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# HF radiation emitted by chaotic leader processes

J.S. Mäkelä[a,*], M. Edirisinghe[b], M. Fernando[b], R. Montaño[c], V. Cooray[c]

[a]Nokia Technology Platforms, Nokia Oyj, Salo, Finland
[b]Department of Physics, University of Colombo, Colombo, Sri Lanka
[c]Division for Electricity and Lightning Research, Ångström Laboratory, Uppsala University, Uppsala, Sweden

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**Abstract**

This paper presents direct measurements of narrowband 10 MHz HF radiation from so-called "chaotic leaders" associated with subsequent return strokes. Although the term is controversial and poorly defined, we find that more than 30% of subsequent strokes in close lightning flashes contain electric field characteristics that are best described as "chaotic". In earlier studies, return strokes have consistently been observed to be the strongest sources of HF radiation, but the results for leader processes are less consistent. We also observe return strokes to be the main HF emitter, and the leaders before the first return stroke in a flash sequence also emit HF though somewhat less intensely. The leaders preceding subsequent strokes typically emit little or no HF radiation, whether they are dart or dart-stepped leaders.

However, it was observed that the presence of a chaotic component increases the leader HF intensity dramatically Defining the HF intensity unequivocally can be problematic for processes like chaotic leaders which have a combination of continuous and impulsive phenomena. Two time-domain methods were used to measure the HF intensity, the peak energy and the RMS energy. In the frequency domain these correspond to the energy spectral density (ESD) and power spectral density (PSD), respectively.

It was found that the methods are not necessarily compatible. Thus, it is suggested that to clarify future work, leader processes should be characterized by the PSD rather than the ESD.


*Keywords:* HF radiation; Lightning; Return strokes; Stepped leaders; Chaotic leaders

## 1. Introduction

The lightning process that has the most dramatic practical consequences is the return stroke, the fast impulse that transfers charge to the ground. However, the return stroke is only one of many electromagnetic phenomena associated with lightning. These phenomena cause observable effects at effectively all frequencies, from quasi-stationary electric fields to visual emissions. From a practical point of view, the low-frequency (LF) range (below about 300 kHz) is the most critical since the return strokes emit most strongly at those frequencies; for example lightning-location devices usually operate at this range. On the other hand, use of very high frequency (VHF, above 30 MHz) enables interferometric measurements of fine structure within cloud processes. The intermediate frequencies (HF, at about 3–30 MHz) have been less extensively studied. There are few significant direct risks from HF impulses, although electromagnetic disturbances

*Corresponding author. Tel.: +358 503 663418.
*E-mail address:* Jakke.Makela@nokia.com (J.S. Mäkelä).

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can be induced in structures like airplanes or other structures in the size scale 10–100 m, since this corresponds to resonant HF wavelengths (Weidman et al., 1981). In principle HF could be used for remote detection of intense storm activity, as implied, e.g., by Taylor (1973) and Mäkelä et al. (2006). However, this approach has not been widely adopted. This is largely due to difficulties in relating any given narrowband HF signal to a specific lightning process, since multiple processes emit HF radiation. In practice, HF radiation can at best give a measure of the energy released during a ''composite'' event consisting of several lightning processes (Le Vine, 1987; Nanevicz et al., 1987).

Possible sources of HF radiation are reviewed by Cooray and Perez (1994). However, as noted by Le Vine (1987), even empirical studies tend to be difficult to interpret and are not always compatible. At a general level, in-cloud processes are known to emit strong HF radiation at least occasionally (Le Vine, 1980; Willett et al., 1989). In many studies, return strokes are found to be strong HF emitters (Weidman et al., 1981; Krider et al., 1977; Cooray and Perez, 1994; Beasley et al., 1982; Willett et al., 1990). Leader processes preceding return strokes are generally observed in these studies to cause some HF, but systematically weaker than return strokes. On the other hand, preliminary breakdowns have been observed to be strong HF emitters by Weidman et al. (1981) and Cooray and Perez (1994). The HF content of subsequent strokes has been studied by and Le Vine and Krider (1977) and Jayaratne and Cooray (1994). The statistics in the studies are not very extensive, but the general implication is that subsequent strokes emit more weakly than first return strokes.

In addition to these well-established lightning processes, there is a somewhat controversial class of events usually known as ''chaotic leaders'', a name first used by Weidman (1982); and cited by Rakov and Uman (1990a). We follow the convention of Rakov and Uman (2003), Section 4.7.6 and keep the term in quotation marks. The term has occurred intermittently in the literature, but no consistent definition has yet emerged, and there are very few systematic studies. The phenomenon may be related to ''chaotic pulses'' as defined by Gomes et al. (2004). These are irregular phenomena in the electric field associated with subsequent strokes, with length and separation both in the 10 μs range, lasting for a few hundred microseconds, and significantly above the noise level of the signal. However, Gomes et al. (2004) do not use the term ''chaotic leader'', since the observed pulses are not always superimposed on the leader activity. Such chaotic structure is claimed to appear in at least 25% of subsequent strokes, possibly more. Other mentions in the literature tend to be more anecdotal. For example, Willett et al. (1990) analyzed the spectra of 15 chaotic leaders, while Willett et al. (1995) report an individual sample of a chaotic leader.

Rakov and Uman (1990a) found 15 such chaotic leaders among 76 Florida flashes (with a total of 270 subsequent strokes). Overall, the data available in the literature are not large enough to provide statistics on this phenomenon.

We have measured simultaneous electric field and 10 MHz narrowband data from three storms Sri Lanka. The detailed analysis contains 34 flashes with 74 subsequent strokes. More than 30% of the subsequent strokes contain examples of what appear to be ''chaotic leaders'' as defined in earlier literature (see Figs. 2–7). We observe significant differences between the HF signatures of ''chaotic'' and ''nonchaotic'' leaders, which suggests that the chaotic leaders are genuine physical phenomena. In particular, whereas normal leaders in many cases emit no HF radiation above the noise threshold, the HF radiation intensity of chaotic leaders can be very high. However, we also show that the definition of ''HF intensity'' needs to be reviewed carefully in the case of chaotic leaders. We therefore describe two complementary methods of defining the intensity of an HF signal, and show that the methods are in agreement for return strokes, but less so for leader processes and especially chaotic leaders.

## 2. Measurements and data analysis

The measurements of simultaneous broadband electric field and HF radiation at 10 MHz were performed in May 2005 at the University of Colombo, about 1 km from the west coast of Sri Lanka (6.91°N 79.86°E). A total of three storms were analyzed in detail (May 8, and morning and evening of May 9). The measurement system is identical to that described in Cooray (1986). The vertical electric field was measured with a flat-plate antenna; the broadband circuitry had a zero-to-peak rise time of less than 30 ns and the decay time constant of 10 ms. The HF radiation was measured with a vertical antenna tuned to a resonant frequency of 10.440 MHz and bandwidth 2.020 MHz. The output from both sources was received by a two-channel NIPIC51232MB) data acquisition card operating at 100 MHz, allowing a 200 ms sample to be captured. The DAQ was set in pre-trigger mode, with the pre-trigger time set at 25 ms. Fig. 1 shows a representative data sample (Flash 27 of May 9).

An instrumental tradeoff had to be made between high resolution and long sample time. The low bit rate means that sub-microsecond phenomena cannot be reliably resolved from the data. The processes of interest are manifested at time scales of a microsecond or more, and on the other hand tropical multi-stroke flashes can last several hundreds of milliseconds. The response function of the antenna is also a factor that limits the accuracy to the microsecond scale, going to zero within about 0.5 μs. To identify any detail in the signal, it is necessary to smooth the signal. Fig. 2 shows that a simple moving average allows fine structure to be identified. A sensitivity analysis was carried out with different averaging windows; it was found that a 50-point moving average (corresponding to a time resolution of 0.5 μs) does not distort intense signals such as return stroke onsets or leader steps. It is important to mention that for this study the electric field was used primarily to identify the various lightning processes, so that sub-microsecond resolution is not needed.

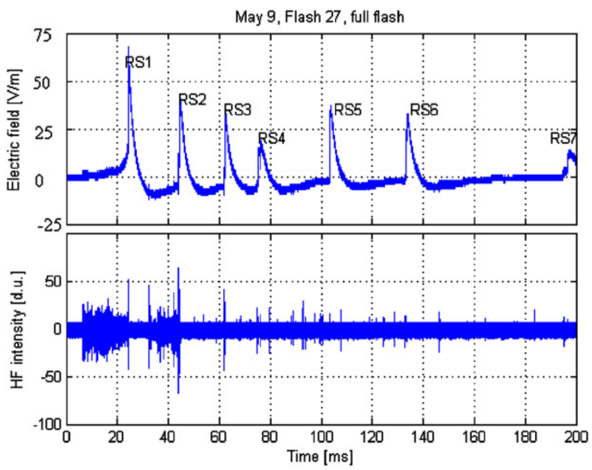


Fig. 1. Representative sample of full flash (May 9 Flash 27). The electric field is shown in the top panel, with the return strokes marked on the graph. The HF intensity in digitizer units is shown in the bottom panel. The system triggered on RS1, with 25 ms pre-trigger.

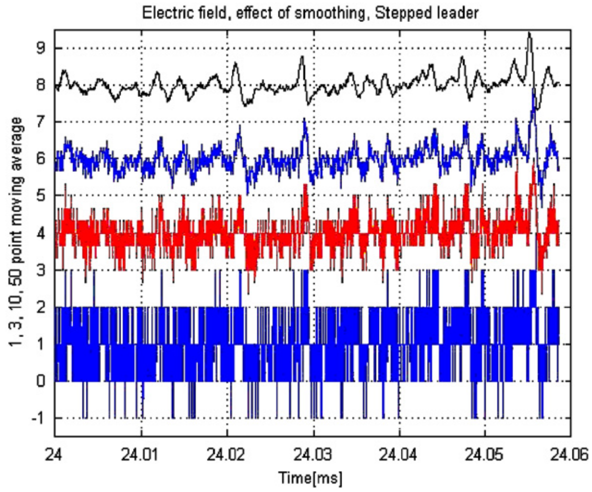


Fig. 2. Smoothing of electric field data in typical stepped leader (60 μs sample). The bottom trace shows the unsmoothed electric field data; the traces above correspond to smoothing averages of 3, 10, and 50 pixels, shifted vertically.

One difficulty in defining a "chaotic" leader is the large variation in individual leader processes. Rakov and Uman (1990b) review earlier studies and conclude that at least for some purposes it may be valid to classify all leaders that occur after the first return stroke simply as "subsequent leaders". The issue is somewhat complicated by the observations of Willett et al. (1995) which show that in some cases subsequent strokes may also present spectral characteristics that are more typical of first return strokes (presumably associated with the formation of new channels to the ground). We can in practice be certain that all of the first return strokes in our data set are channel-forming first return strokes, since all except three displayed unambiguous stepping activity in the leader stage. The presence of a preliminary breakdown signature would be an additional indication of the first return stroke, but such breakdowns are typically very weak or even missing in tropical lightning according to Gomes et al. (1998). The breakdown signals were also weak or ambiguous in our data set (a typical example is seen in Fig. 1), and this criterion was not used.

In the subsequent leaders, stepping activity formed a continuum, so that it is not possible to draw a clear line between pure dart leaders and dart-stepped leaders. On the other hand, there was a class of leaders which was visually completely distinct, as seen in Figs. 3–8. An idealized leader

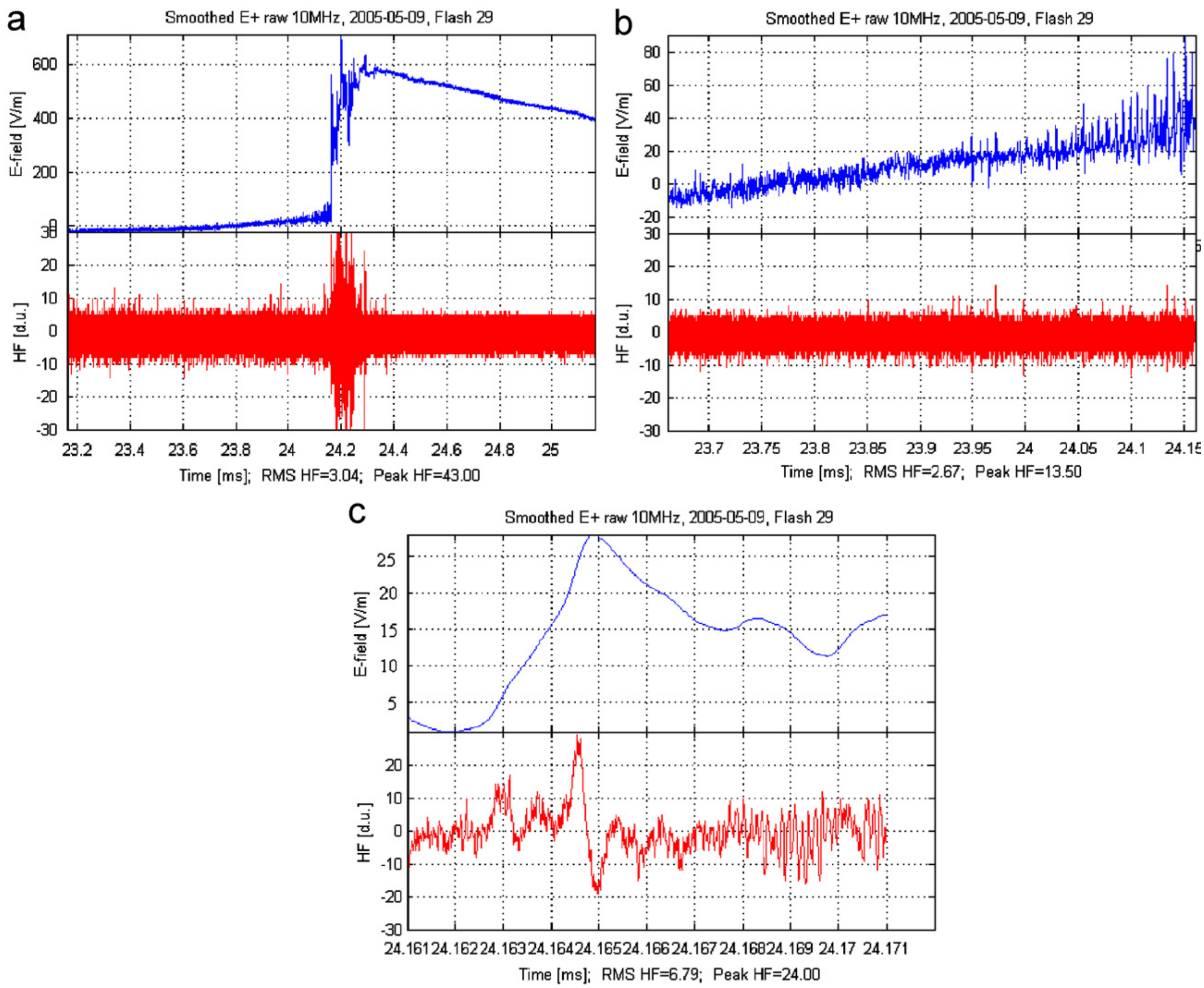


Fig. 3. Stepped leader before first return stroke (Flash 27, Stroke 1), (a) 2 ms sample, (b) leader stage, 500 μs sample and (c) return stroke, 10 μs sample.

process has a monotonically rising static electric field, overlaid with leader steps of microsecond duration at intervals of several to several dozen microseconds (e.g. Rakov and Uman, 1990b). We propose that "chaotic" behavior be defined as a statistically significant deviation from this behavior, consisting of nonmonotonic electric field changes with durations of much more than 1 μs, with amplitudes that are significantly above the noise level of the electric field.

Ideally, the radiation intensity of a given process is calculated as the Fourier transform of the broadband signal, as described, e.g., by Willett et al. (1989). In principle, the same result should be obtained in the time domain with a narrowband signal by calculating the peak intensity of the narrowband signal, as discussed by Le Vine (1987). However, Le Vine (1987) points out that this must be done with great care, and interpreting the results can be difficult at best. For measured signals in the HF range, some discrepancies have indeed been observed. The narrowband measurements tend to give higher intensities, as noted, e.g., by Le Vine (1987), Nanevicz et al. (1987), and Willett et al. (1989). The discrepancy may be due in part to the fact that a narrowband measurement represents a composite of many processes or even instrumental difficulties (Nanevicz et al., 1987), but the presence of unknown physical processes cannot be ruled out completely (Willett et al., 1989).

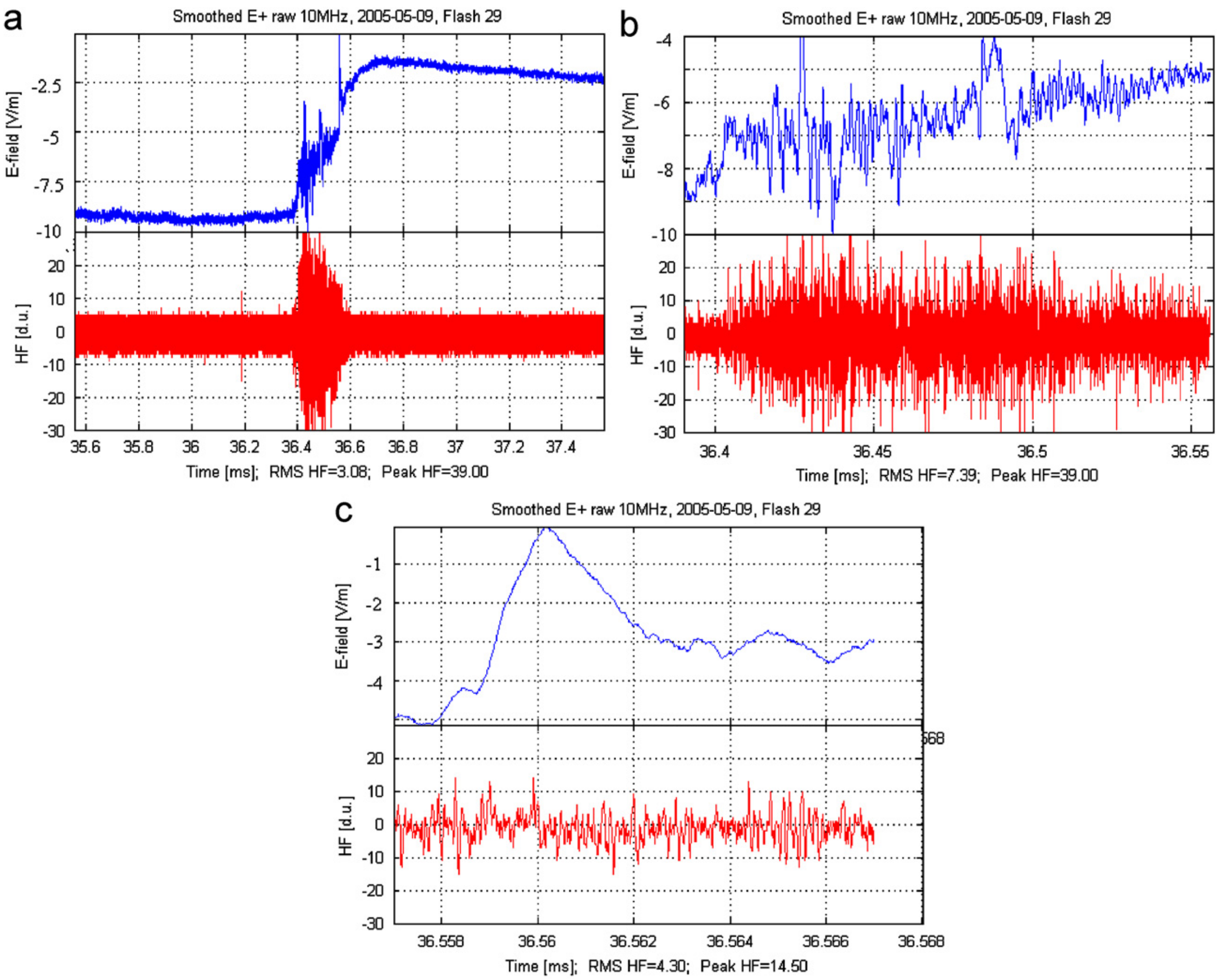


Fig. 4. Chaotic leader (Flash 27, Stroke 2), (a) 2 ms sample, (b) leader stage, 500 μs sample and (c) return stroke, 10 μs sample.

A simple analytical expression can be derived for the highly idealized case of a single impulse, as shown by Le Vine (1987). For such a signal the voltage out of the antenna is

$$e(t) = \mathrm{Re} \int_0^{\infty} 2a(f)H(f)E(f)\mathrm{e}^{-\mathrm{i}2\pi ft}\,\mathrm{d}f, \tag{1}$$

where $H(f)$ is the Fourier transform of the impulse response $h(t)$ of the receiver, and $a(f)$ is the antenna function. For single impulsive signals having center frequency $f_0$, the normal procedure is to assume a flat antenna response $a(f) \approx a(f_0)$ and spectrum $E(f) \approx E(f_0)$, square both sides of Eq. (1), and return to the time domain as $e^2(t) = |a(f)E(f)|^2 h^2(t)$. When both sides are integrated over time, Parseval's relation enables a return to the frequency domain, and solving for the energy spectrum then gives

$$|E(f_0)| = \frac{1}{2\sqrt{\Delta}}\sqrt{\int_{-\infty}^{\infty} e_0^2(t)\,\mathrm{d}t}, \tag{2}$$

$$\Delta = |a(f_0)H(0)|^2 \int_{-\infty}^{\infty} \frac{H^2(z)}{H^2(0)}\mathrm{d}z \equiv G^2 B, \tag{3}$$

where $G$ is the system gain and $B$ the bandwidth. For an ideal bandpass filter of bandwidth $B$ the response function is $H(z) = H(0)$ for $-B/2 < z < B/2$ and zero elsewhere, and Eq. (1) then simplifies to $e_0(t) = e_\mathrm{p}\, sinc(\pi Bt)$, where $e_\mathrm{p}$ is the measured peak of the signal. Hence

$$\int_{-\infty}^{\infty} e_0^2(t)\,\mathrm{d}t = \frac{e_\mathrm{p}^2}{B} \tag{4}$$

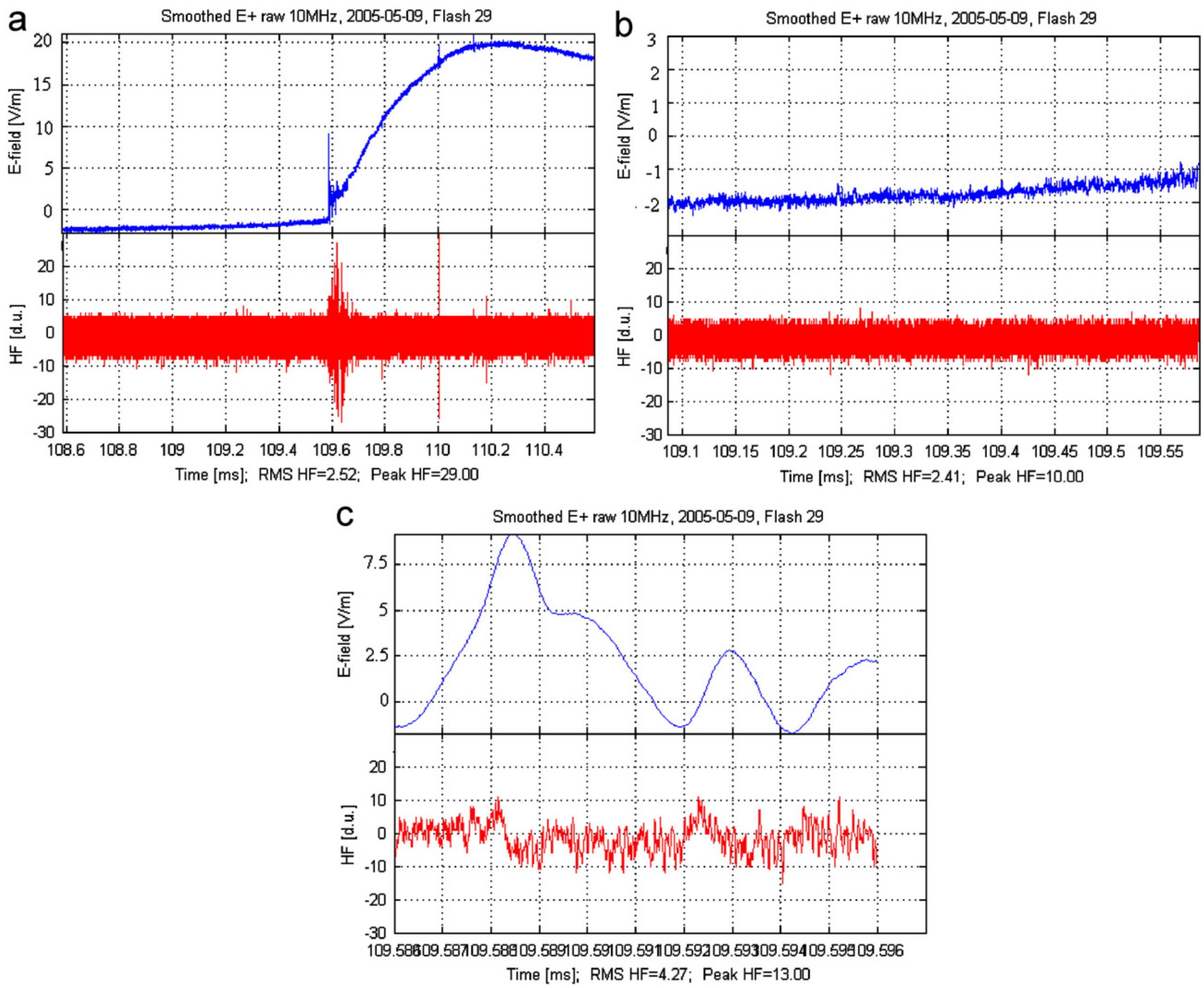


Fig. 5. Chaotic leader (Flash 27, Stroke 3), (a) 2 ms sample, (b) leader stage, 500 μs sample and (c) return stroke, 10 μs sample.

and Eq. (2) simplifies to a function of the measured peak signal $e_p$ only:

$$|E(f_0)| = \frac{e_p}{2GB}. \tag{5}$$

This equation is commonly used to estimate the spectral density, and is valid for ideal measurement systems and a single impulsive signal.

According to Le Vine (1987), the spectrum of a random process should be more generally defined as the Fourier transform of the autocorrelation function, which for specified time window $T$ is

$$|E_r(f_0)| \approx \frac{1}{2\sqrt{\Delta}}\sqrt{\frac{1}{2T}\int_{-T}^{T} e_0^2(t)}. \tag{6}$$

This is dimensionally different from Eq. (2), being related to the power spectral density (PSD) rather than the energy spectral density (ESD). For a discrete signal, the integral can be replaced by a sum, resulting in the estimate

$$|E_r(f_0)| \approx \frac{1}{2\sqrt{\Delta}}\sqrt{\frac{1}{2N}\sum_{k=-N}^{N} e_k^2} = \frac{\sigma}{2\sqrt{\Delta}} = \frac{\sigma}{2G\sqrt{B}}, \tag{7}$$

where $\sigma$ is the standard deviation of the measured set of output voltages. Dividing the two values gives

$$\frac{|E_r(f_0)|}{|E(f_0)|} = \frac{\sigma\sqrt{B}}{e_p}. \tag{8}$$

For the ideal case of a harmonic function, the ratio is linear and the two definitions simply differ numerically by a proportionality constant $\sqrt{2}$. The

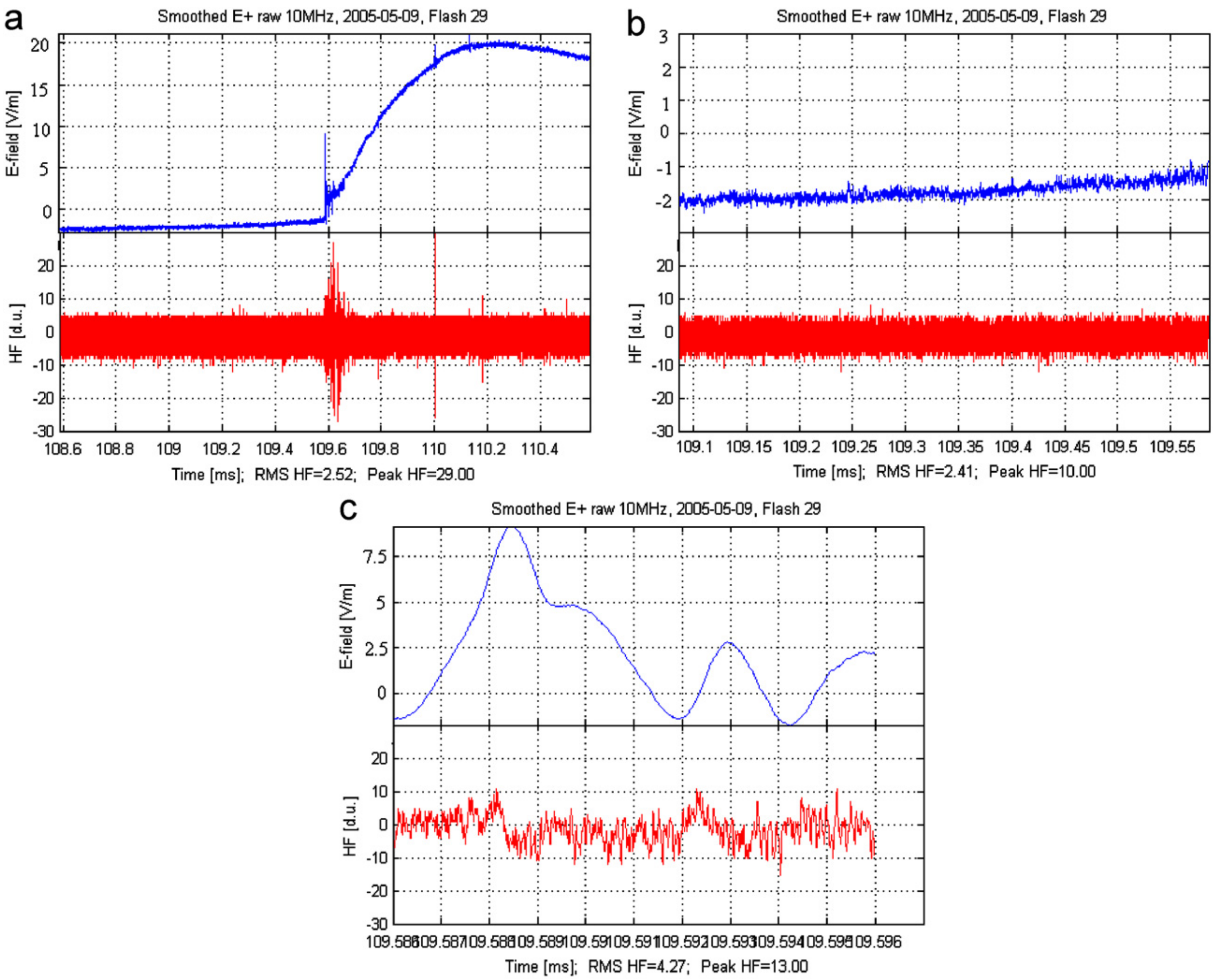


Fig. 6. Dart leader (Flash 27, stroke 4), (a) 2 ms sample, (b) leader stage, 500 μs sample and(c) return stroke, 10 μs sample.

definitions are likewise linearly related for a step function and a fixed sample length, and for these cases we can write

$$e_p \approx k\sigma, \quad (9)$$

with $k$ being a constant. This relation is not valid in general, but it is of interest to determine how large the error in fact is for specific lightning processes.

Defining the start of a leader phase can be arbitrary, especially when the baseline noise level is high. Although leader stages typically are considered to last up to tens of milliseconds (Lin et al., 1979), it was decided to use only the last 500 μs before the return stroke. This eliminates almost all contamination from nonleader processes, while still being a representative sample of the leader phase. When a chaotic structure was seen, only the chaotic segment was used. The chaotic part was almost always shorter than 500 μs, lasting more than the 500 μs in only 3 leaders; in these cases, the time was extended to capture the full chaotic signal.

### 2.1. Sample events

Flash 27 of May 9 is a representative flash from the data set, and is shown in Fig. 1. The individual return strokes in the flash (Figs. 3–6) show that multiple leader types are possible within a single flash. Three zoom levels of each stroke are shown: 1 ms before and after the return stroke (panel a), a blowup of the last 500 μs before the return stroke or the length of the chaotic component (panel b), and the 10 μs immediately after the return stroke (panel c).

Fig. 3 shows the first return stroke of Flash 27 (RS1). Leader steps are seen clearly at the end of the

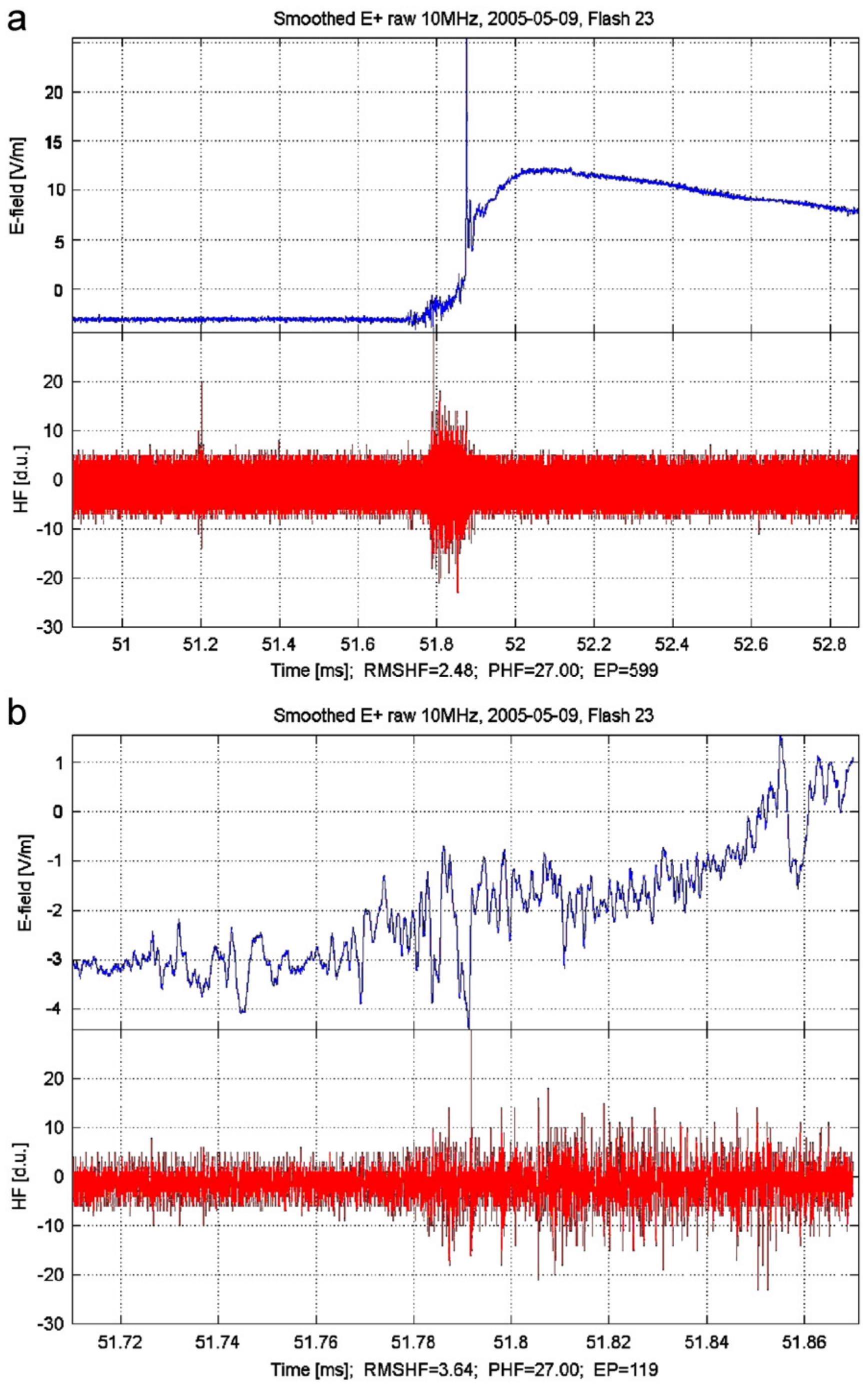


Fig. 7. Chaotic leader, (a) 2 ms sample and (b) chaotic leader stage, 160 μs sample.

leader sample. There is effectively no HF signal above the noise threshold. The return stroke creates an impulsive HF signal. The return stroke has peak value 25 V/m, close to the mean value of about 35 V/m in our data set. Fig. 4 shows the first subsequent stroke of Flash 27 (RS2), which has a chaotic leader lasting approximately 170 μs. The peak electric field of the return stroke is 5 V/m. The HF signal is strong and continuous. Fig. 5 shows the second subsequent stroke in Flash 27 (RS3).

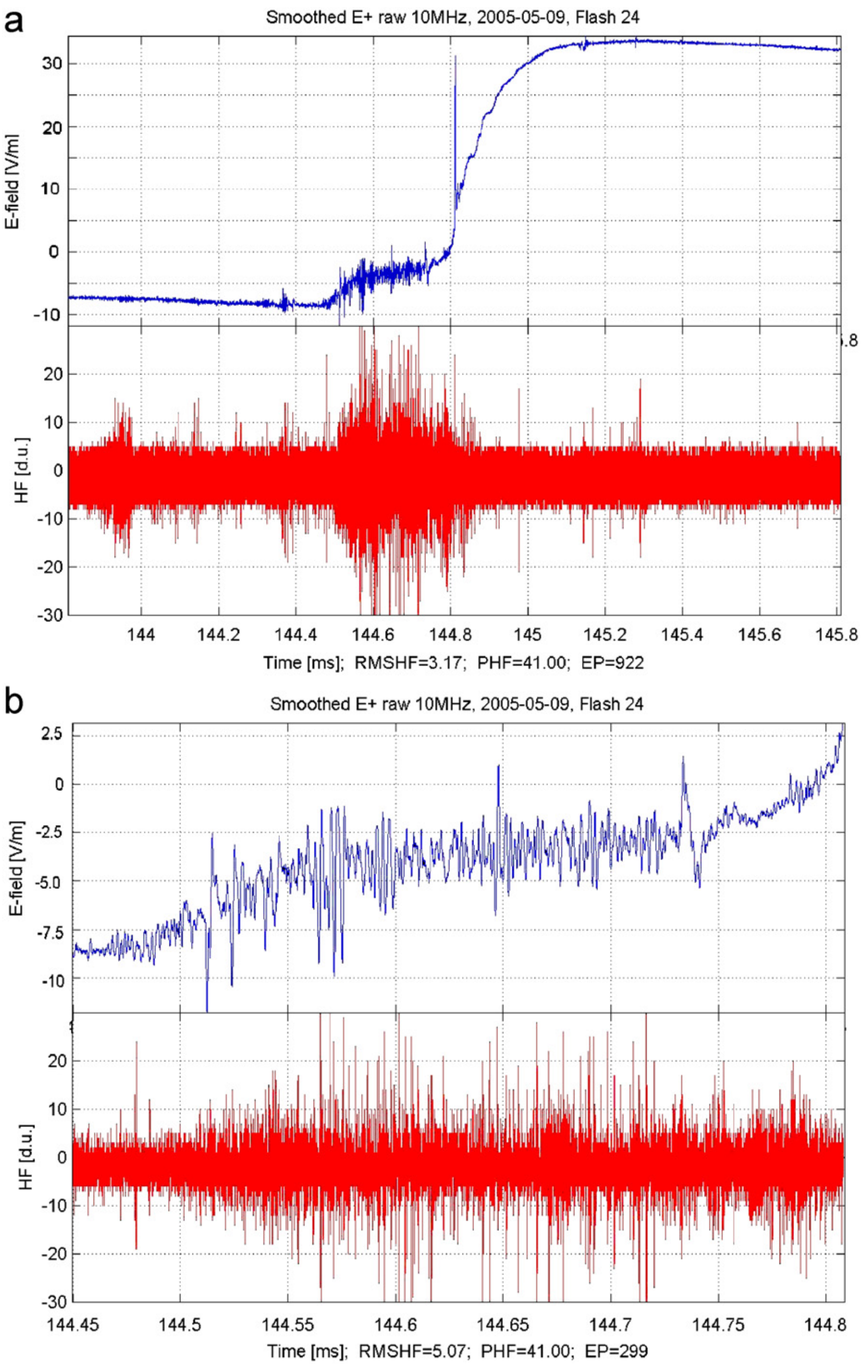


Fig. 8. Chaotic leader, (a) 2 ms sample and (b) chaotic leader stage, 360 μs sample.

There are at least two types of chaotic signals in the electric field (which lasts 390 μs): a slow variation with time scale about 40 μs, and a continuous oscillation with pulse width of about 1 μs. Fig. 6 shows the third subsequent stroke of Flash 27 (RS4). It has a "normal" dart-leader signature with no stepping and a very slow field rise. Figs. 7 and 8 show two additional strokes with chaotic leaders (from Flash 23 and Flash 24, respectively).

Since HF propagation depends strongly on distance, the results should in principle be normalized to a common distance. Usually, a distance of

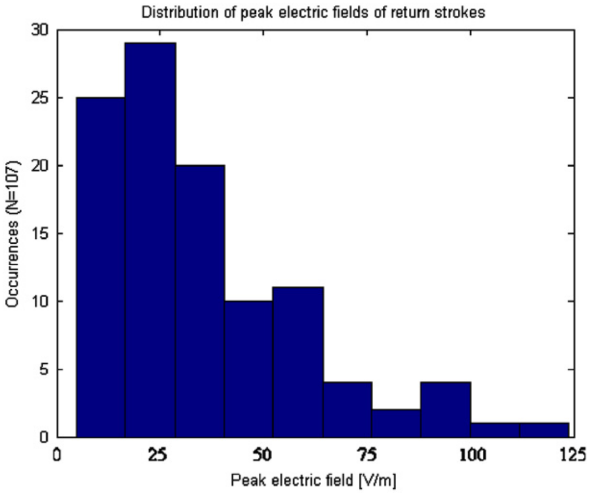


Fig. 9. Distribution of peak electric fields.

100 km is used. In this case, no accurate flash-by-flash ranging was available. Although exact thunder ranging was not successful, all flashes were within audible range, and came from medium-sized single-cell storms. In addition, Fig. 9 shows that the peak electric field value of the return strokes has a median value of 28 V/m, with the 25th and 75th percentiles at 180 and 50 V/m, respectively. Using the inverse relation between distance and the peak electric field change of the first return stroke, this gives distances between 1 and 7 km away from the observation point. Because the ocean is only 1 km away from the measurement point, some of the flashes occurred over the sea, but flash-by-flash direction estimates are not available. HFs attenuate more rapidly over land than over sea, which means that for distant flashes, propagation effects cannot be ignored. However, since the flashes are almost overhead in this data set, propagation has been assumed negligible.

The electric field and HF data were analyzed visually to identify leader types. The start of the return stroke was identified to the nearest microsecond. The 500 μs before that moment represent the leader phase, while the 5 μs after that moment are the return stroke. The stepped leaders associated with first return strokes were classified separately from subsequent stroke leaders. Within our data set, due mainly to the low resolution, no objective criterion could be established for separating dart leaders from dart-stepped leaders based on the broadband data. However, chaotic leaders formed a clear class of their own. For this reason, the "nonchaotic" dart and dart-stepped leaders were simply classed into one category. The classification between "chaotic" and "nonchaotic" was made visually. There is thus room for subjective errors, but such subjectivity has been acknowledged in all previous studies as well. In our case, the categories were very clear, with at most 5 subsequent leaders of 73 (6%) being ambiguous.

## 3. Results and discussion

The full broadband and HF data is available for 34 flashes with 74 subsequent strokes on May 8 and May 9. Table 1 shows the full statistics. In our data, more than 30% of the leaders contain a chaotic element; this is consistent with the 25% minimum occurrence probability observed by Gomes et al. (2004). The average duration of the chaotic component in our data was 290 μs (standard deviation 180 μs).

The HF intensity was calculated with both the peak and the RMS methods. The baseline noise level is rather high, due partly to noise characteristics of the DAQ card but also to a high ambient noise level. The ambient level varied somewhat between different days (the RMS intensity was 2.3 d.u. on May 8 and 1.1 d.u. on May 9) but stayed essentially constant during any single storm. The noise is negligible compared to the peak intensities, but the RMS energies have to be corrected by subtracting the baseline RMS noise. The peak HF value for each process was calculated as half of the peak-to-peak value of the largest excursion around the zero level. The mean and median values are shown in Table 2.

The simple metrics by themselves are not very informative, and the actual distributions must be analyzed to allow any physical conclusions to be drawn. The histogram of RMS intensities is shown in Fig. 10. Return strokes (panel a) exhibit roughly log-normal behavior with mean 3.47 d.u. Nonchaotic subsequent leaders (panel b) are very weak

Table 1
Occurrence probability of chaotic leaders

| | May 8 | May 9 |
|---|---|---|
| Flashes | 14 | 20 |
| Subsequent strokes | 18 | 56 |
| Chaotic leaders | 6 | 20 |
| % of leaders chaotic | 33 | 39 |

Table 2
Statistical values of HF intensities for lightning process

| | HF radiation intensity associated with lightning processes | | | |
|---|---|---|---|---|
| | Return stroke | First stepped leader | Nonchaotic subsequent leader | Chaotic subsequent leader |
| RMS method | | | | |
| Mean | 3.7 | 0.73 | 0.40 | 1.31 |
| Median | 2.8 | 0.37 | 0.18 | 1.20 |
| Peak method | | | | |
| Mean | 24.0 | 17.4 | 12.9 | 26.9 |
| Median | 19.5 | 14.0 | 11.3 | 25.8 |

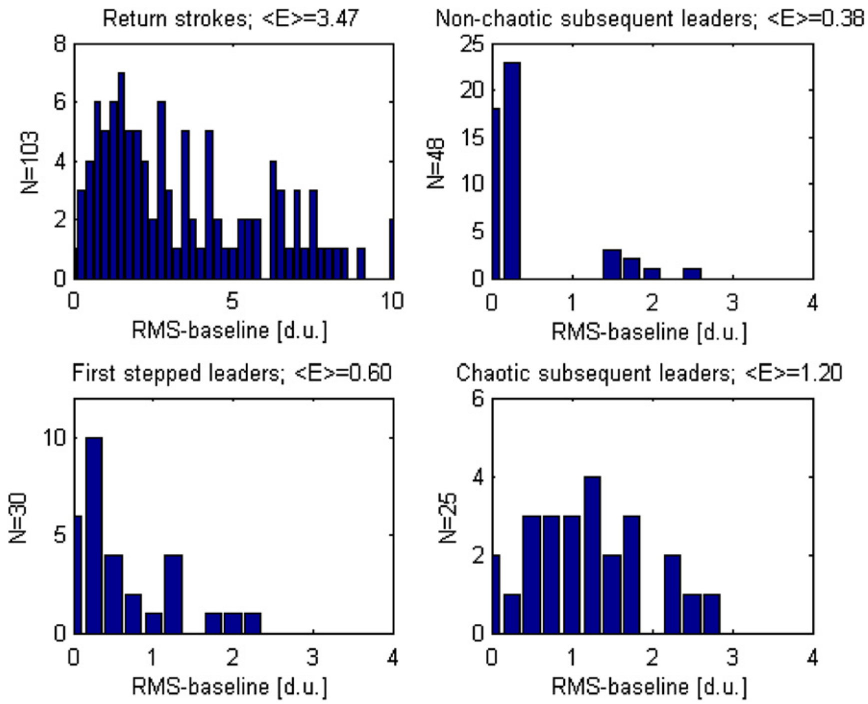


Fig. 10. Intensity distribution (RMS) for the four types of lightning process. Note the different scale of panel (a).

emitters. There are clearly two populations in panel b, with 41 leaders (85%) emitting essentially no HF above the noise threshold and 7 leaders (15%) emitting at a level of about 2 d.u. Those seven leaders are most likely to be dart-stepped leaders, but in the broadband data the populations are not distinct enough to make a classification. First stepped leaders (panel c) are weak emitters, with a mean signal above the noise threshold of 0.60 d.u. The distribution for chaotic leaders (panel d) is completely different, being approximately normally distributed about a mean of 1.20 d.u. The data are consistent with earlier studies which have observed leaders to be weak emitters for the most part; however, our new observed phenomenon is that a chaotic component in a subsequent leader significantly raises the HF level.

Using the peak HF value instead of the RMS energy (Fig. 11) results in slightly different distributions, but the main conclusions are still the same. The distributions for the return strokes, first stepped leaders, and nonchaotic subsequent leaders are approximately log-normal, but chaotic leaders (panel d) show an almost flat distribution. For a

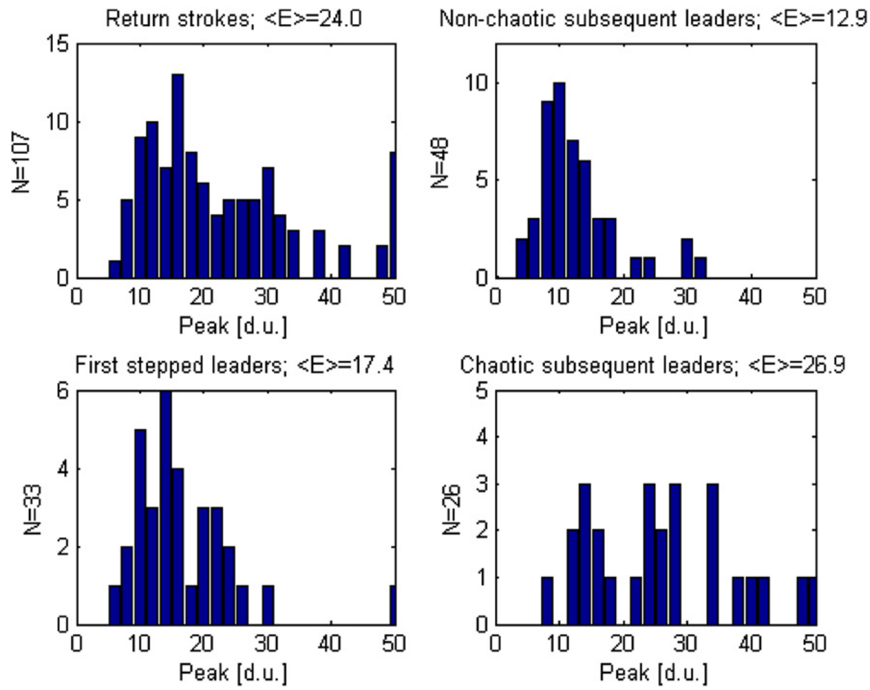


Fig. 11. Intensity distribution (PeakHF) for the four types of lightning process. Note the different scale of panel (a).

temporally extended signal like a leader, the physical interpretation of the highest peak value is ambiguous. However, if it could be shown to follow Eq. (9) even approximately, it could be used as a proxy for the more realistic RMS value. This is useful especially when the noise level is high and the RMS signal is problematic to interpret.

Therefore, to investigate the validity of Eq. (8), the RMS–peak ratio was calculated for each stroke separately and is shown in Fig. 12. If the equation were exactly valid, the plots would fall on straight lines passing through the origin. The data and least-squares fits are shown in Fig. 12, with outliers removed. The values are indeed significantly correlated at $p<0.05$: $r = 0.92$ for return strokes and $r = 0.83$ for first stepped leaders. The correlation of the chaotic subsequent strokes ($r = 0.61$) is also statistically significant. The nominal correlation for the nonchaotic subsequent leaders is 0.73, but this is an artifact due to the presence of two different populations, pure dart leaders ($N = 41$) and dart-stepped leaders ($N = 7$).

In the case of the return stroke, Eq. (9) indeed appears to be validated. It is also a reasonable approximation for first stepped leaders. Thus, the peak time domain value and RMS energy value can be used interchangeably for these two processes. However, for subsequent leaders the simple relationship is violated.

This has some implications for the interpretation of previous studies and for future studies. For a return stroke, which is a single impulsive event, there is no ambiguity in defining HF intensity. However, for leader processes, it is crucial to ensure that a time window has been chosen that represents the process in question. We suggest that some of the difficulties in interpreting HF data in the past are due to this ambiguity. In particular, for very weak events the peak HF and RMS methods can give contradictory results. In the frequency domain, this means that the ESD and PSD are no longer related by a simple linear relationship.

The physical mechanism behind the chaotic leaders cannot be determined based on this data set alone; however, we can at least rule out the possibility that they are preliminary breakdown events. The preliminary variations have time scales of tens of milliseconds (Beasley et al., 1982), and limiting the data set to the last 500 μs makes contamination from these processes very unlikely. Some of the chaotic leaders may contain previously identified impulsive processes such as the bipolar pulses described by Willett et al. (1989); see for example the leader of Fig. 7. We conclude that

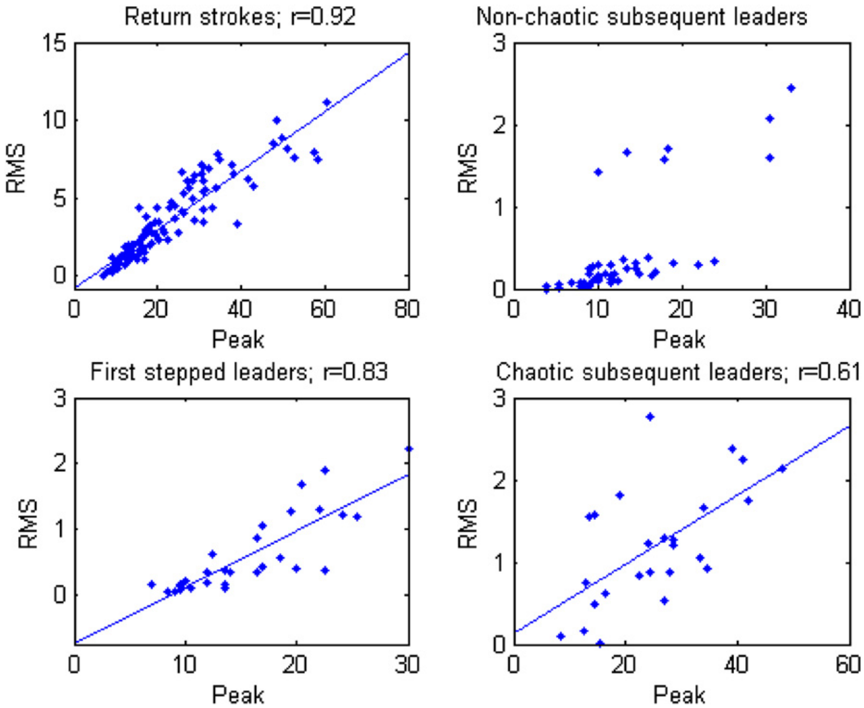


Fig. 12. Correlations of peak and RMS methods for the four identified lightning processes. Note that before the correlations were calculated, outliers were removed: two from the return stroke panel, one from the first stepped leader panel, and one from the chaotic subsequent leader panel. No best-fit line has been drawn for nonchaotic subsequent leaders because the data are not modeled well by a single linear fit.

preliminary breakdowns are definitively ruled out. Our data are not consistent with the hypothesis of a continuum of "chaotic" behavior, as seen in the distribution data of Figs. 10 and 11; rather, a given leader either is chaotic or it is not. However, we must leave open whether we are observing a physically distinct process as implied by Gomes et al. (2004), or a combination of known processes.

Our observations, together with those of Gomes et al. (2004), suggest that chaotic leaders may be a ubiquitous feature of lightning subsequent strokes. If so, the question arises why they are mentioned only sporadically in the literature. A possible explanation is that as with breakdown pulses, there are geographical differences, most of the more extensive leader studies having been done at higher latitudes than of Sri Lanka. No significant differences were however found between Scandinavia and Sri Lanka by Gomes et al. (2004). Another possible reason is that random processes tend to disappear when "composite" or "average" analyses are made. Also, we cannot rule out the possibility that the effect would be much weaker in more distant flashes; as our measurements are all close to the near-field regime.

## 4. Conclusions

We have studied 34 ground flashes in Sri Lanka with a total of 74 subsequent strokes. We identified a "chaotic" component in more than 30% of all leader processes associated with subsequent strokes. The analysis was restricted to the last 500 μs before the return stroke, and thus the phenomenon is definitively associated with the leader process. The average duration of a chaotic component is about 300 μs, and almost never more than 500 μs. The intensities of the HF signals were calculated by two different methods, using the peak voltage in the HF signal (valid for impulsive processes) and also the RMS voltage of the signal (valid for continuous processes). The methods give slightly different results, implying that the definition of "HF intensity" is not completely clear-cut. However, at least for close flashes, return strokes are the most intensive HF emitters. Dart leaders associated with subsequent strokes are very weak emitters, regardless of the intensity metric that is used. The HF activity rises somewhat when the dart leader also exhibits stepping behavior. However, whenever a "chaotic" component is present in a subsequent leader, the HF intensity increases dramatically. The overall RMS energy is only a moderately increased, but individual peaks in the HF time domain signal can be as strong as those associated with return strokes. Although the subsequent leaders and chaotic behavior occur simultaneously in our observations, there is no reason to assume that the leader as such emits the radiation. The chaotic behavior is more properly interpreted as part of the in-cloud charge re-distribution which leads to the formation of a subsequent leader.

Our result suggests that it is necessary to re-evaluate the importance of "chaotic" processes. These processes have been mentioned almost anecdotally in the literature, and there is no generally accepted way to define them. However, our results as well as those of Gomes et al. (2004) suggest that such chaotic leaders may be rather common at least in tropical lightning. Any accurate mathematical analysis is made difficult by the fact that chaotic leaders have both impulsive and continuous characteristics. We propose that for quantifying the intensity of HF emissions from chaotic lightning processes, the RMS value will be more physically meaningful than the more traditionally used peak HF value; or, when working in the frequency domain, it is the power spectral density (PSD) that should be used to characterize all subsequent leader processes rather than the energy spectral density (ESD).

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