producing sprites, Geophys. Res. Lett. 32 (2005) L04812, doi:10.1029/2004GL021943.
[6] R. Roussel-Dupré, E. Symbalisty, Y. Taranenko, V. Yukhimuk, Simulations of high altitude discharges initiated by runaway breakdown, J. Atmos. Sol. Terr. Phys. 60 (1998) 917–940.
[7] T. Neubert, T. Allin, E. Blanc, T. Farges, C. Haldoupis, A. Mika, S. Soula, L. Knutsson, O. van der Velde, R.A. Marshall, U. Inan, G. Satori, J. Bor, A. Hughes, A. Collier, S. Laursen, I. Rasmussen, Co-ordinated observations of transient luminous events during the EuroSprite2003 campaign, J. Atmos. Sol. Terr. Phys. 67 (2005) 807–820.
[8] K. Davies, Ionospheric Radio, Peter Peregrinus, London, 1990.
[9] F. Lefeuvre, R. Marshall, J.L. Pinçon, U.S. Inan, D. Lagoutte, M. Parrot, J.J. Berthelier, On remote sensing of transient luminous events' parent lightning discharges by ELF/VLF wave measurements on board a satellite, J. Geophys. Res. 114 (2009) A09303, doi:10.1029/2009JA014154.
[10] M.A. Uman, The Lightning Discharge, International Geophysics Series, vol. 39, Academic Press, 1987.
[11] S.C. Reising, U.S. Inan, T.F. Bell, W.A. Lyons, Evidence for continuing current in sprite producing cloud to ground lightning, Geophys. Res. Lett. 23 (24) (1996) 3639–3642.
[12] E. Blanc, F. Lefeuvre, R. Roussel-Dupré, J.A. Sauvaud, TARANIS: A microsatellite project dedicated to the study of impulsive transfers of energy between the Earth atmosphere, the ionosphere and the magnetosphere, Adv. Space Res. (2007), doi:10.1016/j.asr.2007.06.037.
[13] F. Lefeuvre, E. Blanc, J.L. Pinçon, R. Roussel-Dupré, D. Lawrence, J.A. Sauvaud, J.L. Rauch, H. de Feraudy, D. Lagoutte, TARANIS—A satellite project dedicated to the physics of TLEs and TGFs, Space Sci. Rev. 137 (2008) 301–315, doi:10.1007/s11214-008-9414-4.
[14] S.C. Reising, U.S. Inan, T.F. Bell, ELF spheric energy as a proxy indicator for sprite occurrence, Geophys. Res. Lett. 26 (7) (1999) 987–990.
[15] J. Li, S.A. Cummer, W.A. Lyons, T.E. Nelson, Coordinated analysis of delayed sprites with high-speed images and remote electromagnetic fields, J. Geophys. Res. 113 (2008) D20206, doi:10.1029/2008JD010008.
[16] A.V. Gurevich, G.M. Milikh, R.A. Roussel-Dupré, Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, Phys. Lett. A 165 (1992) 463.
[17] A.V. Gurevich, L.M. Duncan, A.N. Karashtin, K.P. Zybin, Radio emission of lightning initiation, Phys. Lett. A 312 (2003) 228–237.
[18] M. Füllekrug, R. Roussel-Dupré, E.M.D. Symbalisty, O. Chanrion, A. Odzimek, O. van der Velde, T. Neubert, Relativistic runaway breakdown in low-frequency radio, J. Geophys. Res. 115 (2010) A00E09, doi:10.1029/2009JA014468.
[19] S. Soula, O. van der Velde, J. Montanya, T. Farges, J. Bor, M. Fullekrug, G. Waysand, Analysis of lightning activity and electromagnetic radiations associated with large TLEs, in: EGU2010-14694, EGU General Assembly 2010, Geophys. Res. Abstr. 12 (2010).
[20] O.A. van der Velde, J. Bór, J. Li, S.A. Cummer, E. Arnone, F. Zanotti, M. Füllekrug, C. Haldoupis, S. NaitAmor, T. Farges, Multi-instrumental observations of a positive gigantic jet produced by a winter thunderstorm in Europe, J. Geophys. Res. 115 (2010) D24301, doi:10.1029/2010JD014442.
[21] W. Hu, S.A. Cummer, W.A. Lyons, T.E. Nelson, Lightning charge moment changes for the initiation of sprites, J. Geophys. Res. 29 (2002), doi:10.1029/2001GL014593.
[22] O.A. van der Velde, A. Mika, S. Soula, C. Haldoupis, T. Neubert, U.S. Inan, Observations of the relationship between sprite morphology and in-cloud lightning processes, J. Geophys. Res. 111 (2006) D15203, doi:10.1029/2005JD006879.
[23] R.K. Haaland, W.H. Fellman, H.C. Stenbaek-Nielsen, M.G. McHarg, T. Kanmae, Triangulation of sprite features, Abstract AE21B-0271 presented at 2010 Fall Meeting, AGU, San Francisco, Calif., 13–17 Dec.
[24] T. Farges, E. Blanc, M. Tanguy, Experimental evidence of D region heating by lightning-induced electromagnetic pulses on MF radio links, J. Geophys. Res. 112 (2007) A10302, doi:10.1029/2007JA012285.
[25] U.S. Inan, T.F. Bell, J.V. Rodriguez, Heating and ionization of the lower ionosphere by lightning, Geophys. Res. Lett. 18 (1991) 705–708.
[26] Y.N. Taranenko, U.S. Inan, T.F. Bell, Interaction with the lower ionosphere of electromagnetic pulses from lightning: heating, attachment, and ionization, Geophys. Res. Lett. 20 (1993) 1539–1542.
[27] C.J. Rodger, O.A. Molchanov, N.R. Thomson, Relaxation of transient ionisation in the lower ionosphere, J. Geophys. Res. 103 (1998) 6969–6975.