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Properties of preliminary breakdown processes in Scandinavian lightning

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ABSTRACT

Lightning flashes are usually preceded by preliminary breakdown processes (PBPs) before a stepped leader is initiated. These breakdown processes are not well understood. An early model, the so-called BIL model, has been called into question in later studies. However, we have found that the BIL model is quite successful in describing initial processes at least in high-latitude Scandinavian lightning. We present results from one summer of measurements in Finland, during which the vertical electric field was measured with a standard broadband plate antenna system. Lightning flash locations were provided by a lightning detection network and magnetic fields were measured with an experimental narrowband detection system. The relationship between the preliminary breakdown and the first return stroke (RS) is studied for 193 flashes at distances of 5–70 km. We can identify a preliminary breakdown in at least 90% of the flashes. The peak electric field of the RS is on average four times as intensive as the highest peak of the PBP. However, in 25% of the cases the PBP peak is more intensive. On the other hand, we show that this method of comparing intensities is physically arbitrary, since the PBP is continuous and the RS is impulsive. The narrowband measurement allows a physically consistent definition for intensities as the root-mean-square (RMS) sum of the most intense parts of signals. The PBP and RS are shown to have almost equal intensities at small distances. At larger distances, the PBP weakens more rapidly. This is suggested to be due to different propagation regimes, with the PBP signal changing from space-wave to ground-wave propagation with increasing distance, while the RS is predominantly ground wave at all distances. The result may have practical applications in narrowband detection of lightning. The BIL model suggests a characteristic signal in the narrowband signal, which could be used to identify the start of a lightning flash. The change in the RS–PBP ratio as a function of distance is statistically significant, but is too weak to significantly improve ranging methods.

1. Introduction

Cloud-to-ground lightning is initiated by processes within clouds that involve changes in the field configuration, which lead to streamers, then to leaders, and finally to the return stroke (RS). The earliest and simplest description of the processes is the so-called BIL model defined by Clarence and Malan (1957) for South African lightning. In this model, flash processes are initiated

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by an initial breakdown (B, lasting some milliseconds), which radiates intense electromagnetic radiation. This is followed by a quiet intermediate stage with little associated radiation (I, lasting up to several hundred milliseconds), ending with the onset of stepped leaders (L, lasting a few milliseconds at the most), which again radiate more intensively. The stepped leader stage finally ends at the very intensive RS. In this earliest model, the breakdown was assumed to consist primarily of a vertical discharge between a main negative charge center and a lower positive one. Later studies have shown that the breakdown process can have significant horizontal extent (Krehbiel et al., 1979; Rhodes and Krehbiel, 1989). There is some dispute about whether the breakdown is a unique process or more appropriately to be considered just the beginning of a leader phase. The latter interpretation is supported by the VHF measurements of Proctor et al. (1988), but overall there tends to be more evidence in favour of a unique process (Rustan et al., 1980; Rhodes and Krehbiel, 1989; Mazur et al., 1997).

Although the BIL model is useful as a general description, detailed observations of the breakdown process show considerable variations from study to study, and the terminology is not completely standardized. Beasley et al. (1982) admit that they are "unable to discern any particular significance in the variety of shapes, sizes, and durations of preliminary variations" in their Florida data set; the situation has not significantly changed in the subsequent decades. Trains of relatively large bipolar pulses have been observed in Florida summer lightning by Beasley et al. (1982), in Swedish summer lightning (Gomes et al., 1998; Cooray and Pérez, 1994), in Florida summer lightning (Weidman and Krider, 1979), and in Japan (Ogawa, 1993). Breakdown pulses preceding positive lightning flashes have been observed by Ushio et al. (1998) in Japan and Gomes and Cooray (2004) in Sweden. There are very few measurements in equatorial regions, since even Florida is as far north as 28° latitude. Measurements in Sri Lanka (6° North latitude) by Gomes et al. (1998) suggested that the pulses are much weaker in equatorial lightning, and are in fact not even observed in the majority of flashes. If the measured preliminary breakdown process (PBP) intensity is further affected by the storm type or storm stage (Clarence and Malan, 1957), as well as effects such as the geometry of channels (Rakov and Uman, 2003), it is clear that far larger data sets from around the world are needed if the breakdown process is to be understood better.

One possible way to collect very large data sets is via narrowband measurements using receivers built on principles similar to AM radio, since the needed devices are small and easily portable (Mäkelä et al., 2008a, b). On the other hand, it is well known that the amount of information that can be extracted from a narrowband signal is quite limited, since the method fundamentally measures composites of multiple in-cloud processes (Le Vine, 1987; Nanevicz et al., 1987). In fact, Krider et al. (1996) observed no significant correlation between the electric-field RF spectral density near 5 MHz (bandwidth 0.91 MHz) and the peak electric field. This implies that narrowband measurements may not be directly comparable to wideband measurements at all. On the other hand, Mäkelä et al., 2008a show that the full-flash intensity near 1 MHz is statistically inversely correlated to distance, and can be used for distance estimates. Narrowband measurements therefore have scientific value as long as their limitations are understood. We have used the devices of Mäkelä et al. (2008a) to study Scandinavian preliminary breakdowns together with well-established reference measurements. The reference device (a wideband electric-field measurement) is used to extend an earlier study by Gomes et al. (1998). In that study no distance estimate was available. We analyze the ratio between the PBP and RS peak values in the electric field, and find the same phenomena as the earlier study: the RS is on average significantly stronger than the PBP, but in about 25% of the cases the PBP is more intensive. The ratio does not vary with distance. On the other hand, we show that comparing peak electric fields is a physically arbitrary way to compare the intensities of the two different types of processes. The narrowband system allows a physically more consistent comparison, and the results are somewhat different. The breakdown has an average intensity that is close to the RS intensity. There is also a weak but statistically significant distance dependence, with the PBP weakening more rapidly than the RS. This supports the calculations of Cooray (2007) regarding differential propagation of in-cloud processes (the PBP) and cloud-to-ground processes (the RS).

Our study, then, consists of two interrelated parts: a wideband electric-field measurement that extends the research done by Gomes et al. (1998) using essentially identical devices, and a narrowband magnetic-field measurement of the same phenomena using devices described in Mäkelä et al. (2008a). In Section 2, we describe our measurement system. For practical reasons, the measurements are not direct readouts of the signal at the measurement frequency, but have been downmixed to be compatible with ordinary audio processing. We analyze in detail what the effect is on the system response. In Section 3, we present measurement results from 193 flashes for which the breakdown–RS sequence could be identified from the wideband electric-field data, and for which exact location data were available. In particular, we compare our data set with that of Gomes et al. (1998), and show that while the conclusions in that study appear valid for the vertical electric field, the horizontal magnetic field behaves differently. The relevance of the results for understanding propagation effects is discussed in Section 4. For practical applications, it is shown that the systematic signature does not enable ranging estimates to be improved, but can provide a pattern from which the identification of narrowband signals as CG flashes can be improved. Final conclusions are drawn in Section 5.

2. System description and measurements

The measurement system is described in detail by Mäkelä et al. (2008a). The measurements were performed over the summer of 2006. Two identical stations were used, located in Piikkiö and Jokioinen, Finland (separated by 80 km). The broadband electric field was measured with a parallel-plate antenna of diameter 50 cm and plate separation of 30 mm, attached to a buffer amplifier designed at the University of Uppsala and identical to that described in Cooray (1986). The system has a zero-to-peak rise time of 0.2 μs and a decay time constant of 20 ms. The antenna was attached to a four-channel Agilent oscilloscope with 128 Msamples of memory, operated at 100 Msamples/s. The system also included two narrowband receivers made by attaching inductors to the plate antennas, resulting in resonances at 1 and 20 MHz. However, since there was no gain in the resonators, the signal-to-noise ratio was too low above about 30 km, and the data were not used in this study. The broadband signal was split into two channels (at 100 mV/division and 2 V/division) to achieve maximum dynamic range. The length of a recorded signal was thus 320 ms. The oscilloscopes were set to operate semi-automatically, triggering on any signal that exceeded a preset trigger level. The captured records were stored on a PC, resulting in a dead time of several minutes between triggers. A broadband trigger also sent a trigger to the narrowband magnetic system, which means that every broadband record is matched with a narrowband record. The system was GPS synchronized to UTC time with millisecond accuracy. Lightning location data were provided by the NORDLIS network (Tuomi, 2003).

The narrowband device is effectively an AM radio (Fig. 1). The antenna resonates at a central frequency f_c, while the mixer (local oscillator) is preset to be within 10 kHz of f_c. The signal at the antenna response frequency is $\exp(i\omega_c t)$, which is then multiplied by the mixer signal $\exp(i\omega_{LO} t)$, giving

$$s(t) = \exp[i(\omega_c \pm \omega_{LO})t]. \tag{1}$$

The higher frequency is then filtered with a low-pass filter, and the resultant signal is digitized at a sampling frequency of 44.1 kHz. In other words, the resulting signal is an audio signal, and the data were processed and stored through an audio interface. A software was written that followed the baseline noise level, and stored the signal in 1-s clips whenever any peak exceeded a pre-defined threshold of 6 dB above the baseline noise. This system enabled the data collection to be automated. In Mäkelä et al. (2008a), the effect of mixer stage was not considered in detail since the full-flash energy was used. However, for close-up studies it is crucial to consider its effect. Because the antenna response and mixer are not necessarily in phase, Eq. (1) in fact includes an unknown phase difference φ, and the equation is

$$\exp[i((\omega_c \pm \omega_{LO})t + \varphi)]. \tag{2}$$

Although the phase difference can be ignored in ideal conditions, it introduces a randomizing effect when the input signal has a finite length and is then digitized. Mäkelä et al. (2007) suggested that when measuring the energy of the signal, the root-mean-square (RMS) sum should be used in place of the simple integral. This is seen to be particularly true when the mixer is present. For a single pulse of magnitude x, multiplying x by a random $\sin(\varphi)$ and taking the absolute value gives expectation and RMS expectation:

$$\langle x\rangle = \frac{1}{\pi/2}\int_0^{\pi/2} |x\,sin(\phi)|\,d\phi = \frac{2}{\pi}x,$$
$$\langle x^2\rangle = \frac{1}{\pi/2}\int_0^{\pi/2} x^2\sin^2(\phi)\,d\phi = \frac{1}{2}x^2. \tag{3}$$

In the general case, the signal consists of a series of pulses that are each multiplied separately by a random uncorrelated phase signal, $S_i = x_i \sin(\phi_i)$. This is analytically solvable in the case of a rectangle function of height x and large length N:

$$\langle S\rangle = \sum |x\,\sin(\phi_i)| = \frac{2}{\pi}Nx, \quad \frac{\langle S\rangle}{Nx} = \frac{2}{\pi} \approx 0.637, \tag{4}$$

$$\langle\sqrt{S^2}\rangle = \sqrt{\sum x^2\sin^2(\phi_i)} = x\sqrt{\frac{N}{2}}, \quad \frac{\langle S_{RMS}\rangle}{x\sqrt{N}} = \frac{1}{\sqrt{2}} \approx 0.707. \tag{5}$$

In the case of constant and very long signal, both the sum and the RMS sum are proportional to the unmixed signal multiplied by a constant. In such a case, it makes little difference which is used to characterize the signal energy. However, a simulation shows that the RMS is

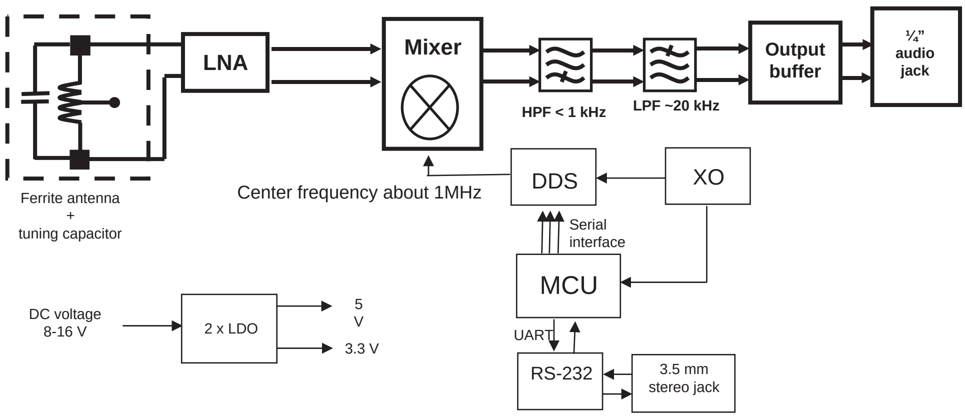

Fig. 1. Schematic of the measurement device.

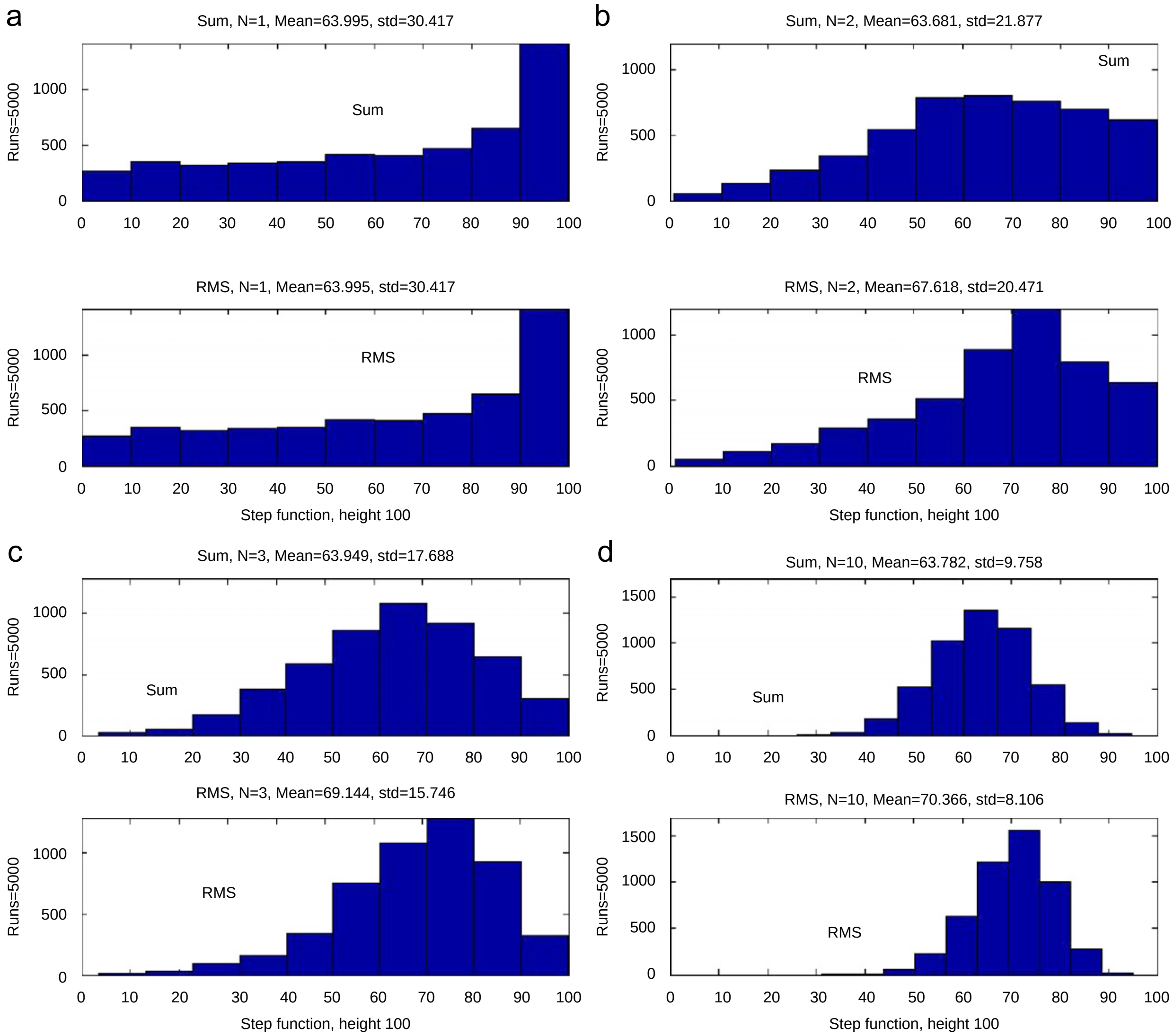

Fig. 2. Effect of mixer.

preferable for short signals. For a single peak, the sum and RMS are of course the same. The distribution is quite flat, so that the effect of randomization is severe (Fig. 2a). However, the value is still likeliest to be near the original input value. For a step with width 2 or 3 (Figs. 2b, c), the RMS becomes more strongly peaked, since the maximum values are weighted more. As the length of the signal grows, the values tend to the constant values defined above (Fig. 2d). Therefore, when very short signals such as the RS are to be compared with long signals like the breakdown, a mixer requires that the RMS value be used.

3. Results

This study analyzes only preliminary breakdowns associated with cloud-to-ground flashes. Since the data collection was automated, a majority of the 4000 captured broadband signals were IC flashes. Although PBP-like structures could be seen in the start of at least some IC events, these have not been analyzed further because there is no ground truth to enable ranging.

The total number of narrowband flashes captured was 430,000, a majority being IC flashes (and no more than 5% man-made interference). Using just the location data, a total of about 10,000 narrowband records could be correlated with a CG flash within 100 km of one of the sites. Due to the long dead time (2–4 min) of the electric-field system, and occasional synchronization problems, the final usable data set consisted of about 200 ground flashes. It was found that over 90% of these flashes had an identifiable preliminary breakdown before the RS, consistent with the observation of Gomes et al. (1998) for Scandinavian lightning. The final quality-controlled data set consisted of 193 CG flashes within 70 km of one of the sites. The number of very close flashes is small because only a few storms passed directly overhead the sites during the summer. Also, in very close flashes the PBP and

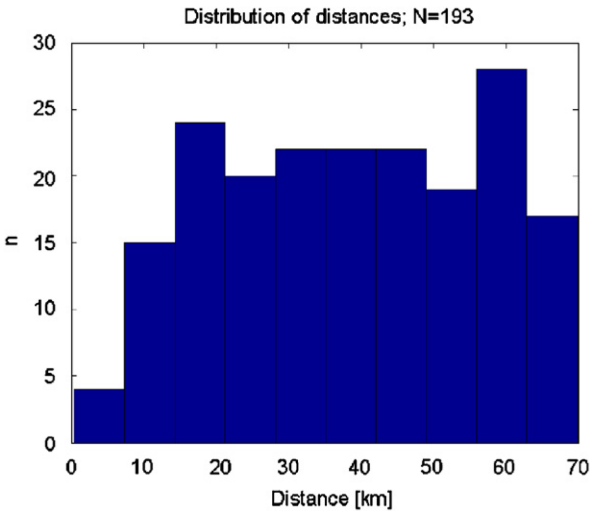

Fig. 3. Distribution of distances in the data set.

RS identification was made difficult by oscilloscope saturation and large electrostatic variations. Very close flashes are thus underrepresented (Fig. 3).

Three different data sources were used in this study:

(a) the vertical electric-field data,
(b) the narrowband magnetic-field data, and
(c) the flash location and times, as given by the NORDLIS network.

Representative data samples from three different distance ranges are shown in Figs. 4–6. The electric-field plots show the distance and stroke intensity given by the NORDLIS system, as well as the peak electric field of the RS. The B, I, and L processes have been noted in the figures. In most cases, the leaders have low peak values and are not seen clearly in the broadband records at this zoom level. The electric-field peaks are approximately consistent with the NORDLIS distances and intensities except for Flash 4c, whose electric field suggests a more distant flash.

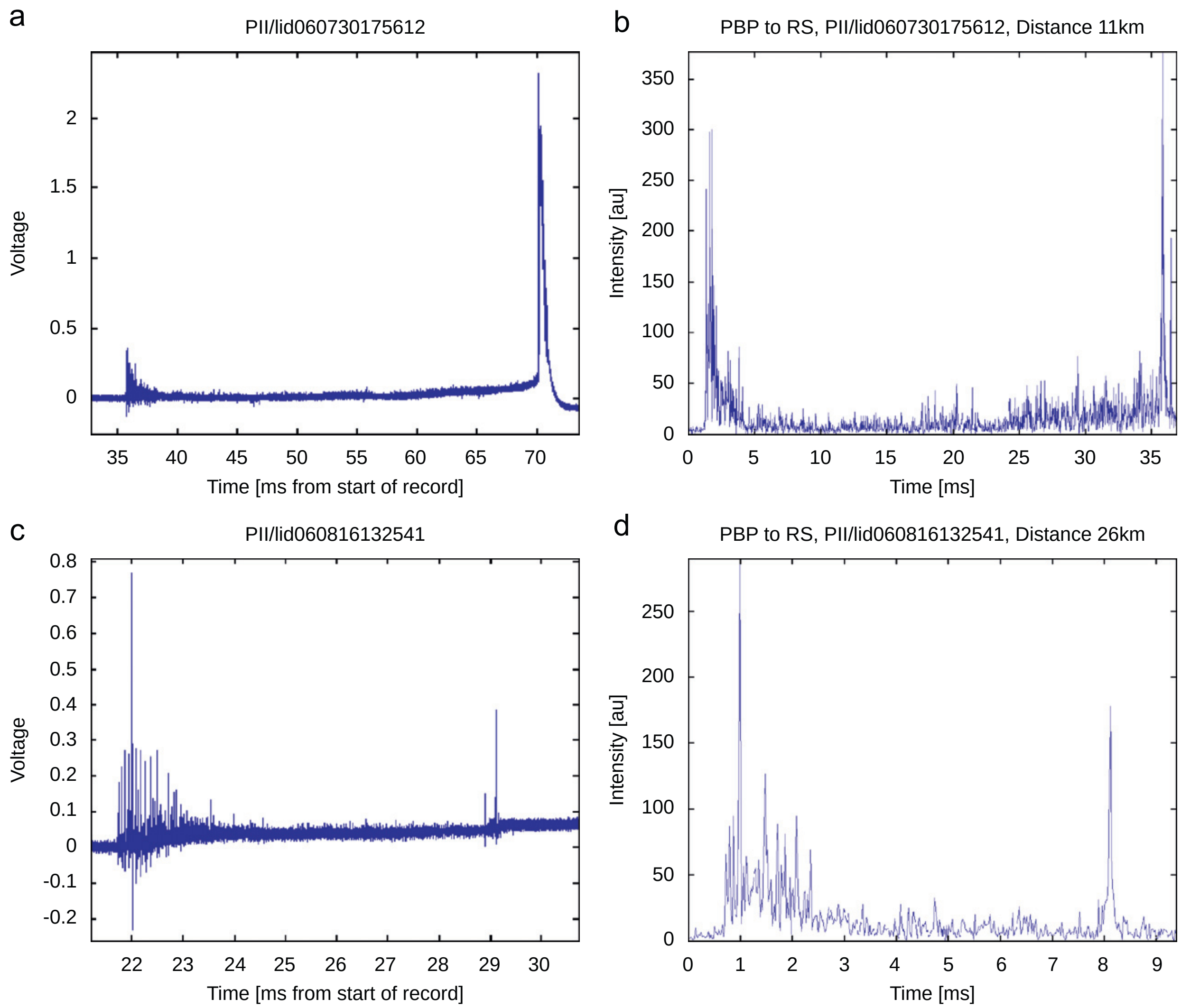

Fig. 4. Breakdown–RS sequence, for two flashes with distance to flash below 30 km. Vertical electric fields are shown in the top row; the corresponding narrowband magnetic fields are shown in the bottom row.

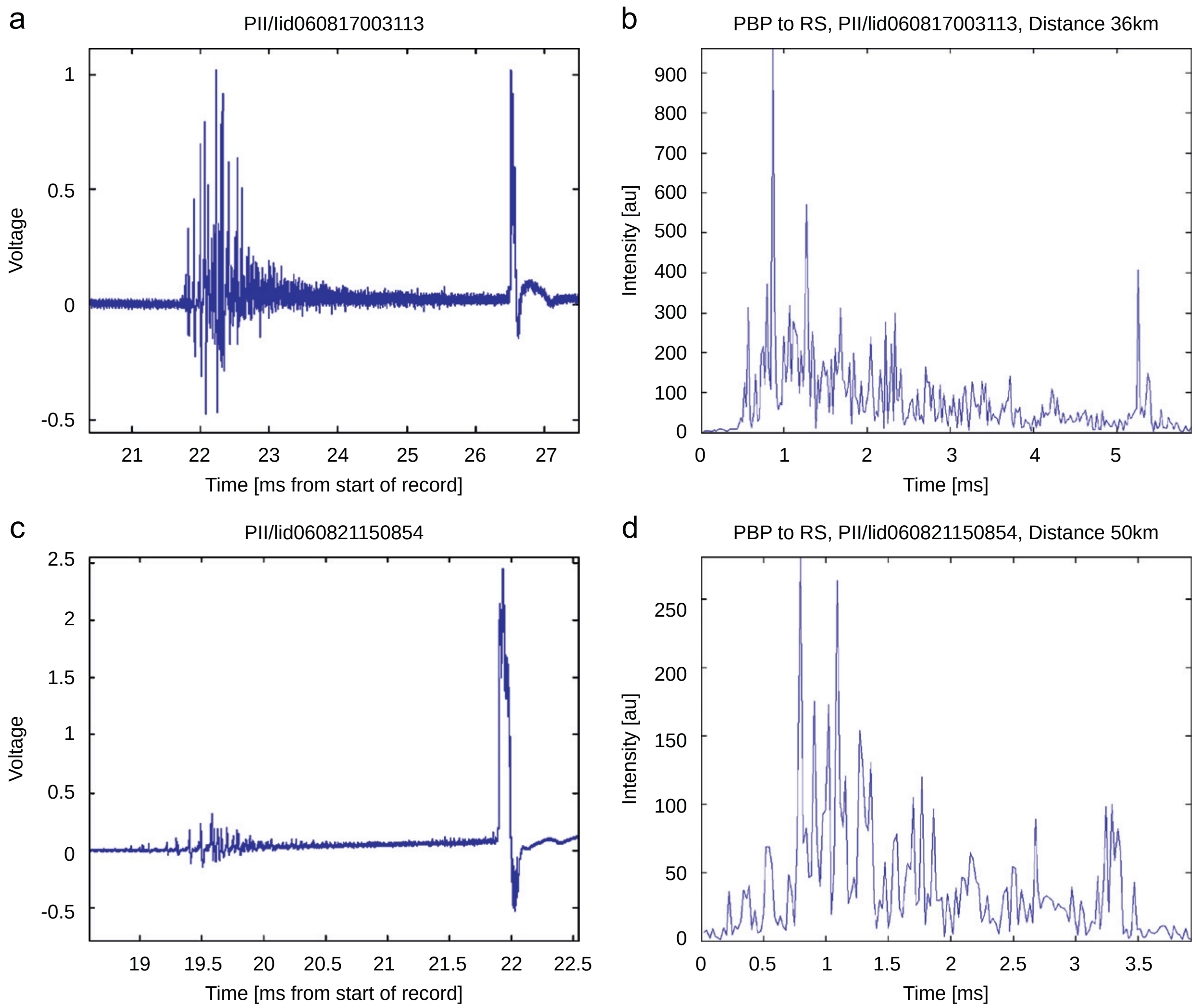

Fig. 5. Breakdown–RS sequences, distance to flash 30–50 km.

However, the NORDLIS distances have been considered as the ground truth in this study. The raw electric field provides the most exact timing and intensity for the first RS. On the other hand, due to the high noise level the start, and especially the end of the PBP, is often impossible to determine visually. The narrowband data, on the other hand, provide the most accurate possibility to time the start of the PBP, with the start of the PBP always showing up as a strong peak not apparent in the electric-field data. This is clearly seen in Figs. 4–6, and is partly due to the instrumentation, since the downsampling and low A/D conversion rate effectively integrate multiple peaks. Such integration however occurs in any narrowband system, since the response is an integral over multiple small-scale processes as noted by Nanevicz et al. (1987). This effect also means that the narrowband system is not capable of measuring the energy of the leader process as such, but rather the combination of the leader and RS processes (in which the RS is likely to be dominant). The exact duration of the PBP–RS process can be best measured by estimating the start of the PBP from the narrowband data, and the RS from the electric-field data. This duration physically corresponds to the amount of time between the RS and the very first in-cloud processes, which are capable of radiating in the HF range, and it can be defined with high accuracy (Fig. 7). The earlier practice (e.g. Gomes et al., 1998) has been to estimate the PBP timing and intensity from the most intensive pulse in the PBP train. The results (not shown) are not dramatically different, although the peak-to-peak method gives slightly smaller time durations, as can be expected since the highest peak is often not the first one in the PBP train.

Although the peak-to-peak method provides an exact numerical value for the PBP–RS ratio, it is not clear what the physical implication of such a number is. Since the PBP has a long duration and is effectively a continuous process, choosing just one of the pulses to represent the PBP is arbitrary. A similar problem was addressed by Mäkelä et al. (2007), where the problem was to compare continuous chaotic leader signals to impulsive RS signals. The solution in that case was to calculate the RMS sum of narrowband electric field from the chaotic leader (in effect

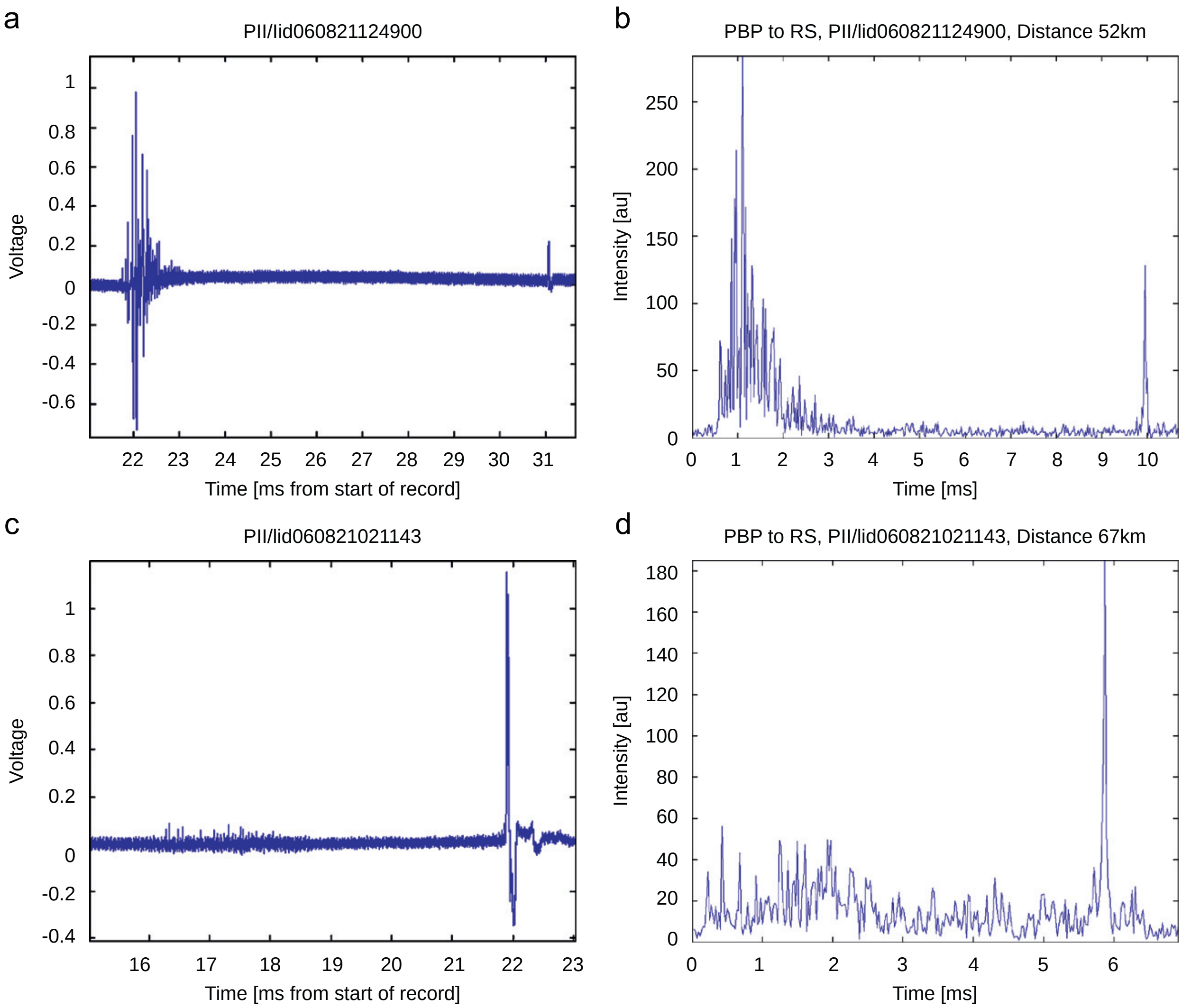

Fig. 6. Breakdown–RS sequences, distance to flash above 50 km.

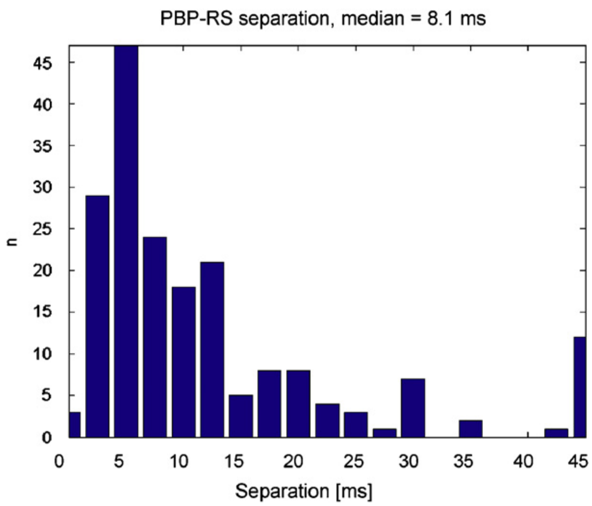

Fig. 7. PBP–RS duration measured from the start of narrowband PBP signal to moment of RS.

the power spectral density) and compare it to the narrowband intensity at the moment of the RS (in effect the energy spectral density). In that study, the problem of comparing two physically different parameters was justified by considering the ratio to be empirical. However, as shown in Section 2, there is in principle no dimensional mismatch, since the ''RMS sum'' of a single peak is equal to the peak itself. On the other hand, the case in Mäkelä et al. (2007) was simpler, since both the start and end of a chaotic leader could be determined with high accuracy. The start of the PBP can be defined from the narrowband signal. However, there is no physically unambiguous way to determine the end of the PBP. In all observed cases, the baseline noise level between the PBP and the RS was larger than before the PBP (apparent in Figs. 4–6). However, the noise level could fluctuate considerably within the I phase. In many cases such as in Figs. 4a, b the drop is rapid and the intermediate phase is almost flat immediately after the PBP, and thus the PBP length estimate is robust. Often, however, the data resemble

Figs. 5c, d and 6c, d in which case some type of intermediate stage is definitely implied, but it blurs into the PBP and in some cases the RS. The estimated PBP durations are shown in Fig. 8. These numbers are only approximate, but the median value of 4.3 ms is the most robust measure. To minimize the amount of subjectivity, the RMS sum was taken not for the entire identified PBP, but for the 10 largest peaks within the range thus identified. This is a physically justified choice, since it represents the most intensive parts of the PBP, and is not affected by errors in defining the length of the PBP. For a typical PBP duration of 2 ms, the number of samples is close to 100, and thus 10 samples represent the most intensive 10% of the PBP. Although the exact number of samples chosen is arbitrary, the results did not change when the number was varied between approximately 5 and 20.

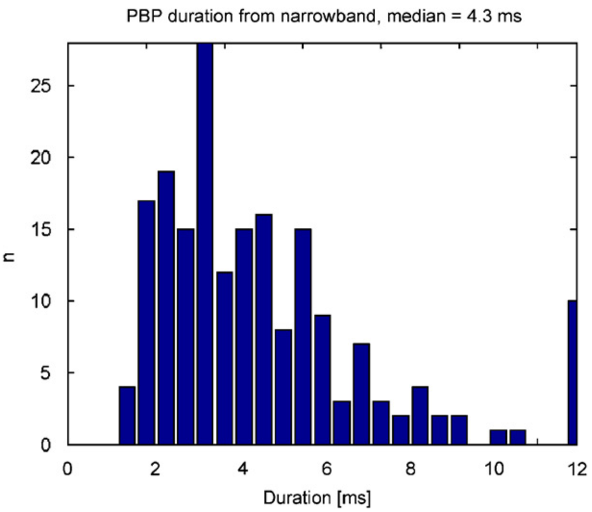

Fig. 8. PBP duration measured from the narrowband data. PBP is defined to start from the moment the intensity rises abruptly, and end when the narrowband intensity drops to the constant level in the intermediate phase. Because the end of the PBP is often poorly defined, the results should be considered approximate.

The calculation of RS intensity is complicated in our system by downmixing and low sampling rate, as any individual peak is not faithfully reproduced (Fig. 2). However, in the HF range the RS is not seen as a single impulse, but rather as intense radiation with a duration of tens to hundreds of μs (Cooray and Pérez, 1994). Given the 22 μs sample interval of our system, the RS will be seen as a continuous process that lasts for several samples. This is clearly seen in Figs. 4–6. To achieve consistency with the energy defined for the PBP, we have therefore defined the RS energy to be the RMS of the three highest values in the RS interval.

Given these caveats, it is necessary to use care in comparing the results with earlier literature. Nevertheless, the most important comparisons are shown in Table 1. On the basis of the available information, it is clear that all the parameter distributions are far from Gaussian, and therefore the exact values are at best indicative. Our measurements are compatible with the earlier measurements at least at non-equatorial latitudes; the results of Gomes et al. (1998) for Sri Lanka appear different, as is suggested by those authors. In Fig. 9, our intensity values are compared with those of Gomes et al. (1998) for Sweden; our broadband measurement system was essentially identical to that of their study. The distributions measured for the electric field are very similar.

Going beyond the statistics of Gomes et al. (1998), with our larger data set the RS–PBP intensity ratio can be plotted as a function of distance. Fig. 10 shows the ratio of the RS peak to the highest PBP peak as a function of distance. No distance effect at all is observed; such a lack of distance effect was also suggested by Gomes et al. (1998). The peak electric field emitted by the RS is stronger than the peak of the PBP by a factor of 4. However, the narrowband magnetic field behaves quite differently (Fig. 11). At short distances, the PBP and RS have more or less identical energies. As the distance grows, the PBP signal attenuates faster than the RS signal. The correlation of the ratio with distance is 0.35, which is weak, but is statistically significant at the 1% level. This empirical result is consistent with the propagation effect

Table 1
Comparison with earlier studies

	Location	*N*[a]	Mean	BP/RS ratio			Separation (ms)	
				G. mean	Range	Mean (std.)	G. Mean	Range (90th percentile)
G98	Sri Lanka	9	0.16	0.15	0.06–0.26	11.9	9.8	3–23 ($\sim$20)[b]
B82	Florida	80				118 (66)		11–500 (NA)
U98	Japan	19				12		1–38 (NA)
G98	Sweden	41	1.01	0.49	0.08–6.71	13.8	8.7	2–70 ($\sim$40)[b]
G04	Sweden	57[c]				56 (48)		NA ($\sim$100)[b]
M08	Finland	193	0.61	0.25	1–6.1	18 (9)	38.5	2–320 (31)
M08[d]	Finland	193	1.24	0.96	0.05–5.30	18 (9)	38.5	2–320 (31)

B (Beasley et al., 1982), G1 (Gomes et al., 1998), G2 (Gomes and Cooray, 2004), U (Ushio et al., 1998), M08 (this study). All studies except the last one measured vertical electric field.

[a] Number of flashes in sample.
[b] Estimated from figures.
[c] Positive flashes.
[d] Narrowband magnetic field.

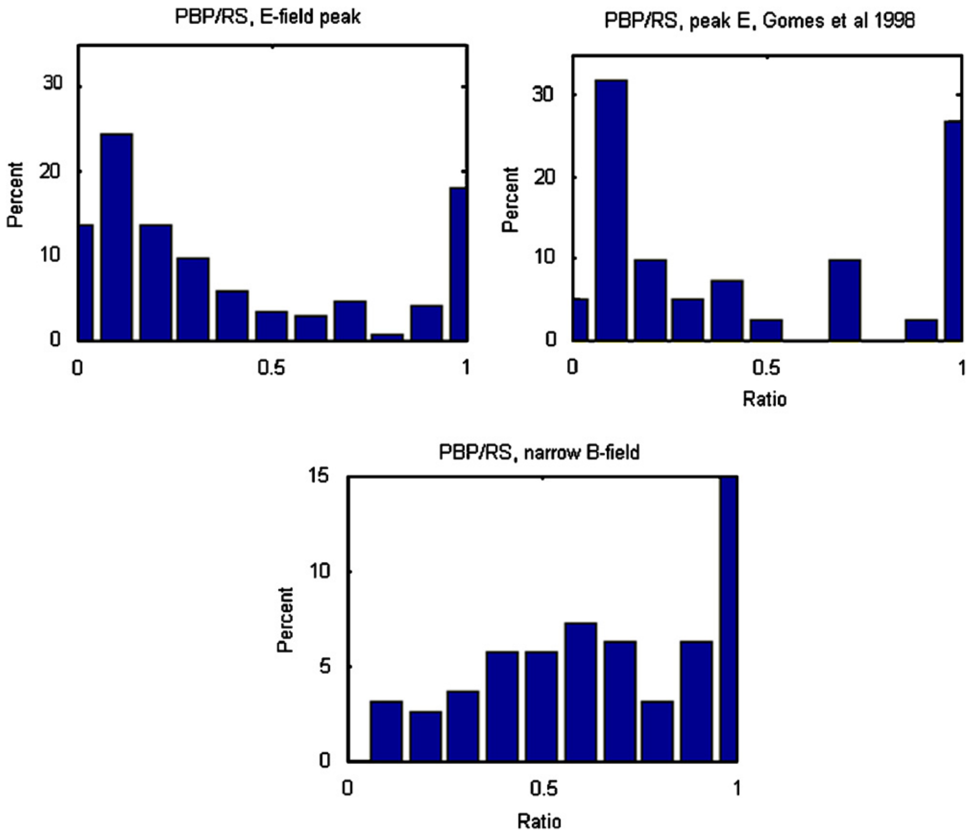

Fig. 9. PBP/RS ratio from three sources: our electric-field measurement (top left), Gomes et al. (1998) (top right), and our *B*-field (bottom left).

described by Cooray (2007). The RS propagates predominantly as a ground wave even at close distances, with no significant change in the propagation regime as distance grows. However, the PBP propagates as a space wave with little attenuation at very close distances. As the distance grows, an increasing part of the signal begins to propagate as a ground wave with significantly stronger attenuation. This differential propagation can also explain one phenomenon left unexplained in Mäkelä et al. (2008a), the rapid drop of the narrowband intensity as a function of distance. As is seen in the data, the in-cloud processes cause a dominant part of the integrated energy. Thus, in very close flashes, space-wave propagation is dominant, while more distant flashes attenuate as ground waves. Due to large scatter in the data points, it is difficult to make a more quantitative analysis.

4. Discussion

We measured preliminary breakdowns and first RSs from 193 Finnish cloud-to-ground lightning flashes. The data set was chosen so that three independent measurements were available: broadband electric field, narrowband magnetic field, and an accurate distance from a lightning location network. The combination allowed the breakdowns to be identified with a high degree of certainty. Like Gomes et al. (1998), we can identify an energetic breakdown process preceding the RS in at least 90% of the flashes. The median time duration of the process is about 4 ms, and the median time from the start of the breakdown to the RS is about 8 ms. There is almost always a quiet time between the breakdown and the RS. Thus, at least in Scandinavia, the basic BIL model of Clarence and Malan (1957) is well supported. However, when the waveforms are analyzed in detail, even with this large data set we could not find a systematic classification scheme for the PBP fine structure. Such variability in the form and shape of PBP processes was also observed by Beasley et al. (1982). The statistical results which we were able to obtain (for RS–PBP duration and intensity ratio) are compatible with earlier studies, but the distributions are non-Gaussian. Gomes et al. (1998) also estimated the intensity ratio between the PBP and RS, which has been estimated by comparing the peak energy of the highest peak in the PBP to the peak electric field of the RS. Although there is no clear physical justification for this method, we performed the same analysis and found consistent results. On average, the RS is about four times more intensive than the PBP. However, in about 25% of the cases, the PBP peak is higher than the RS.

The earlier measurements can be improved by also including a narrowband magnetic-field measurement (operating at 1 MHz in our case). In particular, the start of the PBP is typically much better defined in the

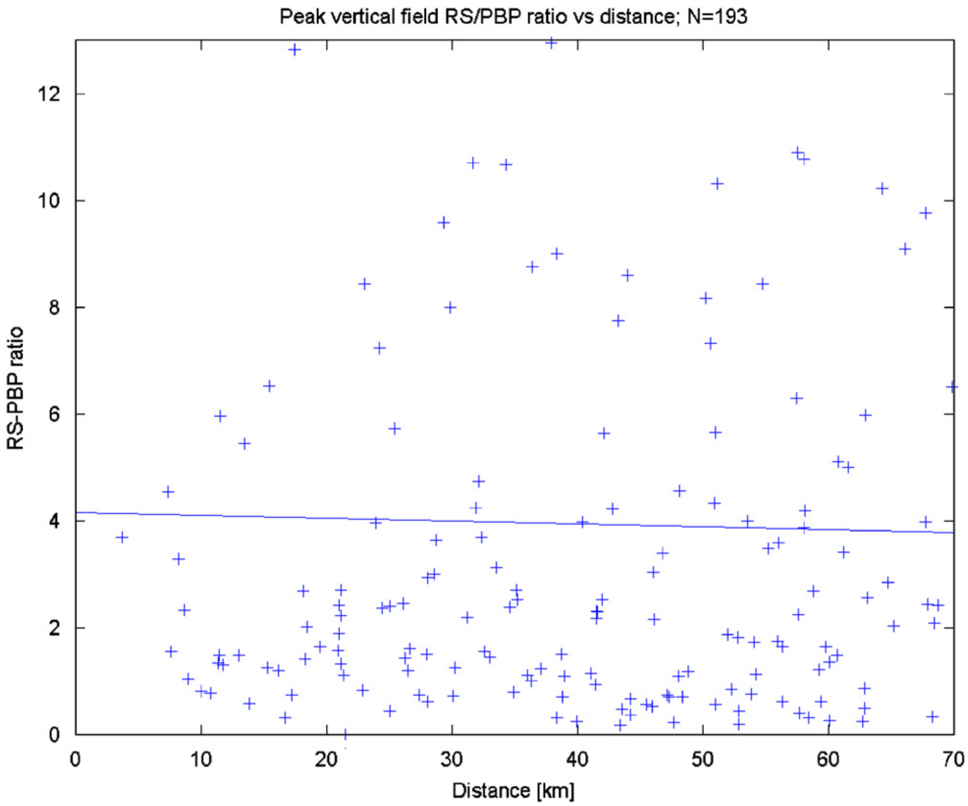

Fig. 10. Ratio of electric-field return stroke intensity to peak breakdown intensity. There is no statistically significant distance dependence.

narrowband magnetic-field signal than in the wideband electric-field signal. The narrowband signal is in agreement with the BIL model of Clarence and Malan (1957). In most cases, there is an interval between the PBP and the RS in which the noise level is low and nearly constant, although higher than just before the PBP. We consider the PBP to end when the energy of the breakdown reaches the level of the intermediate phase. To enable physically consistent comparisons of the PBP and RS intensities, we defined the intensity as the RMS sum of the most intensive parts of each process (the most intensive 10% in the case of PBP, the three most intense peaks in the case of RS). With the RMS method, the PBP and RS have almost equal intensities at close distances. As the distance grows, the RS begins to dominate. The effect is small but statistically significant. Mäkelä et al. (2008a, b) suggest for this same data set that the distance effect could be related to vertical and horizontal current components. The broadband flat-plate antenna measures only the vertical electric-field component, but the narrowband magnetic-field coil antenna would pick up horizontal magnetic-field components due to its directional gain (Mäkelä et al., 2008a). However, for an ideally conducting ground, the horizontal electric field and vertical magnetic field will be zero when the mirror current is considered. For non-ideal conductivity, the small horizontal electric-field component can be modelled by the wave-tilt formula (Master and Uman, 1984) or the Cooray–Rubinstein equation (Cooray, 1992; Rubinstein, 1996). However, measurements by Thomson et al. (1988) show that peak horizontal electric fields from lightning flashes have an amplitude of only 3% of the peak vertical fields even at distances below 40 km. Therefore, although horizontal current components may cause a very small effect in the narrowband magnetic-field measurement, the results are better explained by the differential propagation of cloud and ground waves as discussed by Cooray (2007).

There is a large scatter in the results of Fig. 11. At any frequency, the measured energy will depend both on the characteristics of the individual flash as well as the propagation characteristics of the ground wave. In an ideally conducting ground, the propagation at a single frequency would depend only on distance and thus would not affect the results. However, the actual measurements are all over ground, whose conductivity is non-uniform and unknown. As noted by Master and Uman (1984), earth conductivities can vary widely between 10^{-2} and 10^{-5} S/m. Further, the effect on the attenuation is non-linear and sensitive to assumptions about the ground characteristics. For example, Cooray and Jayaratne (1994) showed that at a fixed frequency of 1 MHz, the attenuation constant can drop by a factor of 100 when the conductivity drops by a factor of 10. At large distances where the PBP and RS both have a significant ground-wave contribution, this attenuation affects the PBP signal and RS signal equally, and thus variations in ground conductivity would cause only small variations in the energy ratio. At closer distances, variations in ground

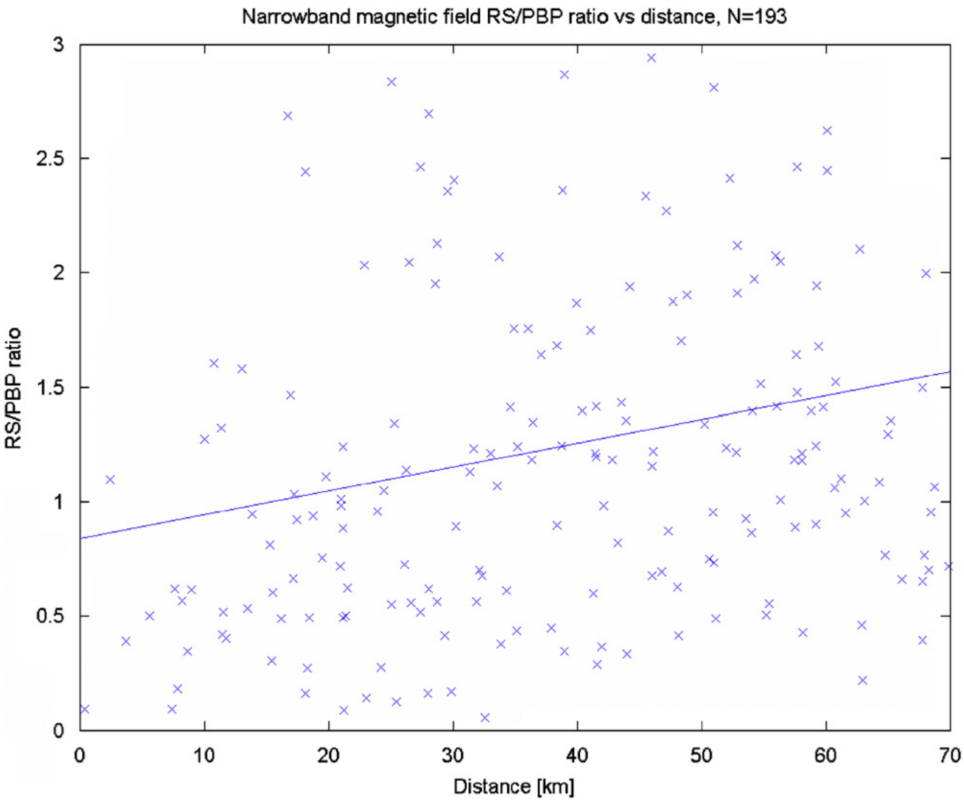

Fig. 11. Ratio of narrowband return stroke intensity to breakdown intensity. The distance dependence is statistically significant.

conductivity should have more effect, leading to larger scatter. The data set is not large enough to determine statistically whether this in fact happens. However, based on geographical considerations, conductivity variations should not be large. Both Piikkiö and Jokioinen are located in the flat south-west part of Finland. Jokioinen is surrounded by primarily rural flat clay-based ground, with no significant geographical variations within a radius of 20 km. Piikkiö has somewhat more geographical variation, with urban development to the west and an ocean bay to the southeast (which is however almost completely filled with islands). However, the large sector from the northwest to the south has a terrain that is very similar to that of Jokioinen. As a first approximation, the conductivity near both sites can be assumed to be approximately constant. Therefore, the scatter seen in Fig. 11 is predominantly due to flash-by-flash differences rather than differences in ground characteristics, especially at large distances.

The measurements support earlier measurements, which had smaller data sets. Consistent with the results of Gomes et al. (1998), we found clear PBP signals in at least 90% of the negative ground flashes. The time interval between the PBP and RS is long tailed, with a median of 8 ms but with about 5% having time separation longer than 40 ms. We were able to measure the duration of the PBP process itself from the narrowband data, and arrived at a median duration of 4.3 ms. A key significance of these measurements is that they provide an experimental validation of the calculations of Cooray (2007) at a general level, even though no quantitative measurements are possible on this data set alone. For completely reliable comparisons, the measurements should be repeated over a highly conductive ocean surface, which would eliminate the uncertainties related to ground conductivity.

The results have some potential to be useful in improving narrowband lightning detection schemes. Visually, the narrowband PBP–RS signal consistently displays what could be called an "M-shaped" profile consistent with the BIL model. The sharp onset of the breakdown causes a nearly vertical impulse at the start of the process. The RS is approximately equal in intensity to the breakdown, causing a symmetric signal; and the quiet intermediate stage causes a dip in the middle of the "M". The typical duration of this "M-shaped" profile is of the order of 10 ms, and it is easily detectable. In principle, the variation in the RS–PBP ratio could provide additional distance information since it causes asymmetry in the M-shape. However, the scatter is too large to make this practical. A more useful approach would be to consider the M-profile in a pattern-recognition scheme. Given that the start of the PBP is so often very abrupt, the PBP–RS sequence could in principle be used to determine the start of the first RS as opposed to subsequent strokes, which do not exhibit this M-profile, or even to separate IC and CG processes. One unresolved issue is related to the latitude effect. PBPs appear to be very strong at high latitudes and very weak at equatorial latitudes (Gomes et al., 1998), while the results in intermediate latitudes in Florida are inconsistent (Beasley et al., 1982). RSs appear to have similar narrowband HF signatures at a variety of latitudes (Cooray and Ming, 1994). However, if breakdowns vary as much as the literature suggests, any detection scheme utilizing the PBP–RS signature will be suspect in the equatorial regions. Therefore, more measurements are needed near the equator.

5. Conclusions

We have analyzed the preliminary breakdown processes (PBPs) associated with 193 negative lightning flashes in Scandinavia. A breakdown pulse can essentially be seen always, unlike at lower latitudes. The intensity of each PBP pulse was compared with the corresponding return stroke (RS) intensity using two different methods. When comparing the peak electric field of the PBP to the peak field of the RS, the RS usually dominates by a factor of 4, but the PBP has a higher peak in up to 25% of the flashes. The PBP–RS ratio does not vary with distance. When the narrowband magnetic field was measured, the intensity was defined to be the RMS sum of the most intense parts of each process. This is a physically consistent and mathematically robust definition. With this definition, the PBP and RS intensities are comparable at close distances, but the PBP intensity drops faster as a function of distance. This is an experimental verification of calculations suggesting that in-cloud and cloud-to-ground lightning will have different propagation characteristics. The RS always propagates as a ground wave, while the PBP changes from space-wave to ground-wave propagation with increasing distance. The results are consistent with the BIL model of RS development, which causes a distinctive "M-shaped" signature in the narrowband signal. This signature has potential to be utilized in a pattern-recognition scheme for identifying lightning flashes in a narrowband detection system.

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