Journal of Atmospheric and Solar–Terrestrial Physics 220 (2021) 105664

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Frequency spectra of various events pertinent to lightning cloud flashes obtained from wavelet transform technique and ratified by narrow band measurement technique

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ARTICLE INFO

Keywords:
Lightning
Cloud flashes
Wavelet transform
Frequency spectra

ABSTRACT

In the present study, frequency spectra of the electric field corresponding to the various cloud events, such as, initial breakdown process, regular pulse bursts, chaotic pulse trains and recoil streamers have been analysed. For the purpose, electric field radiated by cloud flashes were obtained simultaneously by a wide bandwidth antenna system and two narrow bandwidth antenna systems tuned at 3 MHz and 30 MHz. The frequency spectra of the broad band electric field signatures were obtained by using the wavelet transform technique and were compared with the magnitudes of the narrow band signals at the given central frequencies. To the best of our knowledge, it is the first study in which frequency spectra is obtained by transforming the time domain signal using wavelet transform technique and ratified by narrow bandwidth system for the cloud flashes. Fifteen cloud flashes pertinent to the Swedish thunderstorms were selected for the purpose. It is found that, the cloud flashes radiate at frequencies as low as 3 kHz to as high as a few tens of Mega Hertz (MHz). Electric field radiation corresponding to the initial breakdown process were found to radiate in the frequency range of 50 kHz to 5 MHz on the average, maximum energy is being radiated in the frequency range of 500 kHz to 5 MHz. Similarly, the final stage corresponding to the regular pulse bursts was found to radiate in the frequency range of 50 kHz to 5 MHz and that corresponding to the chaotic pulse trains was found to be in the range of 100 kHz to 5 MHz. Whereas, the very narrow pulses at the final stage, that can be termed as pulses corresponding recoil streamers (or Q-streamers) were found to radiate in the frequency range of 50 kHz to well above 10 MHz. Q-streamers can be considered as the strongest source of very high frequency and is justified by the simultaneous measurement of the electric fields at very high frequency (30 MHz) narrow bandwidth system. Rectification of the biasness of the conventional wavelet power spectrum has also been performed, however, no significant change in the spectrum was observed. Therefore, this study provides a strong basis for applying the wavelet transform technique without employing large number of narrowband system to acquire frequency domain information of lightning phenomena.

1. Introduction

Lightning is one of the most common and most fascinating atmospheric phenomena and occurs almost over any region of the globe. Although lightning is believed to be in existence well before the human civilization began on earth, it has not been fully understood to this date. The initiation of lightning within the cloud, exact charge structure of a thundercloud and maximum cloud electric field magnitude, production of x-rays and gamma rays etc., are among the challenges that the scientists have been trying to understand. Lightning can vaguely be categorised into two types, viz. Cloud flashes and cloud to ground flashes. Majority (two third) of the total lightning flashes are believed to be cloud flashes and rest of the one third terminate to the ground and are called cloud to ground flashes or simply ground flashes. The ground flashes, being more spectacular, frightening and deleterious to the lives and structures, are most researched and most understood. Cloud flashes on the other hand, despite their abundance in the atmosphere, are poorly understood. The reason behind is quite obvious. They occur largely inside the cloud obscuring much of their visibility and having less threat on the lives and the structures on the ground. However, with

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https://doi.org/10.1016/j.jastp.2021.105664
Received 29 November 2020; Received in revised form 24 April 2021; Accepted 26 April 2021
Available online 13 May 2021
1364-6826/

the ever increasing use of electronic gadgets, especially in the avionics and increasing usage of fibre composites in the avionics, the threat of cloud flashes should not be underrated. Moreover, to understand the physics of the lightning, its initiation in the cloud, the knowledge of the features of cloud flashes is of much importance. In order to understand the lightning phenomenology, various techniques have been employed, since the beginning of its scientific research some two hundred and sixty-eight years ago by Benjamin Franklin. Much of the knowledge about the physics of lightning was gained with the help of optical measurement and electric and magnetic field measurement techniques. However, majority of the research was confined to the lightning ground flashes and a very less research has been done on cloud flashes. Recently many researchers have been attracted towards a unique lightning cloud activity called narrow bipolar events (NBEs), or compact intra-cloud discharges (CIDs) or narrow bipolar pulses (NBPs) (e.g. Smith et al., 1999; Jacobson and Heavner 2005; Gurevich and Zybin 2005; Sharma et al., 2008; Nag and Rakov 2009; Nag et al., 2010; Rakov and Rachidi 2009; Wu et al., 2014; Marshall et al., 2013 etc. are some to name) for their uniqueness and probable association with the lightning initiation in the clouds, though none of these studies has been able to resolve the mystery.

Although, the cloud discharges can be viewed as being composed of an early (or active) stage and a late (or final stage) (Rakov and Uman, 2003), they are more complex as compared to the cloud to ground flashes. In general, the upper and the lower boundaries of a negative charge region, where the electric fields are highest, are the most likely places for a cloud flash to begin (Rakov and Uman, 2003). Further, it is thought that cloud flashes often bridge the main negative and upper positive charge regions (Rakov and Uman, 2003). The other possibility is to bridge the lower boundary of the negative charge region and the lower positive charge region. According to Nag and Rakov (2009), the downward propagating negative charge might be converted into a cloud flash if the strength of the lower positive charge region (LPCR) is comparable to that of the main negative charge region.

Moreover, the cloud discharges are of much interest to the scientific community in order to understand the initiation of lightning within the cloud. The HF and VHF radiation ($f \geq 1$ MHz) is of more interest as the radiation field of micro discharges lie in this range of frequency (Hayakawa et al., 2008). This radiation contains very important information on discharge processes inside a thundercloud. Apparently, elementary micro discharges with the front duration $t_f \sim 10$ ns and complete duration $t \sim 1$μs are the elementary emitters in the VHF/UHF band (Hayakawa et al., 2008).

The present work is aimed to study the features of electric field produced by the cloud flashes in frequency domain. Attempts have been made to investigate the frequency of radiation by cloud flashes at different stages. The frequency spectra of different lightning events have been analysed by many researchers in the past. The word 'spectrum' is generally used in the literature on lightning in the frequency range to mean the magnitude of the Fourier transform of the electric field radiated during the discharge (LeVine 1987). The measurement of the frequency spectrum in a lightning flash have been made either by monitoring the power received at individual frequencies using a narrow bandwidth recording device or by recording the transient radiation with wide bandwidth device and then Fourier transforming the waveform to obtain a spectrum (Le Vine, 1987; Nanevicz et al., 1987). The measurements of first type were extensively used in 1950's and 1960's however, that of second type were mainly used after 1980 (Le Vine 1987). The frequency spectra, obtained from either ways, were found to be similar. The Fourier transform approach, widely used after Serhan et al. (1980), has an advantage that a spectrum can be associated with a particular lightning process with the shape of the waveform (Willett et al., 1990). Serhan et al. (1980), Willett et al., (1998) analyzing the Fourier transformation of the first and subsequent return strokes, reported that the frequency spectrum falls off nearly as 1/f between the 5 kHz–100 kHz. They have further reported that the trend for the subsequent return strokes is also same but with somewhat low amplitude. Weidman et al. (1981), analyzing the spectra of first return strokes, measurement being carried out almost over the salt water to minimize the propagation effect, reported that 1/f trend can be extended up to 2 MHz, however, the trend changes as $1/f^2$ between 2 MHz and 10 MHz and as $1/f^5$ above 10 MHz. Weidman et al. (1981) further reported that spectra of the fast rising portion of leader steps, the initial fast transition in return strokes and transition in positively intra cloud pulses to be surprisingly similar.

Weidman and Krider (1986), analyzing the amplitude spectra of the fast rising, initial portion of fields produced by return strokes, leader steps and cloud pulses in the range of 1 MHz–20 MHz, reported that the spectrum amplitude varies as 1/f from 1 MHz to 6 MHz and it varies as $1/f^2$ from 6 MHz to 20 MHz. They further reported that the spectral amplitudes of leader steps just before return strokes and the fast portion of cloud pulses that triggered the recording system tend to lie 5–10 dB below the amplitudes of first return strokes over the entire frequency interval.

Analyzing, the electromagnetic field spectra in the interval of 0.2–20 MHz, from first and subsequent return strokes, stepped, dart and chaotic leaders; and characteristic pulses, Willett et al. (1990) concluded that the return strokes are the strongest sources of radiation from cloud-to-ground lightning in the above frequency range. They further reported that the spectra of first and subsequent return strokes are identical in that range of frequency. Moreover, the spectra of stepped and dart stepped leader are nearly identical and are very similar to that of characteristic pulses. The spectral amplitude has been reported to decrease somewhat faster than 1/f in the interval of 0.2–20 MHz, and the energy spectral density as $1/f^2$ up to about 5 MHz. Above 12 MHz, the spectral amplitude is reported to decrease as $1/f^5$.

Sonnadara et al. (2006), analysed the frequency spectrum of lightning cloud flashes in the range of 20 kHz to 20 MHz, for the first 10 ms time window and reported that the frequency spectrum follows 1/f from 20 kHz to 2 MHz and $1/f^2$ above 2 MHz. Unlike the other researchers, Sonnadara et al. (2006) used Fourier transform technique to obtain the frequency spectrum for the whole electric field during the first 10 ms of the cloud flash. Further, the spectra obtained, by Sonnadara et al. (2006), for the individual cloud pulses were not found to follow the trend obtained previously by Weidman et al. (1981). However, the effect of the high pass filter with a pass band at 5 kHz on magnitude of the spectra in the lower frequency region is not clear.

Although, the Fourier transform technique, that is straight forward to obtain the frequency spectra of each individual specific events such as return strokes, subsequent return strokes and cloud pulses has advantages over the narrowband techniques that give the composite spectra of the whole events (LeVine, 1987), it has its limitations too. The Fourier transform technique requires wide bandwidth recordings and large dynamic range because the power at high frequencies tends to decrease rapidly. Furthermore, when a time domain signal is Fourier transformed to frequency domain signal, the time information is lost. This issue is not important while dealing with the stationary signals but while dealing with the transient signals, as that of lightning electromagnetic fields, it becomes significant (Torrence and Compo, 1998). It is therefore wavelet transform technique has been used in the present study. The wavelet transform technique used in this study has already been used by a few authors in the field of lightning electromagnetics (e.g. Miranda 2008; Sharma et al., 2011 etc.). In the study carried out by Sharma et al. (2011), frequency spectra for different lightning events such as negative return strokes, stepped leaders, subsequent return strokes, positive return strokes and narrow bipolar pulses were calculated.

According, Sharma et al. (2011), the range of frequency in which maximum energy is radiated for PB pulses was 51–739 kHz and that for leaders was 87–720 kHz. Whereas, the range of frequency in which the maximum energy was radiated for the negative return strokes was 2.8–40 kHz, that for the first subsequent strokes was 4.5–55 kHz and, for the positive return strokes was 5.5–81 kHz. They also observed that the range of frequency of radiation by Narrow Bipolar Pulses (NBPs) (58–714 kHz) was similar to the range of frequency radiated by PB pulses. More recently, Esa et al. (2014) used the wavelet transform technique to obtain the frequency range of first electric pulse leading to the negative ground flash, IC flash, positive ground flash and Isolated breakdown (IB) pulses and report that the first pulses leading to negative ground flash and cloud flash radiate at much higher frequency range as compared to those leading to the positive ground flash and IB pulses.

Since, the wavelet transform technique has already been used by many of the researchers, (Torrence and Compo 1998; Miranda 2008; Sharma et al., 2011), the details of the wavelet technique will not be discussed and for more details reader is referred to those papers and the references therein. The wavelet transform computation was carried out using the algorithm, used by the Torrence and Compo (1998). The power spectrum obtained by this technique is an average sense, the transform coefficient squared divided by the scale it associates, however, it causes bias in the power spectrum if the integration ranges are different for different scales (Liu et al., 2007). This biased power spectrum can easily be rectified, by dividing each energy value with scale it corresponds to (Liu et al., 2007). More recently, same technique was adopted by Veleda et al. (2012) to rectify the biasness, in the computation of cross wavelet transform (XWT). It has been reported by both Liu et al. (2007) and Veleda et al. (2012), that there is a significant improvement in the power spectra after performing the rectification.

In the present study, the frequency domain features pertinent to the, largely ignored, cloud flashes were analysed by applying the wavelet transform technique. Frequency domain information pertinent to the lightning cloud flashes is very rare in the literature. The electromagnetic radiation by the cloud flashes have been recorded by employing two techniques. One of the techniques is being employing the narrow band filters tuned at certain frequency to sense the electric field radiated by the lightning discharge at that frequency. And the other technique employed is being sensing the electric field by lightning discharge with the help of wide bandwidth antenna system and wavelet transforming the time domain signal so obtained. However, the data collected by later technique were used for the wavelet transform whereas the data recorded by the former technique were used just for comparison.

We believe that the information about the frequency spectra corresponding to the various lightning events is very important for the scientists for the better understanding of the physical processes of the electrical discharges inside the cloud and design engineers for efficient protective measures.

2. Instrumentation

The vertical electric fields of lightning activities were sensed by the wide bandwidth parallel plate antenna system followed by a buffer electronic circuit. The rise time of the wide band electric field measurement system was 10 ns and the decay time constant of the system was 15 ms. The frequency response of the antenna system was examined by using Hewlett Packard network analyser composed of two units (8751 A 5Hz to 500 MHz and 87511 A 100 kHz to 500 MHz). It was found that the response of the antenna system (including buffer) exhibits a constant decay with a factor of about 0.18 up to 50 MHz. The frequency response above 50 MHz does not exhibit such constancy. Although, we have not considered the attenuation factor in this analysis, the frequency response of the antenna system, within the limit of this analysis was constant. Further details of the antenna system can be found in Sharma et al., (2005) and references therein. The narrow band measurement system also consisted of the parallel plate antenna (with similar dimension as that of the wide band system) followed by a tuning circuit. In the case of 3 MHz narrow band system, passive electric components (an inductor and a resistor preceded by a capacitance offered by the parallel plate antenna) were used with a central frequency 3 MHz and having a bandwidth of 264 kHz and unity gain. Whereas, in the case of 30 MHz narrow band system, an active component (an op amp LMH 6609) was used with a bandwidth of 2 MHz with a gain of ~13.5. The parallel plate antenna associated with the wide bandwidth system was placed on the ground at a physical height of 1.5 m and that for the narrow bandwidth system were placed on the roof of the electrically shielded van at a height of about 3 m above the ground. The signals from the antenna system were acquired in the Yokogawa SL1000 digital storage oscilloscope with 12 (8) bit resolution and at a sampling rate of 100 MS/s recorded for 250 ms. The antenna system and the digitizer data acquisition system were good enough to capture the 30 MHz electric field at narrow band and for the broadband system to obtain the wavelet transform of the signal faithfully to 30 MHz (for more details see Ismail et al., 2015).

3. Methodology

The measurement of the electric field produced by lightning pertinent to the summer thunderstorm were acquired at the premise of the Ångstrom Laboratory, Uppsala, Sweden. Both the wide band detecting system and narrow band detecting system (at 3 MHz and 30 MHz) were employed. The electric fields sensed by the wide band and narrow band detecting systems were transferred to the digital storage oscilloscope through 10 m long RG 58 coaxial cables. The signal sent to the oscilloscope were digitized at the rate of 100 MS/s. The digitized data acquired in the DSO were analysed for different lightning events. Although, many of the cloud flashes could not be detected by the narrow band detectors about 200 cloud flashes were detected by the narrow band system at 3 MHz and only 5 of them were detected by the 30 MHz narrow band detecting system.

The total time window of the recording set up was set 250 ms (which was the limitation of the oscilloscope for the given sampling rate i.e. 10 ns) with a pre-trigger time of 75 ms and post trigger time of 175 ms. The time window, so set, was not sufficient to capture some of the whole cloud flashes, however, in many of the records the cloud flash appeared to have ceased within the set time window.

Out of 200 flashes that were carefully examined, we have selected only 15 flashes in this study for the analysis of their frequency content. The selection of the cloud flashes, under consideration, was done on the following two bases. (1) All the 15 flashes, selected in this study, were saved after corresponding thunder was heard during the measurement and that those did not saturate the measuring system. Therefore, all the cloud flashes selected in this study were nearby flashes that did not undergo large propagation losses. (2) The electric field signatures pertinent to each selected flash were meticulously examined for further confirmation of type of flash based on which only the cloud flashes that exhibited the two stage model were considered for the study. The flashes considered in this study, are of very common type, having two stages, initial or active stage followed by the late (final) stage. The active stage consisted of large micro second scale pulses with singly and multiply peaked pulses embedded in them, whereas the late stage consisted of bunches of the pulse bursts and chaotic pulse trains. The initial stage of the cloud flashes was found to have accompanied by both negative type (similar to the negative ground flash that lowers negative charge to the ground) and positive type (similar to the positive ground flashes that lower positive charge to the ground) large microsecond scale pulses. However, the majority of the flashes 149 (74.5%) out of 200 flashes were found to have accompanied by the positive type initial breakdown pulses whereas 51 (25.5%) of them were accompanied by the negative type initial breakdown pulses. From this observation, it can be said that the majority of the cloud flashes (about 75%) to have initiated between the main negative charge centre and the upper positive charge centre and 25% of the cloud flashes initiate between the main negative charge centre and the lower positive charge region (LPCR).

The final stage of the cloud flashes mainly consisted of relatively small pulses of both bipolar and unipolar nature. The bipolar pulses were found to be similar to the initial breakdown pulses and the unipolar pulses generally appeared as regular pulse bursts. The final stage was also found to radiate at HF and VHF as strong as the initial stage and in some cases the final stage was found to radiate strongly at HF and VHF. An example of cloud flash has been depicted in Fig. 1. As is seen in Fig. 1, the final stage is accompanied by the strong HF and VHF radiation. Of the 15 flashes taken into consideration, 5 flashes had their final stage accompanied by the high frequency (3 MHz) radiation stronger than that during the initial stage. Such an observation justifies the fact that cloud flashes begin in a large ambient field between two main charge centres producing large microsecond scale pulses and culminate into dendritic discharges failing to contact any well-defined electrode. Moreover, the occurrence of the bidirectional pulses in the late stage, as observed in this study, is an evidence of more random nature of the cloud discharge.

Wavelet transform technique has been applied to the broad band electric field records of cloud flashes by selecting the window size to 200 μs in order to observe the power spectra produced by the fine pulses and also to obtain the spectrum due to large pulses for each flash record. For the purpose, we selected Derivative of Gaussian (DOG) has been selected, for it is the most appropriate function for the transient phenomenon like lightning electric fields (see Sharma et al., 2011, for more detail). In order to rectify the biasness of the wavelet power spectra, we have made the computation by using the algorithm as suggested by Liu et al. (2007).

For the computation, we have divided each flash signature into two main stages, the initial stage and the final stage in order to have a better knowledge about frequency of radiation in the initial and final stage. In addition, some cloud activities occurring during the late stage (such as chaotic pulse trains and regular pulse bursts) have also been analysed for the frequency spectra of radiation.

In this analysis, in addition to wavelet transform computation of the time domain signals, significance test and cone of influence were also computed. The significance test gives the significance of the wavelet power spectrum above the back ground noise spectrum, generally white noise and red noise, to certain confidence level (95% in the present analysis).

4. Result and discussion

4.1. Initial breakdown pulses

Lightning initiation inside thunderclouds is defined by Dwyer and Uman (2014) as the processes that lead up to the creation of a propagating hot leader channel. Sometimes that ‘‘leader’’ channel is called an initial breakdown or preliminary breakdown channel. An ‘‘electrical breakdown’’ is usually considered to be a self-sustaining discharge that produces a rapid increase in the electrical conductivity that results in the collapse of the electric field (Dwyer and Uman, 2014). The problem of how lightning is initiated inside thunderclouds is not only one of the biggest unsolved problems in lightning physics; it is also probably one of the biggest mysteries in the atmospheric sciences (Dwyer and Uman, 2014). Despite the fact that the breakdown process remains to be a mystery, an initial breakdown takes place within the cloud. The initial breakdown process is thought to be incepted either between the main positive charge region and the main negative charge region or between the main negative charge region and the lower positive charge region (LPCR). In cloud flashes, the initial breakdown process produces the large bipolar electric field pulses called classic type (Nag and Rakov, 2009) that have characteristic frequency of radiation at 10 kHz–100 kHz, and narrow bipolar pulses that are associated with high and very high frequencies. The large bipolar pulses are recently being speculated by Marshall et al. to be associated with the possible initiation of Terrestrial Gamma ray Flashes (TGF). In order to understand the nature of radiation, and hence to understand the physical process associated to

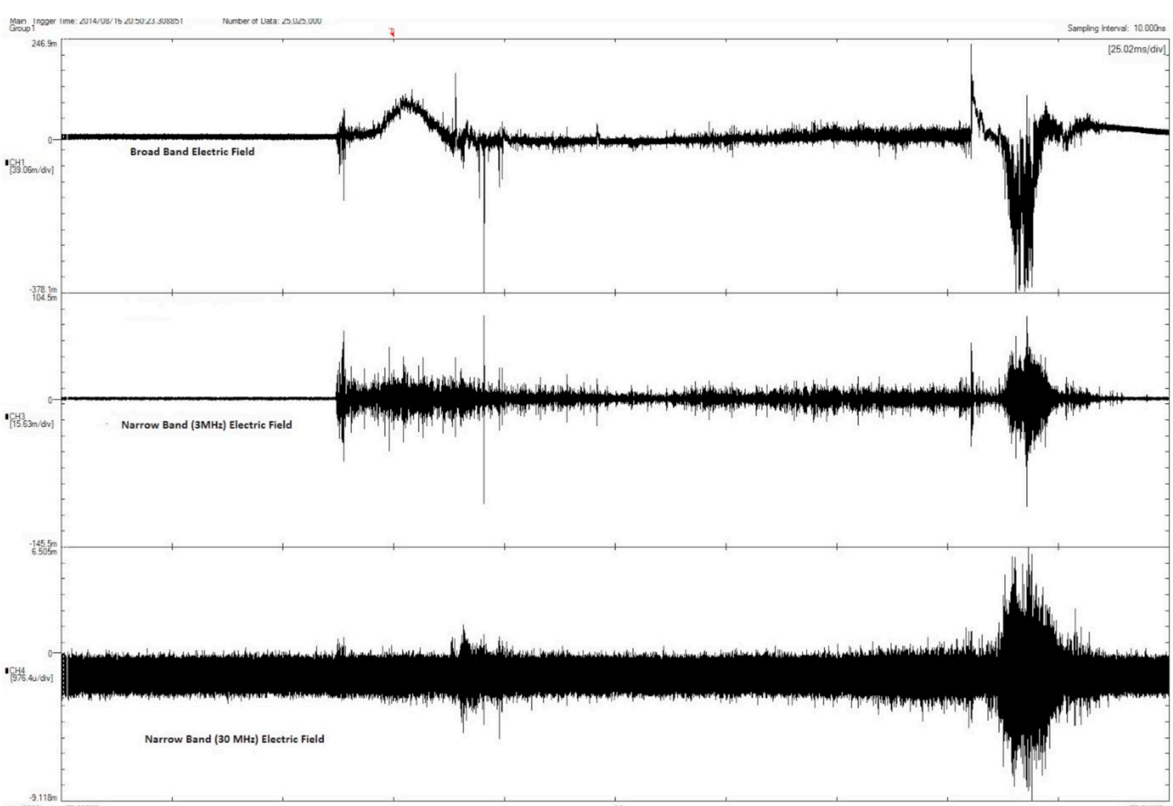

Fig. 1. A record of cloud flash simultaneously recorded through broad band antenna system (upper plot), and narrow band antenna system at 3 MHz (middle plot) and 30 MHz (lower plot). The total time window of the record is 250 ms, at 25 ms/div along the horizontal axis. The unit along the vertical axis is digitizer voltage. As is seen in, the initial stage and the final stage of the flash is accompanied by the HF and VHF radiation. However, the final stage can be witnessed to have stronger VHF radiation as compared to that of initial stage.

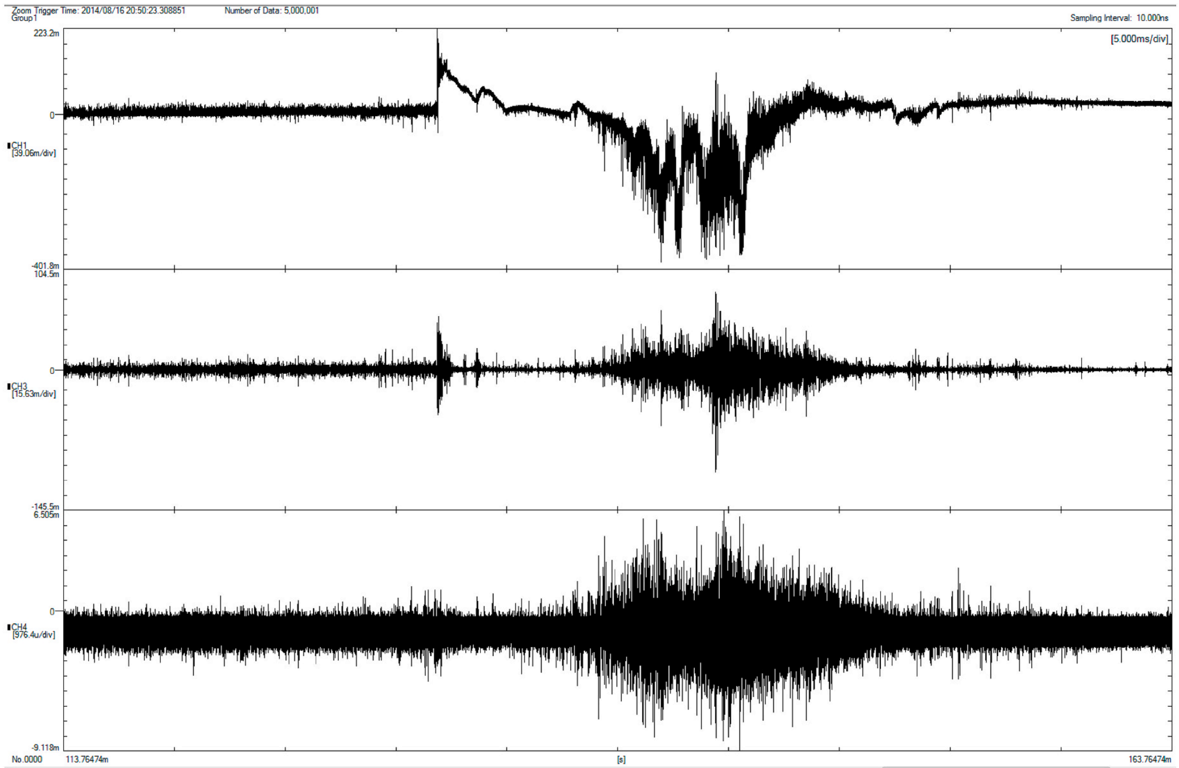

Fig. 2. A record of the final stage of the cloud flash (of Fig. 1), with broad band antenna system (upper plot), and narrow band antenna system at 3 MHz (middle plot) and 30 MHz (lower plot). The total time of the record along the horizontal axis is 50 ms, at 5 ms/div. The unit along the vertical axis is digitizer voltage. Seen in the record is the strong HF and VHF radiation in the final stage. Static field change can be witnessed in the final stage due to the large number of pulses.

the breakdown, the knowledge of the frequency spectrum of the radiation is very important. Moreover, the frequency of radiation of the first pulse of the breakdown process is of much interest in this regard. It is therefore, we have wavelet transformed the first pulse of 15 flashes, with both polarities and observed that, on the average, they radiate in the range of 50 kHz to 5 MHz and the average spread distribution was found to be 500 kHz to 3 MHz. However, the range of frequency of the large pulses in the initial breakdown process was found to be 5 kHz to 5 MHz with an average spread distribution of 1 kHz to 1 MHz. Examples of wavelet transform of initial breakdown pulses are depicted in Fig. 3 (positive unipolar pulse), Fig. 4 (largest breakdown pulse), and Fig. 5 (breakdown pulses with negative initial polarity).

4.2. *Final stage (late stage)*

The late-stage processes apparently serve to transport negative

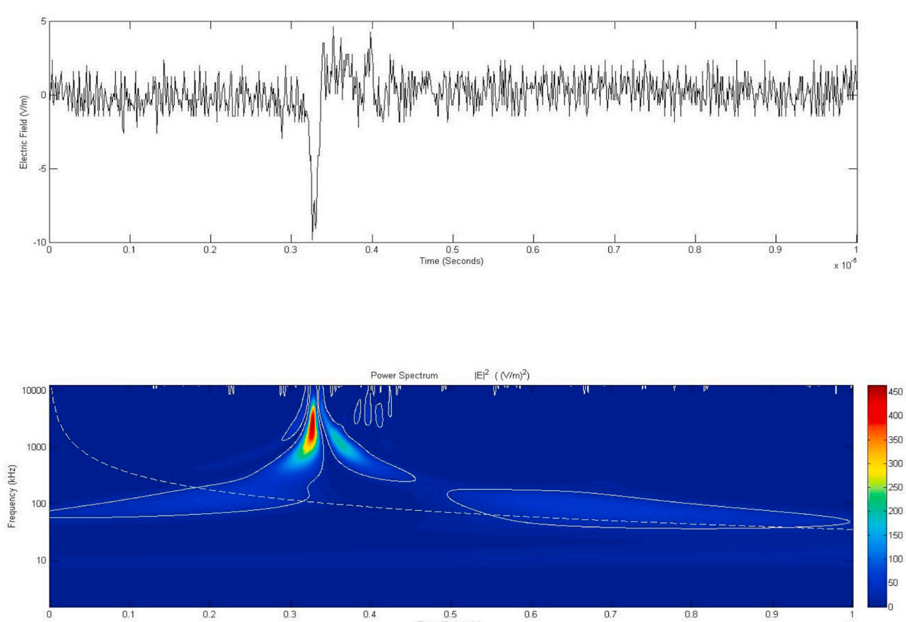

Fig. 3. An example of the wavelet transforms of the first pulse of the initial breakdown stage of the cloud flash. As is seen from the power spectrum, the range of frequency is above 500 kHz to about 9 MHz whereas the spread distribution (the range of maximum energy radiation) is between 0.9 MHz and 8 MHz. The maximum power radiated by the first pulse in this example is 450 $(V/m)^2$. In this computation 10 μs time window was selected just to obtain the frequency power spectrum due the single pulse and to avoid the contribution by other pulses.

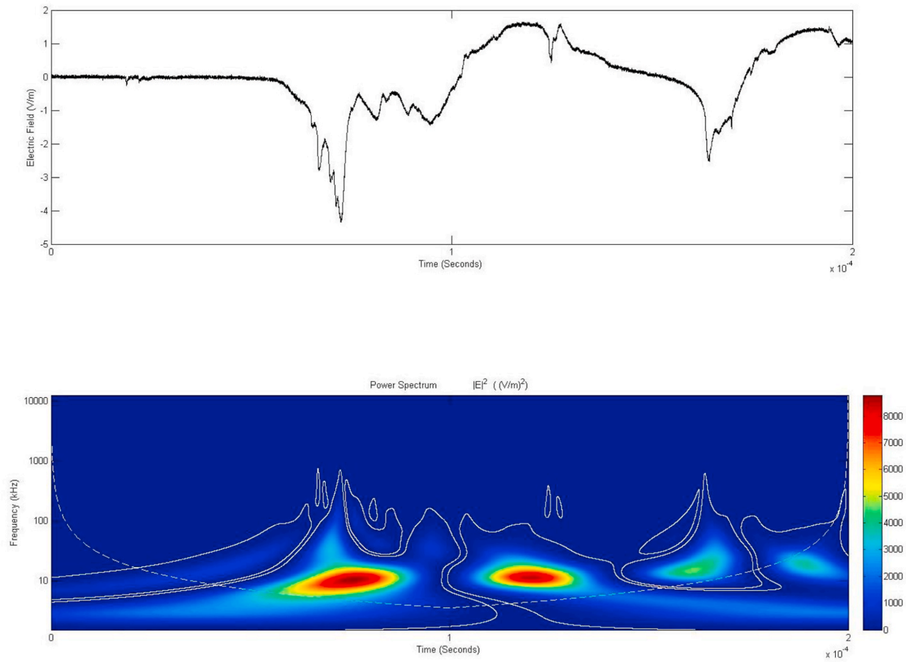

Fig. 4. An example of the wavelet transform (power spectrum) of the largest pulse in the initial breakdown pulse train of the cloud flash. As is seen from the power spectrum, the range of frequency is above 3 kHz to about 100 kHz whereas, the spread distribution is between 5 kHz and 10 kHz (for the initial peak). The maximum power radiated by the first pulse in this example is 3500 $(V/m)^2$.

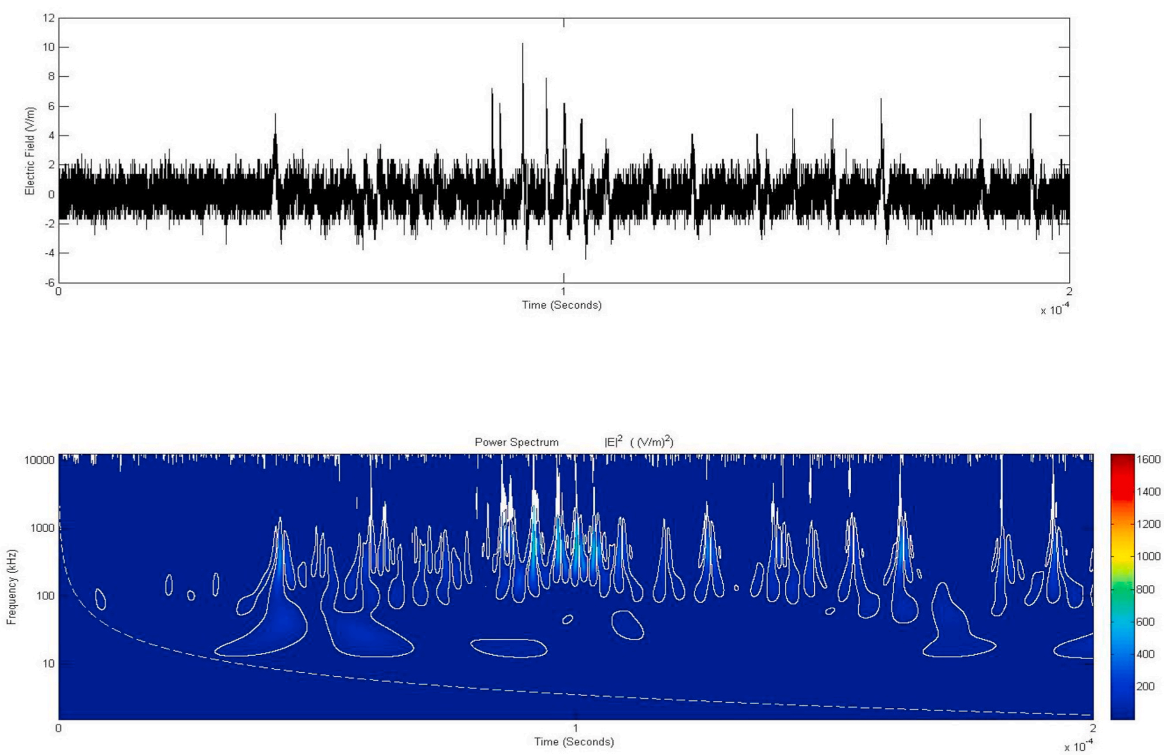

Fig. 5. An example of the wavelet transform (power spectrum) of the initial breakdown pulse train (with negative initial polarity) of a cloud flash. As is seen from the power spectrum, the range of frequency of the majority of these pulse is above 100 kHz to about 5 MHz whereas the spread distribution is between 500 kHz to about 5 MHz. The maximum power radiated by the first pulse in this example is 1000 $(V/m)^2$.

charge to the region of the flash origin from progressively more remote sources in the negative charge region.The electric field changes of the late (or final) stage of the cloud flash are similar to the field changes between strokes and after the last stroke of the cloud-to-ground flash in each case, on relatively slow electric field changes (J-changes) are superimposed step-like changes (K-changes and sometimes "recoil streamers"), typically lasting for 1 ms or so and separated by time intervals of order 10 ms (Rakov and Uman, 2003) and a slightly higher value of interval (18 ms) in Brazilian lightning (Miranda et al. (2003). Further, the J- and K- changes in the ground flash are thought to be similar to those in Cloud flashes and that the J-process in ground flashes is often visualized as a positively charged channel (or channels) extending from the region of the flash origin (following the arrival there of the return stroke) at a speed of order 10^4 m s^{-1}, which is equivalent to supplying negative charge to the origin. K-processes can be viewed as transients occurring during the slower J-process (Rakov and Uman 2003).

4.2.1. Regular pulse bursts

Many K-changes are associated with microsecond-scale pulse activity in the form of trains of relatively small pulses separated by time intervals of about 5 μs. These trains are usually referred to as regular pulse bursts (Rakov and Uman 2003). These regular pulse bursts were reported to have an average propagation speed of 2.7×10^6 m/s (Davis, 1999) which is comparable to the average speed of dart stepped leader in cloud to ground lightning. In the present study, regular pulse bursts pertinent to six cloud flashes were analysed for their frequency content. An example of such pulse bursts along with wavelet transform for the frequency spectrum is depicted in Fig. 6. From the six series of such bursts, the average range of frequency was found to be 50 kHz to 5 MHz with the average spread distribution varying from 100 kHz to 3 MHz.

4.2.2. Chaotic pulses train

The chaotic pulse trains (or leaders) have been reported by many researchers but mostly in connection with the subsequent return strokes of the negative ground flashes (e. g. Weidman, 1982; Bailey et al., 1988; Willett et al., 1990; Rakov and Uman, 1990; Izumi and Willett, 1993; Davis, 1999; Gomes et al., 2004; Mäkelä et al., 2007; Lan et al., 2011, Hill et al., 2012). The term "chaotic" leader is not well defined but has, in general, been used to refer to a relatively continuous sequence of irregular electric field pulses. These pulses were thought to be the initiation of the dart stepped leaders leading to the subsequent return strokes. However, Gomes et al. (2004) used the term chaotic pulse train (CPT) owing to the fact that in many of their records the chaotic pulses did not immediately precede the subsequent return stroke. To the best of our knowledge, the study on the chaotic pulse trains pertinent to the cloud flashes is not available in the literature. In the present study, the chaotic pulse trains were generally, observed in the late stage of the flash, however, in some cases these trains were observed even accompanied by the initial breakdown process. An example of chaotic pulse train pertinent to the late stage of cloud flash and its corresponding frequency spectrum is depicted in Fig. 7. From the figure it can be seen that the average range of frequency of pulse train is above 200 kHz to about 1 MHz whereas, the spread distribution is between 500 kHz and 800 kHz. In the present study, 7 chaotic pulse trains from 5 flashes were wavelet transformed and the range of frequency of radiation from these pulses was found to be 100 kHz to 5 MHz with a spread average spread distribution of 500 kHz to 3 MHz. In an agreement with Mäkelä et al. (2007), the chaotic pulses (pertinent to ground flashes in their report) are the source of HF frequency radiation. More recently, Hill et al. (2012) observed a relatively continuous flux of energetic radiation (X-rays and gamma rays) during the final 10–13 ms of each "chaotic" dart leader. However, these chaotic dart leaders were associated with the triggered lightning. The summary of the frequency of radiation by the chaotic pulse trains and the other events has been depicted in Table 1.

4.2.3. HF radiations

The final stage of some of the cloud flashes were found to be accompanied by the very narrow electric field pulses and VHF radiation. These very narrow (with pulse duration of about 50 ns) pulses can be considered to be somewhat similar to the Q-streamers leading to the k-change as was reported by Proctor (1981) and Hayenga (1984) and apparently random micro-discharges. These streamers were observed by Kitagawa and Brook (1964), Hayenga (1984), Rhodes and Krehbiel (1989) etc to be the source of VHF and UHF radiations. As is seen from Figs. 1 and 2, the strength of the VHF (30 MHz) radiation corresponding to the final stage is stronger than that corresponding to the initial stage. Seen in the wavelet transform (Fig. 8) is that the frequency of radiation is above 10 MHz, however, the energy corresponding to the very fine peaks being overwhelmed by the energy corresponding to the larger pulses (at relatively lower frequency, in the range of 1–5 MHz) cannot be

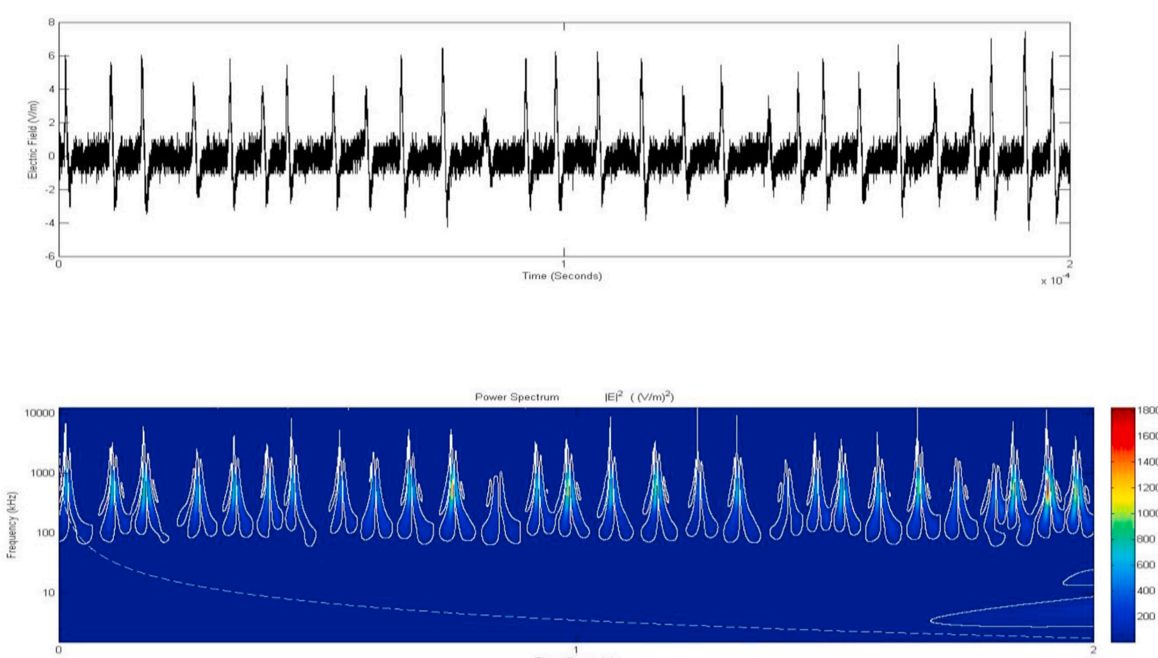

Fig. 6. An example of the wavelet transform (power spectrum) of the regular pulse burst of a cloud flash that occurred in the final stage. As is seen from the power spectrum, the range of frequency of pulse train is above 100 kHz to about 5 MHz whereas the spread distribution is between 500 kHz and 1 MHz. The maximum power radiated by the first pulse in this example is 1400 $(V/m)^2$. The summary of the frequency of radiation can be seen from Table 1.

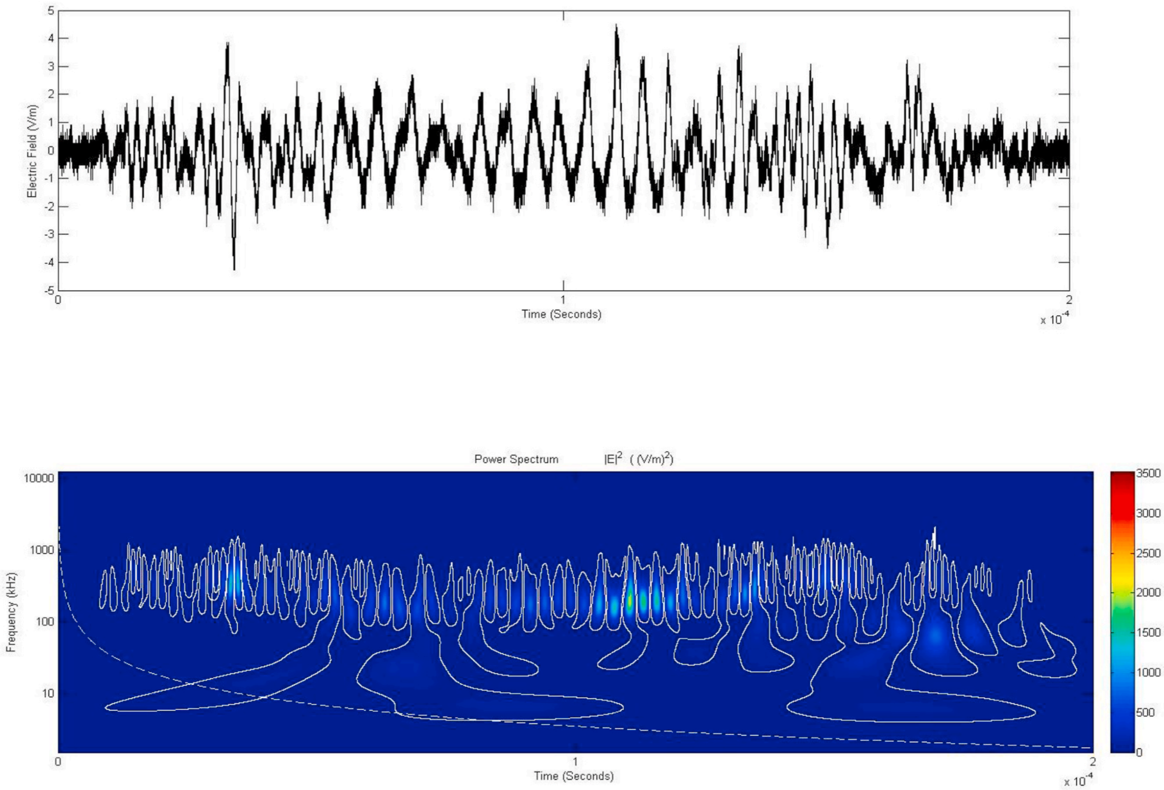

Fig. 7. An example of the wavelet transform (power spectrum) of the chaotic pulse train of a cloud flash that occurred during the final stage of a cloud flash. As is seen from the power spectrum, the average range of frequency of pulse train is above 200 kHz to about 1 MHz whereas, the spread distribution is between 500 kHz and 800 kHz. The maximum power radiated by the first pulse in this example is 2200 $(V/m)^2$.

Table 1
Summary of the range of frequency and spread distribution of different events pertinent to the cloud flashes.

Event/s	Sample	Range of frequency			Spread distribution		
		minimum (kHz)	Maximum (MHz)	average range (Hz)	Minimum (kHz)	Maximum (MHz)	average range (Hz)
IB Pulse train	15	3	10	50 k-5 M	10	5	500 k-3M
First pulse	15	50	10	100 k-5M	50	8	500 k-3M
Largest pulse	15	3	5	15 k-1M	5	3	50 k-500k
Regular Pulse Bursts	6	10	10	50 k-5M	50	5	100 k-3 M
Chaotic Pulse train	7	50	10	100 k-5M	100	5	500 k-3M
Final stage strong VHF	3	50	> 10	100 k-8 M	100	> 10	500 k- 5M

distinctly seen, though, the white contours are distinct well above 10 MHz. By selecting the narrow window size, one can obtain the frequency spectra in the higher frequency region.

5. Summary and conclusion

Frequency and power spectra corresponding the different events pertinent to Swedish cloud flashes were obtained by using the wavelet transform technique. To the best of our knowledge this is the first time that the wavelet transform technique has been applied for the cloud flashes to extract the frequency domain features while retaining the time domain features. For the purpose, Derivative of Gaussian (DOG) function was selected as the mother wavelet owing to the fact that they are the most suitable wavelets for the transient signals such as lightning. In order rectify any deviation or biasness in the conventional wavelet power spectrum computation was done by dividing each energy value by scale for 10 selected signatures, however, no significant change was observed.

Although, the narrow band antennas were also employed for the measurement of electric field radiation, they were tuned at 3 MHz and 30 MHz only. In order to acquire the knowledge about frequency of radiation by the different events the wavelet technique is more efficient than the Fourier transform technique and is much convenient and cheaper compared to that of narrow band technique, in which a large number of antennas are to be employed.

The initial breakdown process consisting of large micro second scale pulses as well as narrow pulses were found to radiate in the frequency range 50 kHz to 5 MHz with the average spread distribution of 500 kHz to 3 MHz. The minimum frequency of radiation corresponding to the large pulses was found to be as low as 3 kHz, which is similar to that radiated by the return strokes pertinent to the ground flashes, whereas the maximum frequency corresponding to the narrow pulses was found to be 10 MHz. Similarly, the first pulses of the IB process and that of the cloud flash was found to radiate in the frequency range of 100 kHz to 5 MHz, on the average, with the average spread distribution of 500 kHz to 3 MHz. However, some of the first pulses could radiate as low as 15 kHz and some other radiate as high as 10 MHz. On the other hand, the average range of frequency corresponding to the largest pulse from each IB train was found to be 15 kHz to 1 MHz with an average spread distribution of 50 kHz–500 kHz.

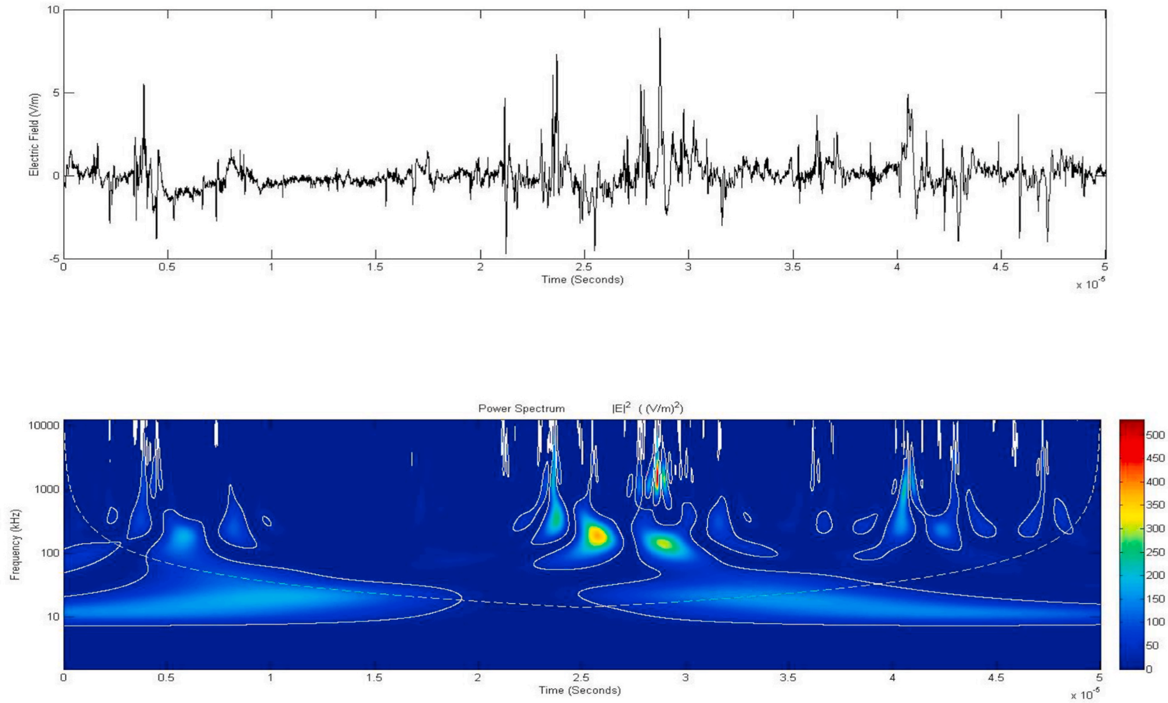

Fig. 8. An example of the wavelet transform (power spectrum) of the large pulses occurred during the final stage of a cloud flash. As is seen from the power spectrum, the average range of frequency of pulse train is above 100 kHz to above 10 MHz. The maximum power radiated by the first pulses in this example is 500 $(V/m)^2$. It should be noted here, this part of the flash exhibited maximum energy radiation at 30 MHz narrowband filter as compared to the initial stage as is seen from Fig. 1, (For the clarity of the spectrum only 50 μs time window has been wavelet transformed).

Late (final) stage of the cloud flashes was found to be accompanied by several events such as regular pulse bursts, chaotic pulse trains and bursts of very narrow pulses that are strong radiators of very high frequency (VHF). These pulses can be considered as the recoiling streamers similar to what are termed Q-streamers. From the present analysis, the final stage of the cloud flash can be considered as the source of electromagnetic field radiation in the frequency range of 10 kHz to well above 10 MHz (or in the VHF range from the narrow band detector). The regular pulse bursts were found to radiate in the frequency range of 50 kHz to 5 MHz on the average, whereas the chaotic pulse trains were found to radiate in the frequency range of 100 kHz to 5 MHz. Similarly, the final stage of some of the cloud flashes were found to be very strong radiator of VHF, corresponding to the recoil streamers.

From the present study it can be inferred that the cloud flashes can be the source of electromagnetic radiation from a few kHz to several tens of MHz. Since, the measurements were carried out on the ground the VHF and UHF components of the radiation from those cloud flashes might have undergone propagation loss. Nonetheless, our wide band measurement system and the digitization of the signal was just sufficient for the spectral range up to 30 MHz, yet due to the spectral energy corresponding to the very narrow pulses being overwhelmed by those of relatively larger pulses, significant spectrum corresponding to those pulses could not be obtained. It has been observed that the initial stage of cloud flash radiates predominantly in the low frequency range and that the final stage radiates in the high and very high frequency range.

It is believed that the information about the frequency of radiation from the cloud flashes (which is relatively very rare in the literature) is very important for the scientific community working in the field lightning physics, design engineers concerning to the protection from transients specially for the avionics and tall communication towers.

In conclusion, simultaneous measurement of electric fields pertinent to the lightning activities were conducted with wide bandwidth and narrow bandwidth system using the parallel plate antenna system of same dimension. The signal obtained with wide bandwidth system were wavelet transformed to extract the frequency domain information and compared with those obtained by narrow bandwidth system. The frequency spectra pertinent to the cloud flashes obtained from the wavelet transform technique are found to resemble with those acquired with narrow bandwidth system. This study provides a basis for measuring the electric fields with wide bandwidth system and obtain the frequency domain information without deploying several narrow band system retaining time domain as well as frequency domain information. This technique would also be useful to understand the nature of discharge at various stages of lightning and hence its morphology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Authors would like to highly acknowledge the **Erasmus Mundus 'EXPERT4Asia'** program for the financial support to **Shriram Sharma.** Authors also like to acknowledge, the excellent facility provided by the division of electricity and lightning research, Ångstrom Laboratory, Uppsala University for this research. The Participation of M.M.Ismail is funded the Ministry of Education of Malaysia and Universiti Teknikal Malaysia Melaka.

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