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Single-station narrowband ranging of active storm cells without lightning-type discrimination

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ABSTRACT

We present a statistical technique for ranging the edges of active storms cell using a very simple narrowband receiver tuned to 1 MHz (the MW band in radio, just below HF frequencies). We show that a principle based on the "30–30 rule" can be used to define practical warning levels. From the measurements carried out in Finland, we show that the narrowband source intensities of cloud-to-ground lightning vary log-normally; this results in a ranging uncertainty of about 20%, which can be reduced if a suitable floating average is used. Based on one storm, we suggest that the differences between intra-cloud and ground-to-cloud signals at 1 MHz are small enough to make an IC–CG discrimination. Eliminating such a discrimination allows all lightning impulses to be used in the range and improves the accuracy, since more flashes are then available as inputs into the distance-estimation algorithm. Although the system is only validated against a single storm, we provide definitions by which this and other narrowband detectors could be independently verified; existing narrowband devices have not been verified in this manner, due in part to a lack of such standardized definitions.

1. Introduction

Narrowband methods for lightning detection are not widely used at present. A rudimentary technique was presented by Mäkelä et al. (2008a) and further described in Mäkelä et al. (2008b). Mäkelä et al. (2008a) noted that the technique, which is essentially just a modified AM radio, has the potential to be designed into an extremely low-cost and portable system that warns of approaching thunderstorms. Such devices in fact already exist in the market, and can protect small installations or even individual people. However, American Meteorological Society (2002) noted that they have not been independently verified. In practice, such verification would not be simple to perform, since there is not necessarily a unique ground truth. We suggest that some of the controversy around stand-alone devices is due to the lack of standard definitions regarding the physical parameter that is being measured. Traditionally, lightning-detection systems are optimized to measure the locations of ground strokes. It is therefore possible to determine the ground truth of systems by comparing the measurements to actual strike locations. Such comparisons have been done by Idone et al. (1998). An alternative approach is to estimate the probability of lightning striking a given location within a given time. Although such exact predictions are not yet realistic with current technologies, an acceptable solution would be to measure the distance and approach speed of the closest lightning flashes, whether IC or CG flashes. A key problem with this approach is the difficulty of measuring the ground truth of IC flashes. An early narrowband device, which was in operational meteorological use, was described by Kohl (1980). The ground truth was obtained by comparing the distance to the closest radar echo, which assumes that any lightning activity is associated with a cloud that causes a radar echo. The device was shown to have a reasonable detection accuracy and warning capability which is of operational use within the limitations of the 1980s technology.

In Section 2, we describe a principle by which lightning risk could be quantified even when exact ranging estimates or flash intensities are not known; the principle in fact does not even require an IC/CG differentiation. The rest of the paper demonstrates that a risk-based system of this type could be built around the narrowband principle described by Mäkelä et al. (2008a). In Section 3, using two-station measurements we show that the

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narrowband intensities of CG flashes follow a log-normal distribution, with a scatter that is no larger than observed for return stroke peak intensities. In Section 4, we show for one storm that at any given distance, CG and IC flashes have energy distributions that are comparable, and therefore ranging is possible without a CG/IC differentiation. In Section 5, we discuss the implications for creating practical narrowband lightning-detection systems of this type, especially given the difficulty of defining the ground truth. We also attempt to explain the physical phenomena that explain the signals we measure. Final conclusions are drawn in Section 6.

2. Using statistical rules to estimate lightning risk

The so-called 30–30 rule (e.g. Holle et al. (1999)) is an extremely simple yet effective example of a statistics-based approach to lightning risk . The rule states that protective actions should be started when the time between the visual flash and its associated audible thunder is 30 s or less (in other words, the distance is 10 km or less). The user should then stay in a protected area until 30 min have passed from the last audible thunder. Although the ‘‘30–30 rule'' is basically a useful mnemonic, the numbers are based on valid statistical measurements and an understanding of the parameters that are of interest to ordinary users. For any ordinary user, the distance as such is not really of interest; what matters is the risk that lightning strikes close by. According to Krider (1988), the distance between consecutive flashes is 2–3 miles, although Lopez and Holle (1999) found somewhat larger distances. Since there are large storm-to-storm variations (and possibly latitudinal effects that have not been well studied), Holle et al. (1999) do not define a single number for the minimum safe distance from a given flash, but consider 10 km (30 s) as a useful approximation. We suggest that to gain any acceptance, a risk-based warning should be designed around the 30–30 rule. We further suggest that three zones can be defined to correspond to different modes of operation. As in the case of Holle et al. (1999), these values should not be considered exact.

Zone 1 (‘‘danger distance''): the range in which the user is in immediate danger of being struck, according to the 30–30 rule. For consistency with the 30–30 rule, this range is taken to be 10 km. At this range, even a single lightning flash should in principle launch a warning. In contrast, ranging within the zone does not have to be exact according to the philosophy of the 30–30 rule; it makes no difference to the risk level whether the storm is 6 or 8 km away.

Zone 2 (‘‘tracking distance''): If a remote detector is to have any practical value, it must range storms at significantly more distant ranges than zone 1. This allows lightning risk to be evaluated before the storm poses a real risk, mainly by tracking the approach speed of a storm or the growth of a new cell. Ranging in this zone, therefore, must be reliable and respond quickly to changes in the storm distance. A practical monitoring system has to alert the user of a possibly increased risk level without yet triggering the full alarm. In a practical application, the tracking distance should not be too large; a storm at 50 km distance poses no real and immediate risk to the user, and giving a warning would lead to too many false positives, which eventually lead to warnings being ignored. There is no physical reason to suggest a specific value of the tracking distance. In principle, a value can be derived from average speeds of storm cells, but in practice lightning activity does not always move as well-defined cells. For the type of technique described in this paper (using a single station operating at a single frequency), propagation effects mean that a realistic accurate tracking distance is approximately 20 km.

Zone 3 (‘‘monitoring distance''): At distances larger than the tracking distance, a practical system needs to monitor for the presence of lightning activity, but the user should normally not be alerted. The ranging must be accurate enough to establish whether a storm is approaching the tracking distance, but high accuracy is not required. On the other hand, any practical system has a minimum usable signal intensity, set both by the expected signal intensities and by the receiver sensitivity. This corresponds to a maximum confident ranging distance. At the practical level, there is also an upper distance limit after which a storm is irrelevant to any user; this distance is certainly less than 50 km.

The zoning principle loosens ranging accuracy, which is needed. A detection system should be calibrated so that it has maximum accuracy within the tracking range. The crucial variable, and a quantitative metric for the detection accuracy, is the accuracy in determining when the flashes have moved in or out of the danger zone and into the tracking zone. Within the danger zone, ranging does not need to be accurate as long as the flashes are correctly calculated to be within the danger zone; thus, saturation of the receiver would be acceptable, potentially simplifying the system design. On the other hand, any statistical technique will have difficulty dealing with the case of convective storms developing almost overhead; since the statistical approach requires several flashes to be ranged, there is a risk that the detector would not react to the first few flashes of an isolated overhead storm. A system that raises an alarm on every signal above the threshold level would be impractically sensitive to interference sources. However, as will be shown, our method can also utilize IC flashes, which are usually more numerous than CG flashes. Although not perfect, a method that utilizes both CG and IC is therefore more robust against this problem than the one detecting only CG flashes.

3. Narrowband source characteristics

According to Mäkelä et al. (2008a), the integrated narrowband energy of CG flashes has an approximate distance dependence

$$I = a + b/R_i^k \tag{1}$$

where a and b are empirically determined constants and k is approximately 3. The source intensity was assumed to be nearly constant, which is not a physically realistic assumption, but resulted in a useful empirical relationship. However, we can estimate the distribution of source intensities using a subset of the data of Mäkelä et al. (2008a) in which the same ground flash was measured at two stations. Our hypothesis is that if the distribution of source intensities is sufficiently narrow and symmetric, the variation simply introduces a scatter in the measured values, and the equation is statistically valid for large data sets. During the summer of 2006, measurement stations were located in Piikkiö and Jokioinen, 70 km apart and both in southwestern Finland. Because the reliability of the narrowband measurements degraded with increase in distance, only those flashes were chosen that were within 70 km of both Piikkiö and Jokioinen. This defines a roughly elliptical area in which the land is predominantly clay-based rural terrain, with some swamps but no major lakes or urban areas. The locations of CG flashes were given by the lightning-detection network operated by the Finnish Meteorological Institute. After quality control, the final data consisted of 864 flashes, sufficient for a robust statistical estimate.

As a first approximation, we assume the intensity to drop as a simple polynomial that depends only on the source intensity I_0 and distance R for both stations

$$I_i = I_0/R_i^k \tag{2}$$

With two stations and known distances, there are two equations and two unknowns. The solutions are given by

$$k = -\frac{\ln(I_2/I_1)}{\ln(R_2/R_1)} \tag{3}$$

$$I_0 = \sqrt{I_1 I_2 R_1^k R_2^k} \tag{4}$$

The distribution of the measured values for k using Eq. (3) is shown in Fig. 1. Although there is some scatter, the median value is 3.3. In Fig. 2, the source intensities have been calculated from Eq. (4). The distribution is long-tailed and reasonably modeled by a log-normal distribution with $\sigma^* = 0.36$. However, three additional factors must be considered. Eq. (2) is likely to be piecewise valid but may not be exact for all distances; with two stations it is not possible to include more terms in the approximation. Eq. (3) is numerically unstable when $R_1 \approx R_2$. In addition, if the propagation characteristics of the ground are non-uniform, the values in Eq. (2) must be multiplied by attenuation parameters α and β, which depend on the ground conductivity of the propagation path from the flash to the given station. Unless the ground is completely homogeneous, the values of α and β will vary from flash to flash. Ground conductivities can vary from 10^{-2} to 10^{-5} S/m as discussed by Master and Uman (1984), while the

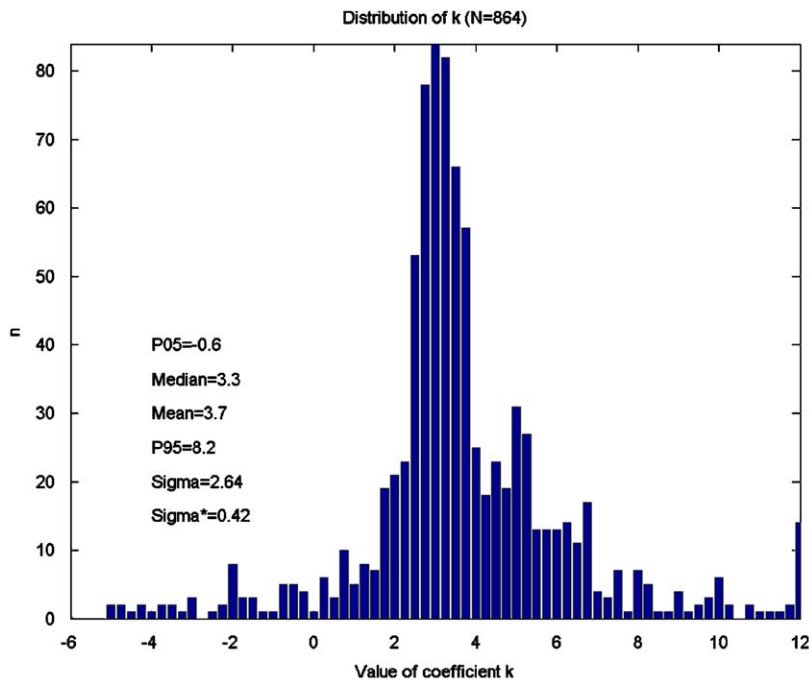

Fig. 1. Distribution of coefficient k for all flashes measured at two stations.

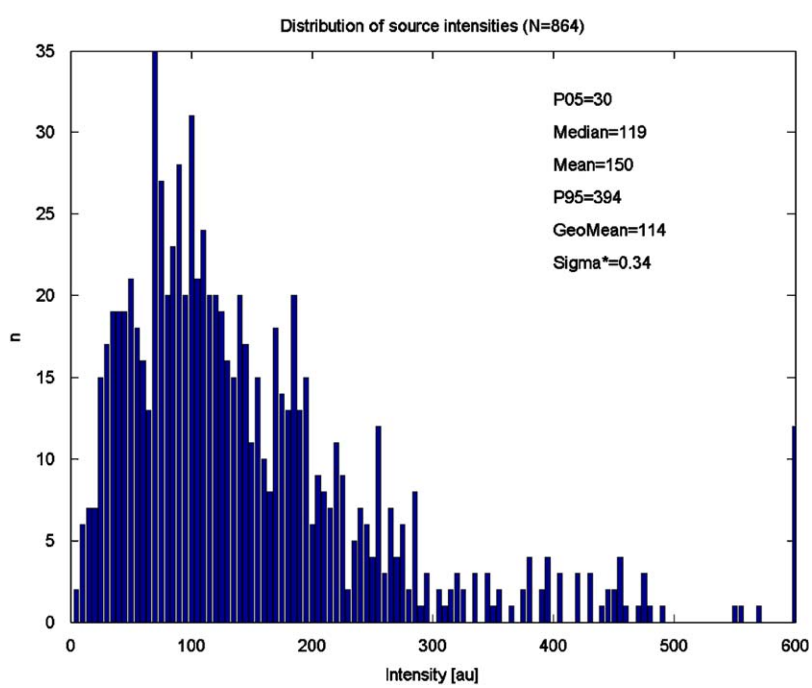

Fig. 2. Distribution of source intensities from all flashes measured at two stations.

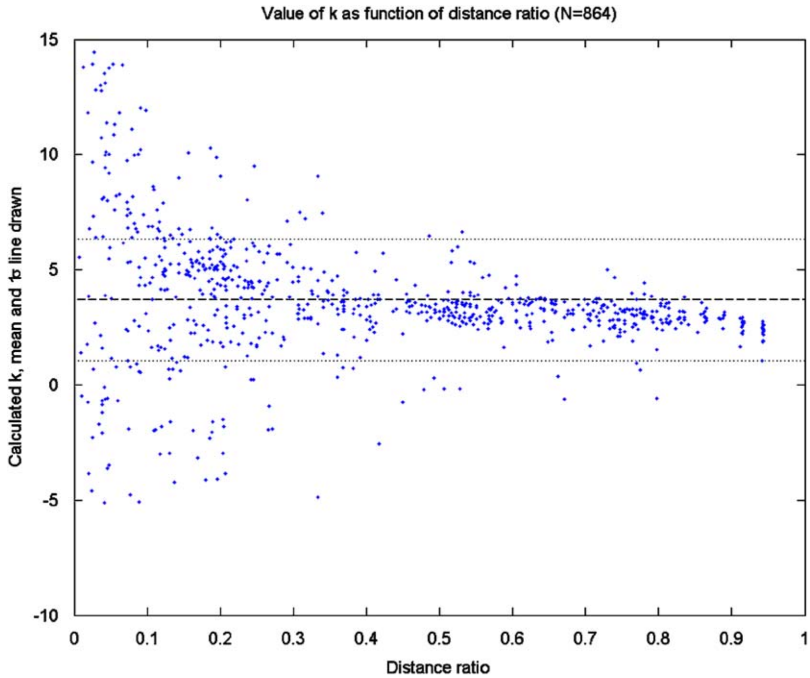

Fig. 3. Value of k as a function of the distance ratio between stations. When the stations are equidistant, propagation and numerical instability affect the results more dramatically.

attenuation constant at 1 MHz can drop by close to 30 dB when the conductivity drops by 10 dB (Cooray and Ming (1994)). The equations therefore become

$$k = -\frac{\ln(I_2/I_1) - \ln(\beta/\alpha)}{\ln(R_2/R_1)} \tag{5}$$

$$I_0 = \sqrt{\alpha\beta}\sqrt{I_1 I_2 R_1^k R_2^k} \tag{6}$$

The error introduced in k can be analyzed as a function of the distance ratio $D = |(R_2 - R_1)/(R_2 + R_1)|$. For small values of D, Eq. (5) will be dominated by the $\ln(\beta/\alpha)$ term in addition to being numerically unstable. However, a simple argument suggests that the value of β/α will be symmetrically distributed around the value 1. Consider the ground as a mesh in which individual cells can have random values of ground conductivity. The attenuation of a flash signal will depend on the first approximation on the average conductivity along the line connecting the flash and the station. If there are no asymmetries in the ground conductivity, for a large number of flashes the statistical distributions of α and β will be identical. The mean value of β/α therefore tends to 1, and $\ln(\beta/\alpha)$ tends to zero. Thus, the extra term in Eq. (5) is distributed around zero, and simply causes more spread in the calculated values of k. This analysis is not valid if there are major conductivity asymmetries in the terrain, for example large lakes near only one of the stations. However, there are no such asymmetries in the region between Piikkiö and Jokioinen. The spread should be most severe for small D. This is in fact seen in Fig. 3, where the calculated values of k are plotted as a function of D. The mean and 1σ lines are drawn as horizontal dotted lines; as is seen, the equation is unstable for small D. The analysis was redone for data for which D is large enough for Eq. (5) to be well-behaved; $D > 0.4$ was chosen. The results (Figs. 4 and 5) show that the main features of distributions are not changed. The average value of k approaches 3.1, while the source intensity distribution is not essentially changed. In other words, the errors cancel out for a large-enough data set.

The effect of source variability on distance estimate can now be estimated. Although any single flash is ranged inaccurately, averaging several flashes will lead to an improved accuracy. We have simulated this improvement by assuming that intensities are picked from a log-normal sample with $\mu = \ln(2000)$ and $\sigma^* = 0.36$, which corresponds to a mean distance of 10 km. The simulation results are shown in Fig. 6. When the sample has only one flash, the distribution is wide with a standard deviation of 1.1 km or a 2σ uncertainty of more than 20%. When two, three, or four samples are averaged, the standard deviation of the distribution reduces to 0.79, 0.64, and 0.56, respectively. Thus, when just four samples from the same distance are averaged, there is a 95% probability that the distance error is 10% or less.

4. Separating CG and IC flashes

The analysis in Section 1 was based on CG flashes for which an accurate ground truth existed. For IC flashes, no such ground truth was available, since the VHF lightning-location system of the Finnish Meteorological Institute was not sufficiently accurate in 2006. We therefore determined IC locations indirectly from the CG locations. This can be done with reasonable accuracy if there is a single storm cell with small horizontal extent and no other storm activity within several hundred kilometers, since any IC flashes occurring before or after a CG flash will have occurred in the same cell. In such a case, the accuracy is not necessarily much inferior to a direct measurement with a VHF imager; note that even with a VHF imager, the large horizontal extent of a typical IC flash makes it impossible to define a single unambiguous value for distance. Such ideal cells are not common, and only one such event occurred during the measurements, on July 30, 2006, between 1430 and 2000 local time (UTC+3). Several well-defined individual cells were formed close to the Piikkiö site and moved to the northwest, and there was no other significant activity within several hundred kilometers. The CG flash development is shown

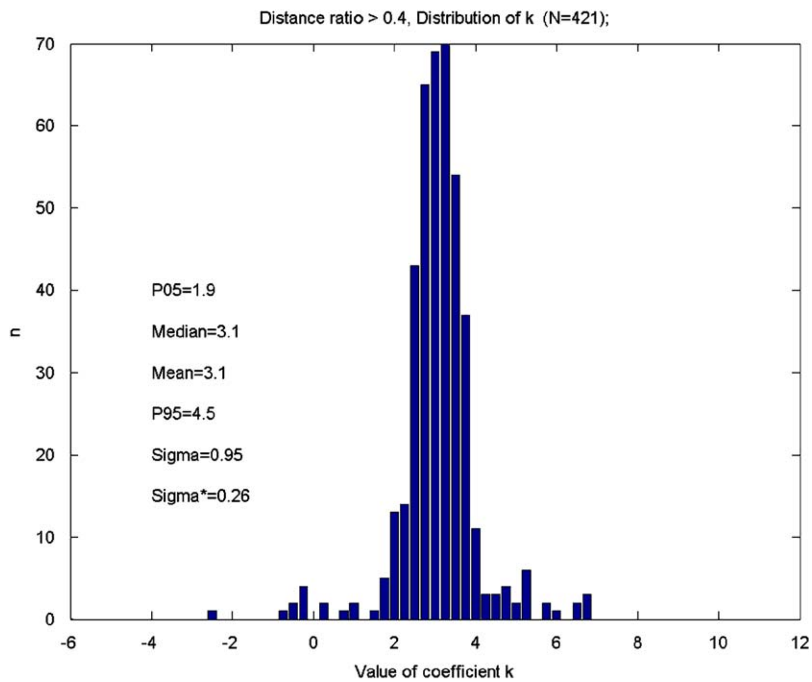

Fig. 4. Distribution of k using only the measurements for which distance ratio >0.4.

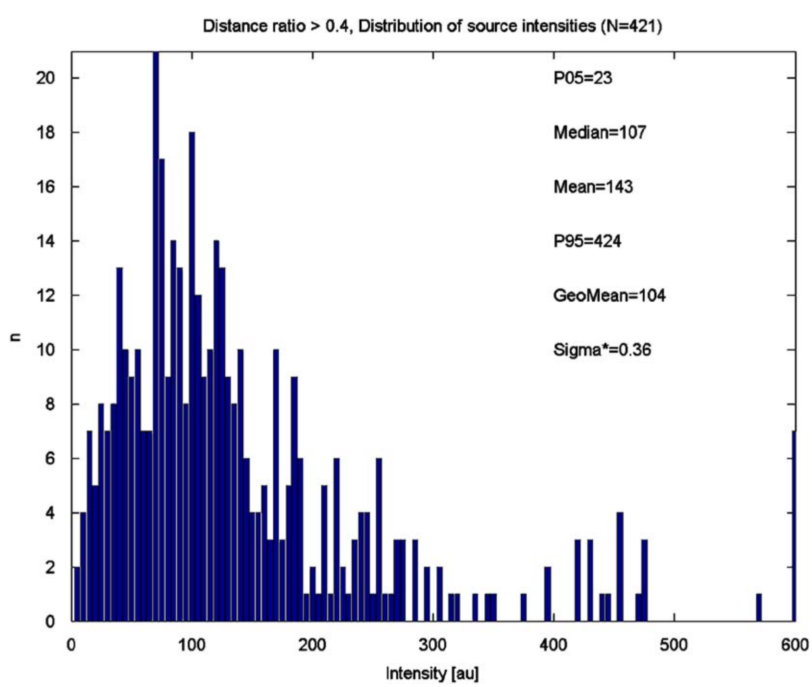

Fig. 5. Intensity distribution for distance ratio >0.4.

to be two-dimensional in 15 min increments in Fig. 7 and in one dimension in Fig. 8.

A total of 412 CG flashes were identified within 30 km by the lightning-detection network during the series of storms. In the same time period, 1473 narrowband signals were triggered. Among these records, 341 could be unambiguously tied to a CG flash. This implies a rather low detection efficiency, but it is at least in part due to the automatization of the measurements. A relatively high triggering level of 6 dB above the baseline level was used to limit the number of spurious signals. At this level, weaker flashes can be missed. Among the remaining signals, 43 were due to known instrumental errors and 102 consisted of single impulsive peak, which is consistent with an interference signal (either from a light switch or from a distant storm that was located over the ocean). This left 987 flashes, which are consistent with IC flashes within the same distance range as the CG flashes. There is a 3:1 ratio between IC and CG. The data are summarized in Table 1.

At a qualitative level, Mäkelä et al. (2008a) suggest that there are differences between CG and IC signals, with IC flashes having longer duration and smoother energy envelope than CG flashes. Rather than making the differentiation using a waveform analysis,

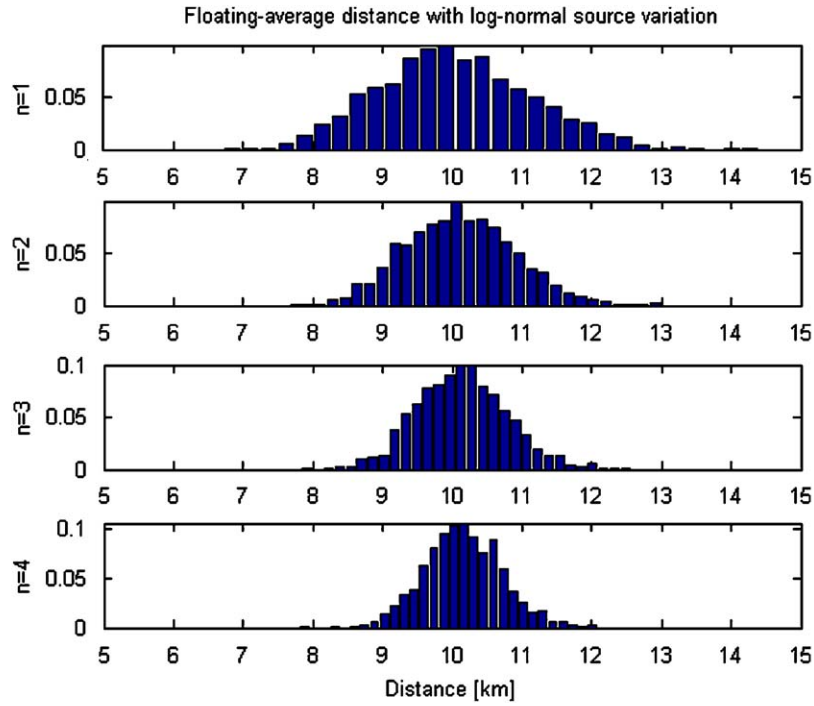

Fig. 6. Simulated effect of log-normal source variation on statistical distance estimate. The mean distance is 10 km. The top row shows the probability distribution of a single flash; the lower panels show the distribution when 2, 3, and 4 samples are averaged. The standard deviations are 1.1, 0.79, 0.65, and 0.55.

we evaluated whether IC–CG differentiation could be done by reducing each flash to a few statistical parameters. As discussed by Mäkelä et al. (2008a), the antennas have a directional gain, which was avoided by adding signals from two orthogonal coils. Because noise levels are high and the flash duration can be highly variable, it is necessary to subtract the baseline noise level to avoid having noise level dominate the calculation. If the signal is Gaussian noise, 99.994% of the measurements should be within four standard deviations of the mean. Each one-second record has 44,100 samples, which means that less than three samples should be above the 4σ level. It is therefore optimal to use the 4σ level as the baseline. A "glitch" is defined to be a discrete impulse during which the signal intensity remained above the baseline level. This definition should reveal whether the qualitatively observed features are quantitatively correct. The CG flashes should have a small number of glitches with relatively high energy, while IC flashes should have a larger number of glitches, often with lower energy. Representative results are shown in Fig. 9. The signal duration (Fig. 9a) is simply the number of peaks above the 4σ level. The number of glitches (Fig. 9b) is a measure of the smoothness of the signal; a small value indicates that the signal is relatively smooth. The 10–90% cumulative energy distribution (Fig. 9c) is a robust estimate for the duration of the flash. There are clear differences in the distributions, but they are not large enough to enable a robust differentiation based on such simple metrics alone. For a traditional ranging system, this lack of IC/CG differentiation would be a hindrance. However, when a statistical risk-based approach is used, such differentiation is not necessary for a practical application.

CG/IC differentiation would only be needed if CG and IC flashes at the same distance have significantly different average energies. However, our measurements showed that they do not differ significantly. In Fig. 10, the energies of CG and IC flashes during the storm are compared in the time domain. Since the storm cells were small, it can be assumed that any IC flashes just before and just after a CG flash will be located at approximately the same distance. For every CG flash, the energies of IC flashes 5 min before and after the CG flash were calculated, and the average was taken. The results are shown in Fig. 11, where the CG energies have been sorted for clarity. There is considerable scatter, and for the very highest CG energies, the IC energies appear to be systematically lower. The implication therefore is that overhead CG flashes tend to radiate more intensively than overhead IC flashes. However, there is a correlation of 0.5 between IC and CG flash energies (Fig. 12), which is significant at $P = 0.01$. This correlation justifies using all flashes without making any IC/CG differentiation. Despite adding scatter, this has several obvious advantages. The detection is simplified considerably if there is no need to differentiate IC and CG, and the energy of any incoming flash can be used directly. (In a practical system, there still has to be a method to distinguish lightning flashes from manmade noise). More significantly, including IC flashes increases the data set, which is available for ranging (in this particular case, by a factor of three). From the point of view of providing a warning, it makes little difference whether the observed flash is an IC or a CG flash; both show that the cloud is electrified enough to produce flashes, and therefore is a hazard.

The procedure for ranging the edge of the cell therefore becomes a matter of measuring full-flash energies, calculating the distance corresponding to the flash energy, and averaging the distances for several flashes in order to eliminate the scatter in the data. In principle, the simplest algorithm for achieving this is a floating average of measured distances over a pre-set amount of time T. However, when the objective is to range the edge of a cell rather than its "average" position, a simple floating average will overestimate the distance to the edge. An additional parameter M is needed, and only the M most intensive flashes during the time period T should be used. Four parameterizations for the July 30, 2006 storm are shown in Fig. 13. Since the energy values are in arbitrary units, it is necessary to calibrate them to achieve a distance estimate. For simplicity, the data were fitted into Eq. (1) with the constant being set to 0 and k to 3.3. The constant b was

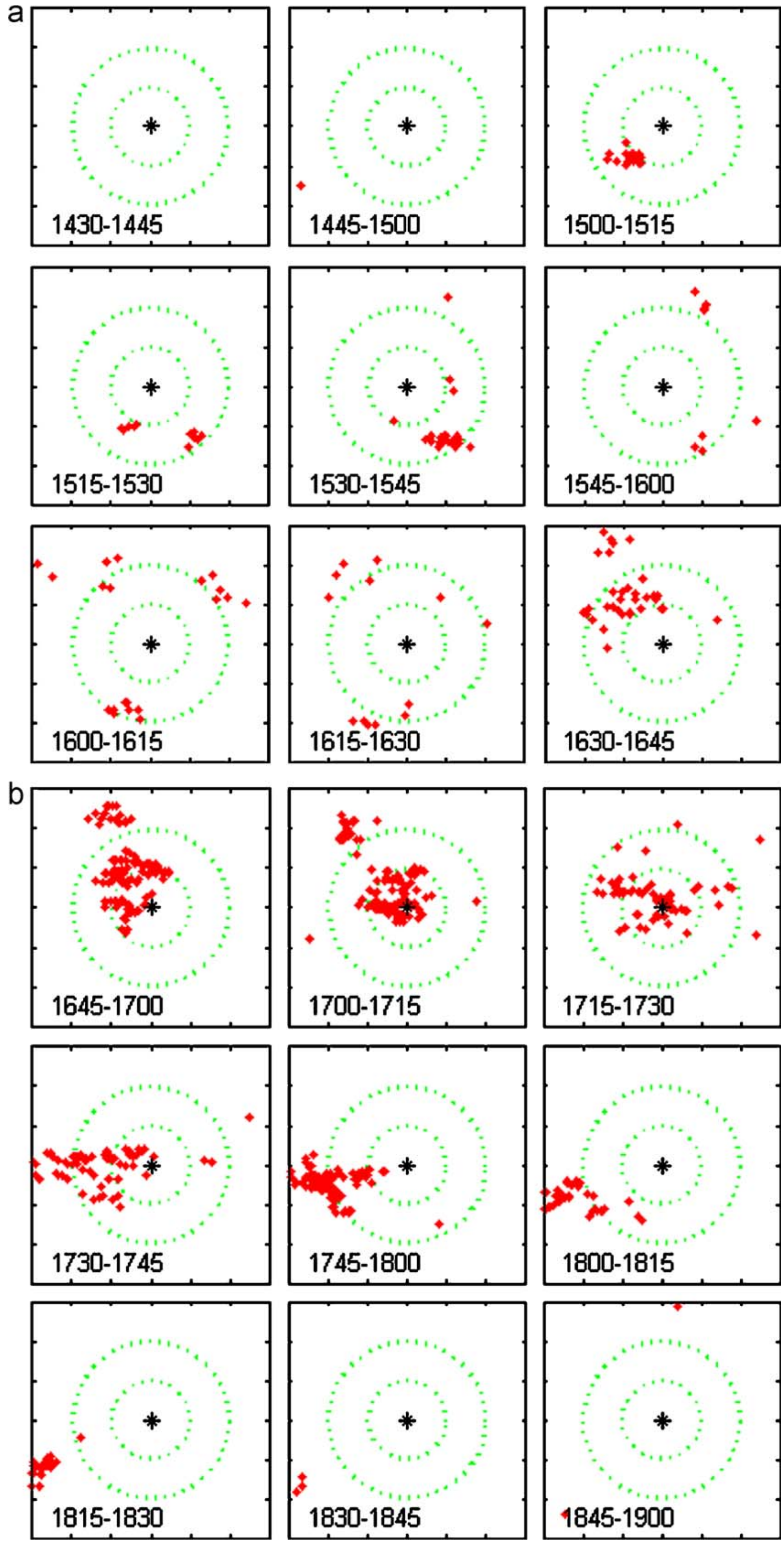

Fig. 7. Time behavior of July 30, 2006 storm, in 15 min increments (Local Time). Piikkiö is located at the center and the axes are 30 km in either direction. Circles have been drawn at the 10 and 20 km distances. In addition, a few isolated CG flashes occurred between 1930 and 2000 (not shown).

defined so that the calculated distances would be most accurate at 12 km. With this calibration, the transitions across the danger distance are rendered accurately, but within the danger zone itself, the range is less accurate (in this case, it is overestimated). This is however considered to be acceptable according to the zoning principle.

The source variations shown in Fig. 6 imply that even if all flashes are exactly at the edge, using a single flash ($M = 1$) results

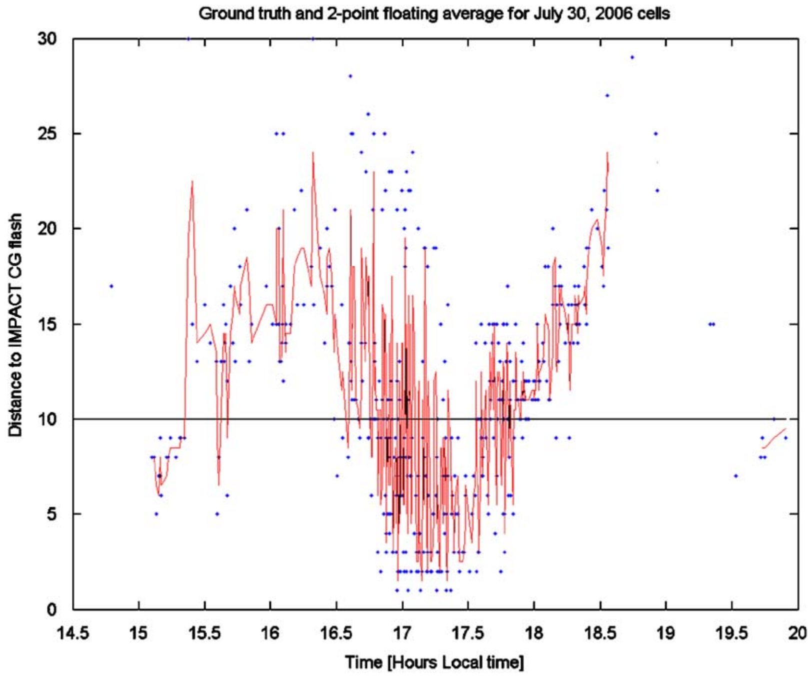

Fig. 8. Distance to CG flashes for July 30, 2006 case. Dots are individual ground flashes; the line is the average of two consecutive flashes. The danger distance (10 km) is shown as a horizontal line.

Table 1
Distribution of signal types in July 30, 2006 storm.

Type	*N*	%
Instrumental flaw	43	3
CG	341	23
Noise	102	7
IC	987	67
Total	1473	

in a 20% distance uncertainty. This is clearly seen in Fig. 13a, where the estimate for the edge fluctuates widely. If several flashes are used, the uncertainty decreases. Thus, M should have a value of at least 2. On the other hand, if M is too large, the distance will be systematically overestimated, since some of the flashes will be from the center of the cell. A large value of M also causes a time lag: an approaching storm will not be detected fast enough since the older, more distant flashes will keep the average lagging, while a receding cell will be estimated to be within warning distance for too long. This is clearly seen in Fig. 13d, where a choice of $T = 10$ and $M = 10$ results in the tracking of the ''average location'' of the cell rather than its edge, and response to the approach is delayed badly. The optimal value of M is therefore more or less the same, regardless of the storm type. Based on the results in Figs. 6 and 13, an optimal value would be approximately 3 or 4.

The value of T depends more closely on the climatology. The known statistical flash rates of storms are of some use. Boccippio et al. (2000), using global satellite data, have measured the flash rate per cell to be 4 flashes/min or less for about 80% of all storms. For storms occurring in Florida, Peckham et al. (1984) report maximum flash rates between 4 and 14 flashes/min. However, these figures are maximum rates; for our application, low-flash-rate storms and the initial phases of storms are the more difficult and important cases. In the case of the July 30, 2006 cell the CG flash rate rarely exceeded 1 flash/min. Even with the higher IC rate, the number of usable flashes was typically 3/min or less, scattered throughout the cell. Thus, to get a sample with several flashes near the edge, several minutes' sampling time is needed. In a practical system, the tracking could be improved by making the sampling rate adaptive.

5. Discussion

We have shown that narrowband ranging has the potential to be accurate, if some limitations are accepted. For Scandinavian CG flashes, the source intensities were consistent with a log-normal distribution, with the majority of flashes being within a factor of four of the median intensity. It was shown that due to the rapid drop as a function of distance, these source variations only cause variations of about 20% in the range estimate. Further, when the average of several flashes is used, the theoretical range uncertainty can be reduced to about 10%.

Ground propagation will significantly affect the results, especially for distant flashes. However, it was shown by Mäkelä et al. (2008b) that the fast increase in the intensity is largely due to the fact that a significant part of the narrowband energy is emitted by cloud processes. The radiation from these processes propagates as a space wave when distances are small, and ground propagation has a negligible effect. There is no exact cutoff at which the propagation regime changes, but based on geometrical considerations and the calculations of Cooray (2007), space-wave propagation is still significant at distances larger than 10 km. Thus, the most crucial part of our system (alerting accurately when lightning occurs in Zone 1 or 2) should not be radically affected by propagation. However, above distances of about 20 km, variations in ground conductivity can dominate the measured intensities. At minimum, this will increase the scatter; in the worst case, it can lead to systematic or directional errors (in particular, underestimating the distance to flashes over the ocean). The results of Mäkelä et al. (2008a) imply that the system used in this paper has reasonable ranging accuracy to over 50 km, but this can in part be ascribed to the homogeneous terrain. In

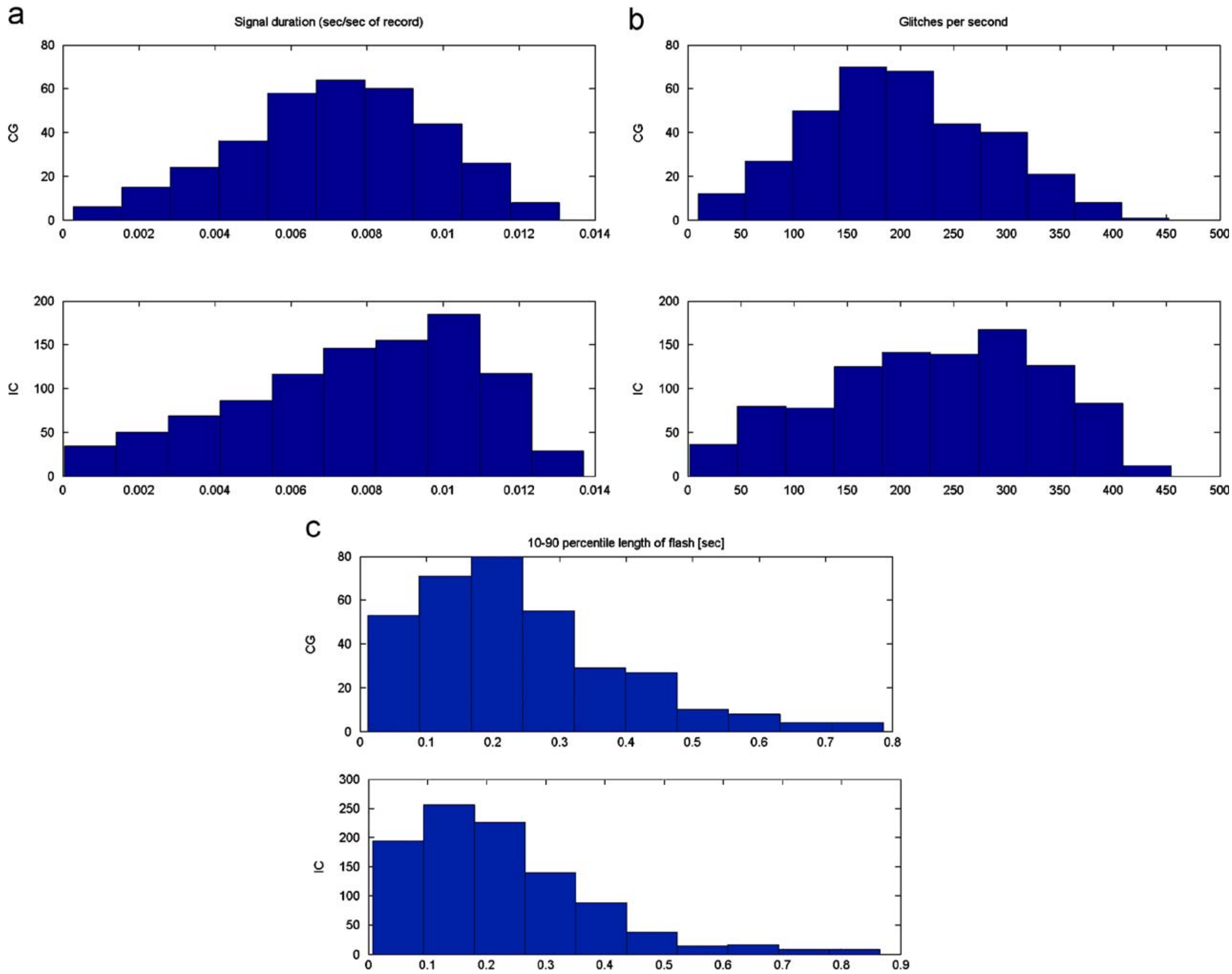

Fig. 9. Representative distributions of parameters of CG (top panels) and IC (bottom panels). (a) The signal duration is the number of peaks, which are above the 4σ level. IC flashes are somewhat longer than CG flashes, (b) glitches are discrete impulses, and a small value indicates that the signal is smooth. IC flashes have the most glitches, implying that they have more fine structure, and (C) the 10–90 percentile energy best represents the time from the beginning to the end of the flash. The IC and CG durations are not significantly different by this metric.

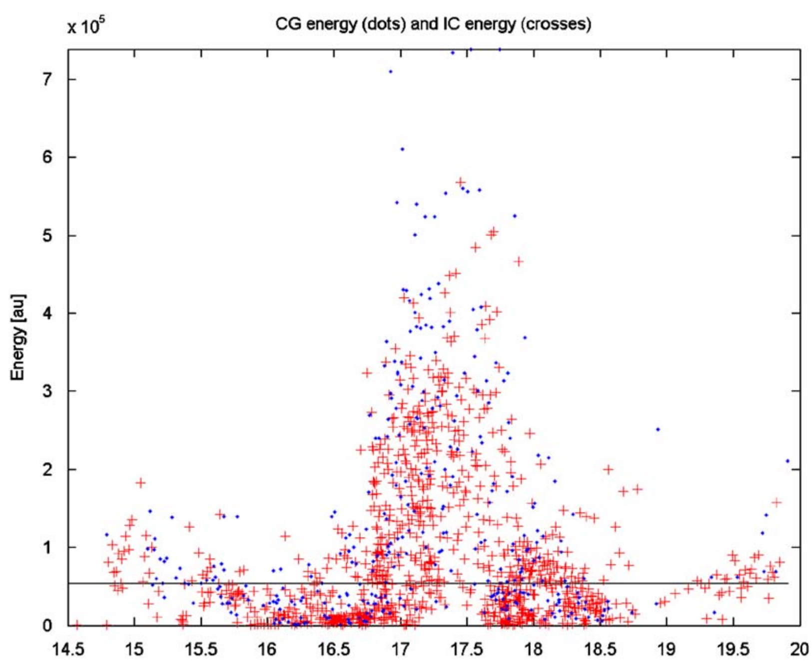

Fig. 10. Time behavior of IC (crosses) and CG (dots) energies for July 30, 2006 storm.

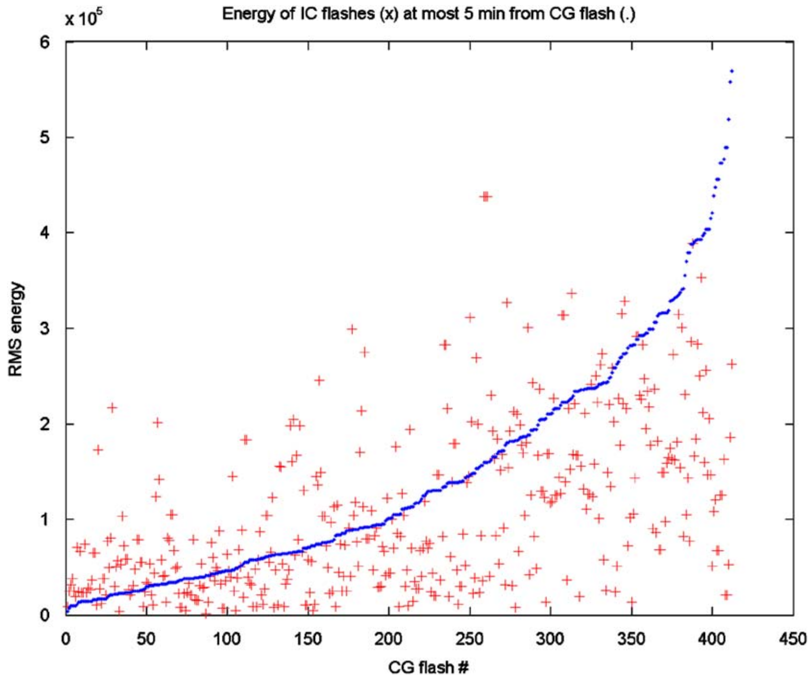

Fig. 11. IC flash energy compared to CG energy.

general, the accuracy can be expected to degrade faster unless the terrain conductivity is factored in.

The main open question about the validation procedure is whether the CG flash location can in general be used as a proxy for the IC location. In our specific data set, the cells were spatially small and essentially vertical (as seen in the CG location data as well as visual observation of the storms), precluding significant horizontal extent in any flashes. Furthermore, Proctor (1997) made observations with a VHF imager in South Africa, and showed that most IC flashes have a horizontal extent between 4 and 8 km, although extents of more than 20 km were also measured. They also noted that especially when the IC source altitude is low (less than 7 km), there is no a priori way to determine from the stepped leader phase whether a given flash will continue as an IC flash or become a CG flash. In combination, these factors justify our use of the CG locations as a proxy for the IC locations in this particular case. It is less clear whether this is a valid assumption globally. Much larger horizontal extents for IC flashes in the tropics have been suggested by Mazur et al. (1998) in the case of "spider" lightning; however, there are no statistics on the horizontal extent of these flashes, nor is it really known whether they are common or anomalous. There is not even a quantitative way to define an exact "distance" to such a flash. However, with our risk-based approach, the parameter of interest is the distance to the closest part of the flash. Since the intensity drops rapidly as a function of distance, this closest part dominates the signal. For a channel oriented radially to the observer, the distant parts contribute little, while if the channel is tangential to the observer, most of the channel contributes. Crucially, this results in an error, which is always on the side of caution: the closest position of the flash may be ranged to be too close, but in principle never too distant. When horizontal extents are only a few kilometers, the effect is negligible. With very long channels, the number of false positives will increase.

Although there are differences in the time-domain behavior of IC and CG flashes, our results (based on a single storm) suggest that the radiated HF energies are not very different. Such equivalence is perfectly feasible at a given frequency if there is a highly dominant process that occurs in both IC and CG flashes. At present there is not sufficient consensus on the formation of HF radiation to determine whether such a process exists. First return strokes are generally found to be very strong individual emitters (Weidman et al. 1981; Beasley et al., 1982; Willett et al., 1990; Cooray and Pérez, 1994), while Le Vine and Krider (1977) and Jayaratne and Cooray (1994) found subsequent strokes to emit significantly less. Willett et al. (1990) analyzed the spectra of characteristic pulses before the stepped leader phase, and found they have intensities about 10 dB lower than the return stroke. On the other hand, Mäkelä et al. (2007) found that a "chaotic leader" associated with a subsequent stroke can emit significantly; such a

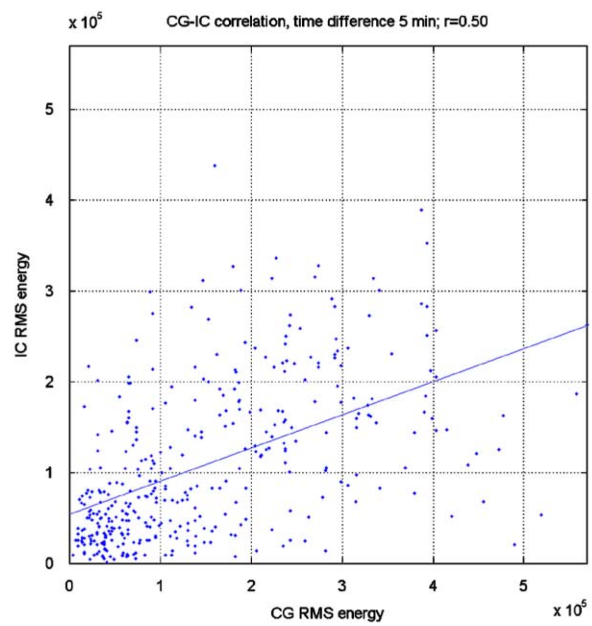

Fig. 12. Correlation of CG and IC energies.

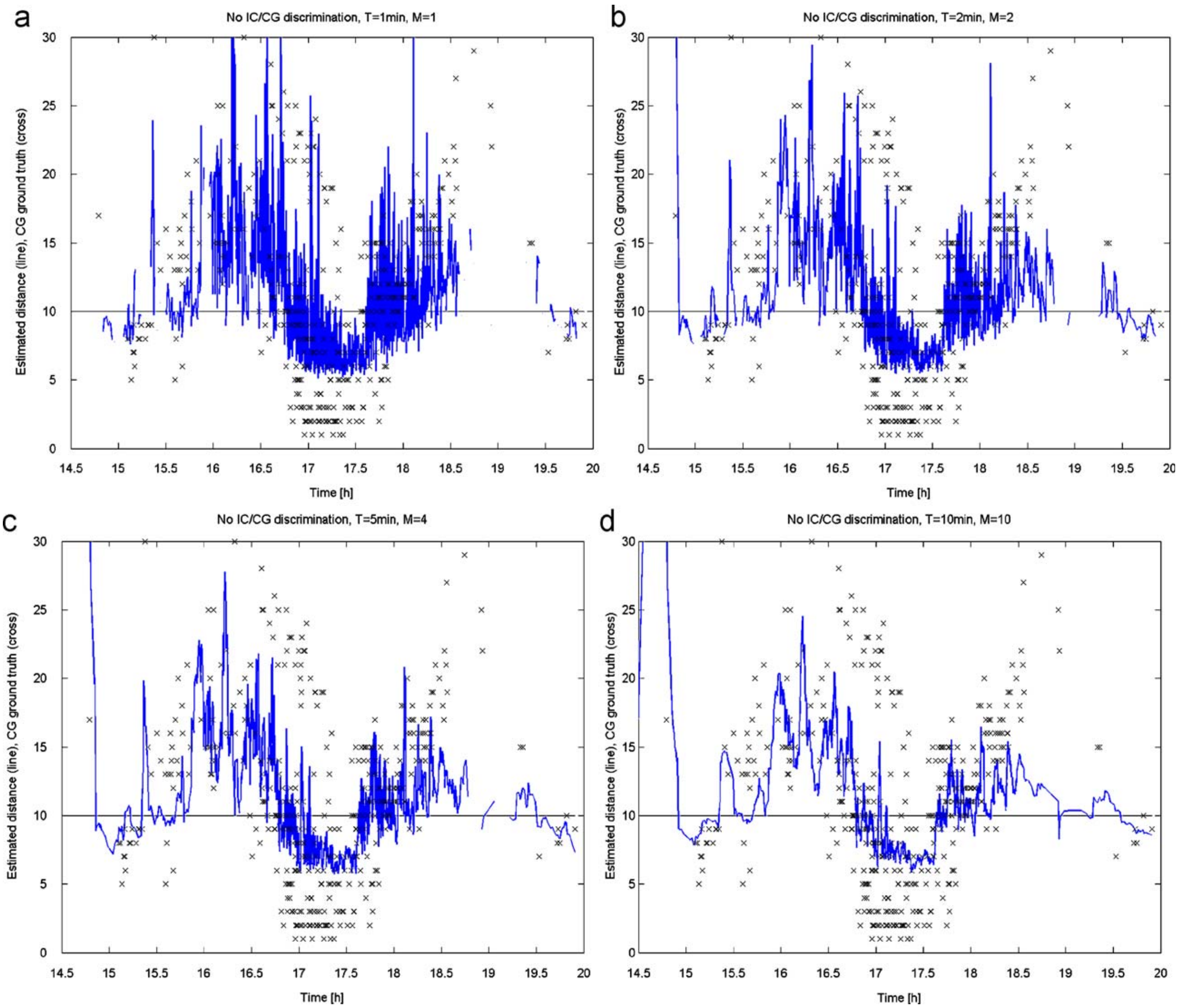

Fig. 13. Four examples of effects of floating average parameters. The distance has been calculated using the equation $I = b/R^{3.3}$, and normalized to 12 km. Note that this approximation overestimates the distance when the flashes are within the "danger zone" (10 km, drawn with a solid line), but still places the flashes within the danger zone. (a) Using only single most intensive flash over 1 min gives fast response but high scatter, (b) using $T = 2$ min, $M = 2$ flashes gives less scatter while still responding quickly to approach, (c) using $T = 3$ min, $M = 4$ flashes gives a smooth response, but is slow in giving an alarm and slow in giving an all-clear, and (d) using $T = 10$ min and $M = 10$ flashes essentially follows the "average" location of the cell, but is inadequate for warning purposes. Either (b) or (c) may be optimal for this particular cell (and this climatology).

chaotic leader was considered most likely to be associated with an in-cloud process. HF radiation in cloud flashes was measured by Jeyanthiran et al. (2006), who found high HF intensities associated with the onset of cloud flashes. Le Vine (1980) showed that bipolar pulses are very strong HF emitters, verified further by Willett et al. (1989). In other words, the existing experimental data cannot answer the question. It must also be noted that the earlier studies analyzed peak intensities rather than energy; when integrating over the whole flash, a long-lasting low-intensity process may well have a larger total effect than a single impulsive event. Within our data set, we compared the narrowband intensity of CG flashes to flash multiplicity and found no statistically significant correlation. This suggests that compared to other processes, subsequent strokes as such are not significant radiation sources.

The issue of system calibration has not been addressed. Our calibration is purely empirical, and due to the nonlinear characteristics of our receiver, we cannot invert the measurements to measure the absolute narrowband energy spectral densities. Although absolute measurements have been made (see e.g. Le Vine (1987) and Nanevicz et al. (1987)), they are average results for a large number of flashes, using a wide variety of techniques and normalizations. The calibrations used in existing commercial narrowband devices have not been published in the open literature, and in any case are likely to be highly dependent on the specific system characteristics. There have been direct narrowband measurements using parallel-plate antennas (e.g. Cooray and Pérez, 1994; Jayaratne and Cooray, 1994), but these have very high noise levels. The spectra from individual lightning processes have been transformed from broadband data by Willett et al. (1990) and Weidman and Krider (1986), but again the issue of noise has not been addressed in these studies. In addition, the measurements have typically not measured the full flash, especially its in-cloud processes, which are a crucial part for narrowband detection. Therefore, there is no adequate standard set of records that could be used to generate electromagnetic signals against which narrowband devices could be tested. Such a standard set should be collected if adequate verification is to be performed. However, calibration can also be done in the way done in this paper, using natural flashes and lightning-detection networks. This method is relatively simple to automate, but it should be done separately for each receiver type. Further, it would need to be done at several geographical locations.

The methods we have described can be used to scientifically verify other existing narrowband devices, as required by American Meteorological Society (2002). Such verification is made difficult by the fact that it is often difficult to tell what parameter such a device is specifically measuring. We suggest that because of fundamental physical limitations, such devices are best suited to measure the distance to the closest edge of an ongoing storm, and their performance could be quantified according to how accurately they track this edge. In particular, transitions across the danger distance (10 km) need to be accurately determined. However, obtaining unambiguous ground truth is not simple. Ideally, it should be given by a combination of CG lightning-detection networks (used in this study), VHF imaging of in-cloud processes (not used in this study), and radar information (not used in this study).

6. Conclusions

We have shown that if the requirement for accurate flash-by-flash positioning information is loosened, a lightning-detection system can be designed based on very simple principles. The warning principle for such a system can be based on the so-called 30–30 rule. We showed that the full-flash energies of lightning flashes are distributed log-normally, with the 5th and 95th percentiles of the intensity being within a factor 4 of the median intensity. The source intensities are constant enough that ranging based on signal intensity alone is realistic, since the intensity drops vary rapidly as a function of the distance. A ranging accuracy of 10% is theoretically obtainable if several flashes are averaged. We further showed that variations in ground propagation variations will lead to large uncertainties when the distance is larger than 20 km, but can be neglected for shorter distances. If very simple parameterizations are desired, it is difficult to differentiate between IC and CG flashes. However, we showed for one Finnish storm that CG and IC flashes have comparable narrowband source intensities, and therefore ranging of the closest edge of an active storm cell does not require CG/IC differentiation. Using both CG and IC flashes in this manner improves the ranging accuracy, since a larger data set can be used. Although our data set is too small to consider the method to be fully reliable, we propose methods by which narrowband devices in general can be independently verified.

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