Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 156–168

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

# Using full-flash narrowband energy for ranging of lightning ground strokes

J.S. Mäkelä[a,*], N. Porjo[a], T. Ahola[b], A. Hämäläinen[b], J. Jantunen[b]

[a]*Nokia Oyj, Salo 24101, Finland*
[b]*Nokia Research Center, Helsinki, Finland*

Received 19 February 2007; received in revised form 19 September 2007; accepted 28 September 2007
Available online 6 October 2007

**Abstract**

We demonstrate that narrowband measurements can be used for rudimentary ranging of cloud-to-ground lightning flashes. The system at present responds to both intra-cloud and cloud-to-ground lightning; ranging is demonstrated for a subset of flashes known to be cloud-to-ground lightning. The system uses a ferrite-core antenna with a length of about 4 cm and diameter 4 mm, and operates on a narrow band at about 1 MHz, close to the HF band (3–30 MHz). It downmixes the signal to audio frequencies and operates in a manner which is very similar to an AM radio. The system triggers on all impulses which exceed a given adjustable threshold above the ambient noise level, and records 1 s of data. Such a system was used to collect lightning-caused electromagnetic disturbances during summer 2006 in Finland. The output is compared to two scientifically verified references: a flat-plate broadband antenna measuring the vertical electric field and a commercial lightning location network giving flash location. A key aim of the system is to reduce the information to as few parameters as possible. Peak intensity and full-flash energy were used as simple parameters. It is shown that accurate flash-by-flash ranging is not possible with this method; however, it is shown that the method can be used to track clusters of ground flashes within a range of about 50–100 km with an accuracy of about 10 km.


*Keywords:* HF radiation; Lightning detection; Narrowband measurement

## 1. Introduction

There are a variety of methods for the remote detection of lightning. The main commercial driver for such systems is early warning and therefore protection of property and individuals (Cummins et al., 1998). Existing systems have largely been driven by a need for high accuracy, fast response, and accurate flash-by-flash ranging. If a low performance is sufficient, well-verified flash counters have been presented in the literature that could be used as rudimentary warning devices. Flash counters can detect the presence of lightning within an effective radius of about 20 km and are capable of differentiating between intra-cloud (IC) and cloud-to-ground (CG) lightning flashes (Anderson et al., 1979; Mackerras, 1985). They are not widely used at present, however. A category of detection technology that has not been covered in the recent scientific literature is electronically simple low-end detectors small enough to be portable. Such devices, if accurate

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

1364-6826/$ - see front matter 
doi:10.1016/j.jastp.2007.09.014

and reliable, could potentially be useful for triggering warnings to users, or automatic protection actions for small installations. Even relatively modest performance would be sufficient to fulfill this need. A useful benchmark is the "30–30" rule described e.g. in American Meteorological Society (2002). Danger begins when the time between flash and thunder is less than 30 s, and the danger is over when no thunder has been heard for 30 min. In the simplest case, a flash-counter functionality could be sufficient if the range is large enough; however, a crude level of ranging would be desirable. Such portable or handheld devices are indeed marketed and commercially sold. However, as noted by the American Meteorological Society (2002), their performance has not been rigorously and scientifically established. Although there is little open literature about such devices, the information available from patents suggests that they generally sample electromagnetic interference at some specified (narrowband) frequencies, and trigger an alarm when an energy threshold is exceeded.

Such interference, even from very distant sources, can also be heard on an ordinary AM radio. Although this interference is often ignored by ordinary users, storm-chasing hobbyists have long used these disturbances to determine the presence of lightning activity. Our system is, in effect, a modified AM receiver which is optimized to capture such disturbances. The system has a small ferrite-core coil antenna that resonates at about 1 MHz, slightly below the HF band (3–30 MHz). The system then downmixes the signal to audio frequencies, similarly to the way an AM radio does. This signal is then processed in the time domain. Narrowband methods of this type are well known to present only a picture of the "composite flash" as discussed by Nanevicz et al. (1987) and Le Vine (1987). In other words, especially when the bandwidth is narrow, a variety of processes including preliminary processes, subsequent strokes, and in-cloud processes are combined into a single signal with little internal structure. Although subtle differences in radiation intensity have been observed between 3, 5, and 10 MHz by Edirisinghe et al. (2006), we make the assumption that the existing literature on HF radiation is valid down to 1 MHz. The average radiation intensity is known to drop as $1/f$ in this region (Le Vine 1987). As noted by Le Vine (1987) and especially Nanevicz et al. (1987), making different narrowband studies compatible can be very problematic because of the different assumptions made about bandwidth. IC processes are suggested to be very strong sources of HF radiation by Le Vine (1980) and Willett et al. (1989). The general consensus is that return strokes are very strong HF emitters, possibly the most intense (Weidman et al., 1981; Krider et al., 1977; Cooray and Perez, 1994; Beasley et al., 1982; Willett et al., 1990). Subsequent strokes have been studied by Le Vine and Krider (1977) and Jayaratne and Cooray (1994) and were found to be weak emitters. In general, leader processes are weak HF emitters, although in the case of "chaotic leaders" the intensity can be high (Mäkelä et al., 2007). Taylor (1973) observed narrowband HF radiation to correlate with severe weather and tornados, but no further scientific development in this direction is known. Overall, the literature suggests that the HF region is suitable for detecting the existence of lightning, but many details about how to interpret the signal are still open.

Our tests were performed at high latitudes in Finland, during the summer of 2006. The system was operated in a data-collection mode, triggering whenever an energy threshold was exceeded and storing 1-s records of downmixed narrowband data. The data were post-processed later. The results presented here pertain only to the ranging of flashes which are known from reference devices to be ground flashes. A full lightning detection system requires distinguishing between CG and IC flashes. Although a fully functioning system is not operational yet, we show that the signal output can be interpreted based on known scientific understanding of lightning processes. We also present correlations to two known reference sources. First, the data are compared at millisecond accuracy to reference broadband data. Second, the results are compared statistically to reference data from a lightning location system. Simple parameterizations were used to define estimates of the full-flash energy. These parameters are such that they can easily be calculated in real time with modern microprocessors. This improves both the speed and simplicity of the overall system. It is shown that narrowband measurements can be useful for lightning detection, if it is accepted that the accuracy is limited to following storm cells or fronts rather than pinpointing single flashes. It is shown that two orthogonal coil antennas improve the performance significantly, but even a single coil provides adequate performance for many applications. The method is not well suited for measuring the direction of a storm, but for example approach speed of the threat can be estimated.

The measurement location and setup are described in Section 2. Section 3 shows typical data outputs for CG and IC flashes. In Section 4, the data are compared at millisecond resolution to the broadband reference. Section 5 shows the statistical correlation between the measurements and the lightning location data, including an event in which the distance to a well-defined active storm cell was tracked over 3 h. The results are discussed in Section 6, as well as limitations of the method. Conclusions are drawn in Section 7.

## 2. Measurement sites and system

The measurements were carried out at two locations in Finland. The site in Piikkiö, Finland (EUREF coordinates 60.419839N, 22.47147W) was located on the premises of a private home in a thinly built one-story residential area. Another site was located in the meteorological observatory of the Finnish Meteorological Institute in Jokioinen, Finland (EUREF coordinates 60.813826N, 23.497903W). The site is about 80 km due northeast from Piikkiö. The ground between the sites is predominantly clay, with no major lakes, and thus propagation is mainly over the ground except for a small sector of ocean to the southwest of Piikkiö. The measurements were carried out between July 1, 2006 and September 10, 2006 (69 days). The narrowband system and the broadband reference were both synchronized to the same GPS device with millisecond-level precision.

A schematic of the narrowband detection system is shown in Fig. 1. In effect, the devices are simplified AM radios, operating at a central frequency and bandwidth that could be adjusted by choice of coil and resonators. The data were then downmixed to audio frequencies using a mixer, which means that audio hardware and software could be used in all the processing, and also decreased the data storage need considerably. The key parameters are the antenna's resonant frequency $f_c$ and the local oscillator (mixer) frequency $f_{LO}$. The antenna resonates as $\exp(i\omega_c t)$; the mixer signal is multiplied giving $\exp[i(\omega_c \pm \omega_{LO})t]$; the higher frequency is filtered out. The data were then digitized at 44.1 kHz to produce an audio output signal. The downmixing simplifies the system requirements dramatically, but has the side effect of losing some information. In particular, all phase information is lost, and the amplitudes of sharp peaks in the high-frequency signal are randomized when multiplied with the mixer signal. This means that the system output for very abrupt peaks such as return strokes will be non-linear and non-deterministic. For the measurements shown in this paper, the center frequency was about 1 MHz.

An RME Fireface 800 audio interface was used to enable simultaneous data capture from up to nine narrowband receivers, with GPS time synchronization to UTC time with better than millisecond-level accuracy. The audio output was continuously fed into a computer and analyzed by software. Since the noise level at a given frequency varies significantly as a function of atmospheric and ionospheric conditions, the system had to be adjustable. The noise floor level for each channel was periodically measured as a minimum of peak values from recently captured blocks of audio. Data capture was activated when the signal amplitude exceeded a relative threshold value above the baseline noise floor. The trigger level could be manually adjusted, and was kept at a value of 6 dB throughout the measurements. This was chosen as a suitable compromise that triggered on most close lightning flashes while still keeping the data amounts manageable. The signal from 130 ms before to 770 ms after the trigger was saved to ensure that all preliminary processes were recorded; the total recording length was thus always 1 s.

For the statistical results presented in this paper, the uncorrected front-end data were used, which means that the times are accurate to the nearest second. Given the low flash rate in Finnish storms, this means that flash-by-flash correlation is possible with sufficiently high accuracy. The total triggers for the whole summer are 204,000 in Jokioinen and 124,000 in Piikkiö. The locations were well protected from manmade interference, with manmade interference contributing less than 5% of all triggers (estimated from triggers during lightning-free days).

The reference instrumentation in the Piikkiö and Jokioinen sites was essentially identical. Three parallel-plate antennas were used with diameter 50 cm, and plate separation of 30 mm. One of the antennas was attached to a buffer amplifier designed at the University of Uppsala and identical to that described in Cooray and Perez (1994). One plate had a 470 μH air-core inductor causing resonance at 1 MHz. The broadband signal was split among two of the channels set at different voltage settings (100 mV/division and 2 V/division).

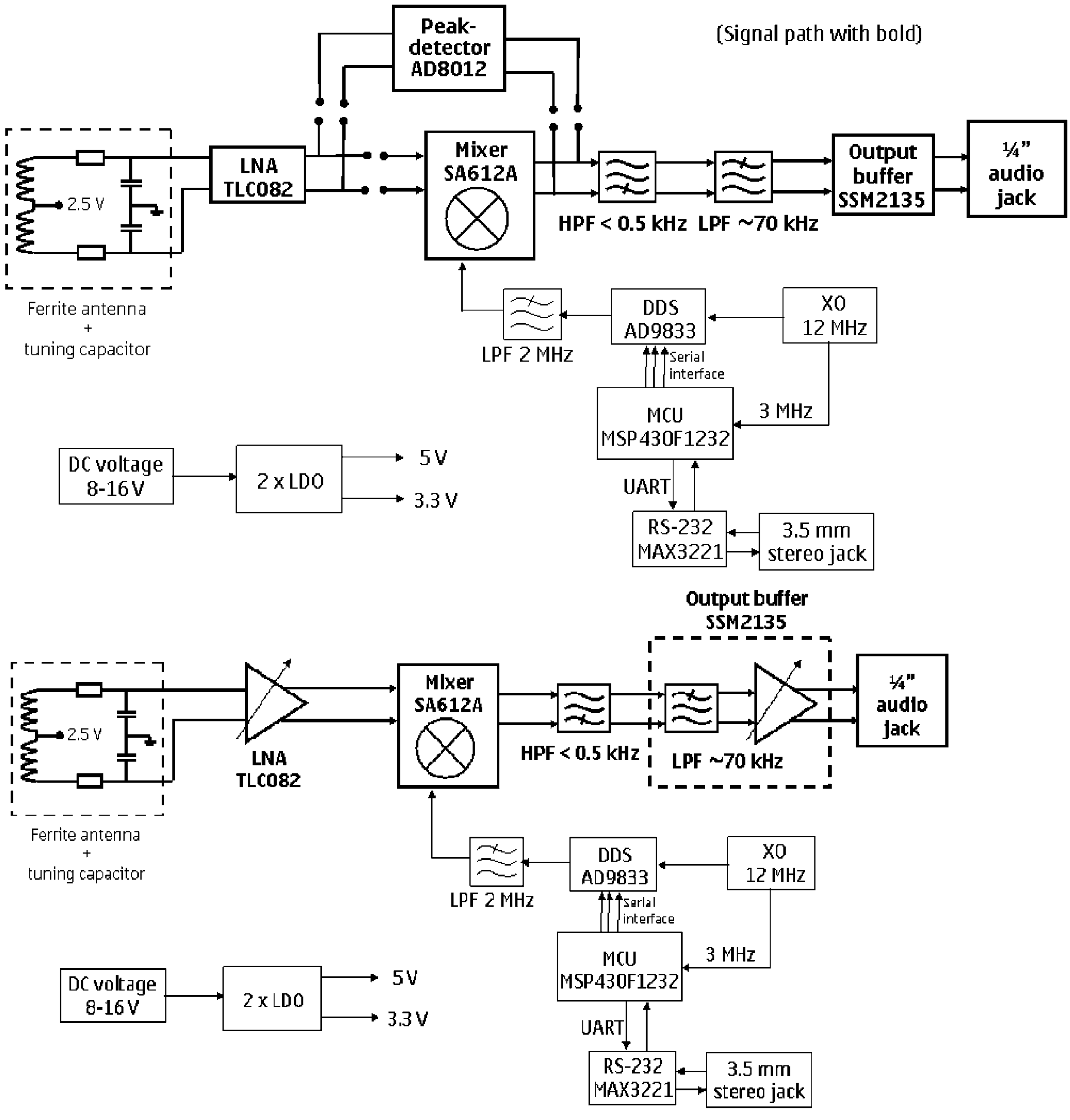


Fig. 1. Schematic of the narrowband detection system electronics.

The oscilloscope and front-ends were synchronized with the same GPS device, enabling time synchronization of both to UTC time with an accuracy of about 1 ms. The oscilloscope was operated at 100 Msamples/s, giving a record length of 320 ms per channel. Thus, the reference device did not capture the whole 1-s signal captured by the narrowband devices.

Reference flash location data were provided by the Finnish Meteorological Institute. The characteristics of the specific Scandinavian system are described e.g. by Tuomi (2003). The system in use in 2006 utilized multiple sensors located throughout Scandinavia, and was capable of measuring the individual strokes of well-defined vertical ground flashes to a typical accuracy of better than 1 km and a time accuracy of 0.1 ms synchronized to UTC time (Tapio Tuomi, personal communication). The detection efficiency of all such systems is known to be less than 100% (Cummins et al., 1998), and we have observed some anomalies in the data, as shown in Fig. 4 of Section 4. However, the location data have not been further quality-controlled for the purposes of this paper.

## 3. Sample outputs

There was no discernment in the data capture between cloud-to-ground CG lightning, IC lightning, and noise; the aim was to capture all disturbances that exceeded the threshold. In all cases, the top panel shows the east–west coil, and the bottom panel the north–south coil. The CG flash in Fig. 2 was identified from the lightning location data; it was captured both in Piikkiö (top) and in Jokioinen (bottom). The IC flash of Fig. 3 was identified from the lack of any CG flashes around the time of the flash; thus, the identification is only probable. Qualitatively, there are differences in the different signals, with CG signals typically highly peaked and rather short in duration (at least in Scandinavia) while IC signals are long in duration and have less pronounced peaks. The signals from noise sources can be extremely varied. The identification between CG and IC signals (and noise) is beyond the scope of this paper; the rest of this paper uses only the subset of flashes for which a corresponding CG flash is found in the lightning location data.

As discussed by Mäkelä et al. (2007), for a narrowband system the peak of the signal is not in general the best parameter to measure signal intensity for continuous processes. The RMS energy is expected to be more reliable especially when multiple processes are overlaid. For our system, with its phase randomization, the effect on the peak should be particularly severe. In order to compare the methods in practice, two simple parameters were calculated in real time for each 1-s signal: the highest peak measured during the second and the glitch energy, which is defined as the area under the curve of a time–voltage plot. Due to the relatively high ambient noise levels, we needed to normalize the glitch energy so that pure noise gives a value of zero. Thus, the whole 1-second flash was stored in memory, and the variance $\sigma$ calculated. The glitch energy was then defined to be the square sum of all values which exceeded $3\sigma$. This is effectively equal to the RMS energy of the signal minus the RMS energy of the noise, especially when there are only a few well-defined peaks above a constant noise background. The physical interpretation becomes slightly distorted when the signal-to-noise ratio is low and the signal consists of multiple weak pulses just above the noise threshold. This type of signal is associated in particular with distant IC pulses. However, for the main features of interest (close flashes), the glitch energy is an easily calculated parameter which is also valid physically, and hence a usable parameter.

## 4. Sample flash (July 24, 2006 at 10:22:49 UTC)

One event is shown here which confirms that the front-end response is correlated with the response of the broadband electric field. The lightning location system identified a multiplicity-eight flash about 80 km due northeast of Jokioinen (Table 1). The first five subsequent strokes were captured by the broadband system. It must be noted that the return stroke that triggered the broadband is not actually identified in the lightning location data. However, the broadband data of Fig. 4 show that the triggering event was unequivocally a return stroke. Such errors in the lightning location data are seen occasionally. For the purposes of presentation clarity, only the first 160 ms of the signal are shown in Fig. 4. Rows a and b show the narrowband data from two orthogonal coils, oriented in the north–south and east–west directions, respectively. The units are arbitrary and proportional to the voltage from the antenna coil. Rows c and d show the raw output from the flat-plate antenna resonating at 1 MHz (raw and smoothed with a 100-point moving average to lower the noise level). Row e shows the broadband electric field data. The times of return strokes given by the lightning location system are given in row f. Seven key points of correspondence have been marked with A–G. Point A is the preliminary breakdown. Since the flash occurred almost due northeast, it should be seen equally in both coils. The non-linear antenna response is apparent between A and B; the return stroke is by far the most intense peak in the flat-plate resonators but is not even the largest peak in the narrowband sequence. The peak at C was not identified as a return stroke in the lightning location system, and the detailed broadband data (not shown) suggest that it was an in-cloud pulse. Randomization of the phase is particularly apparent in the narrowband

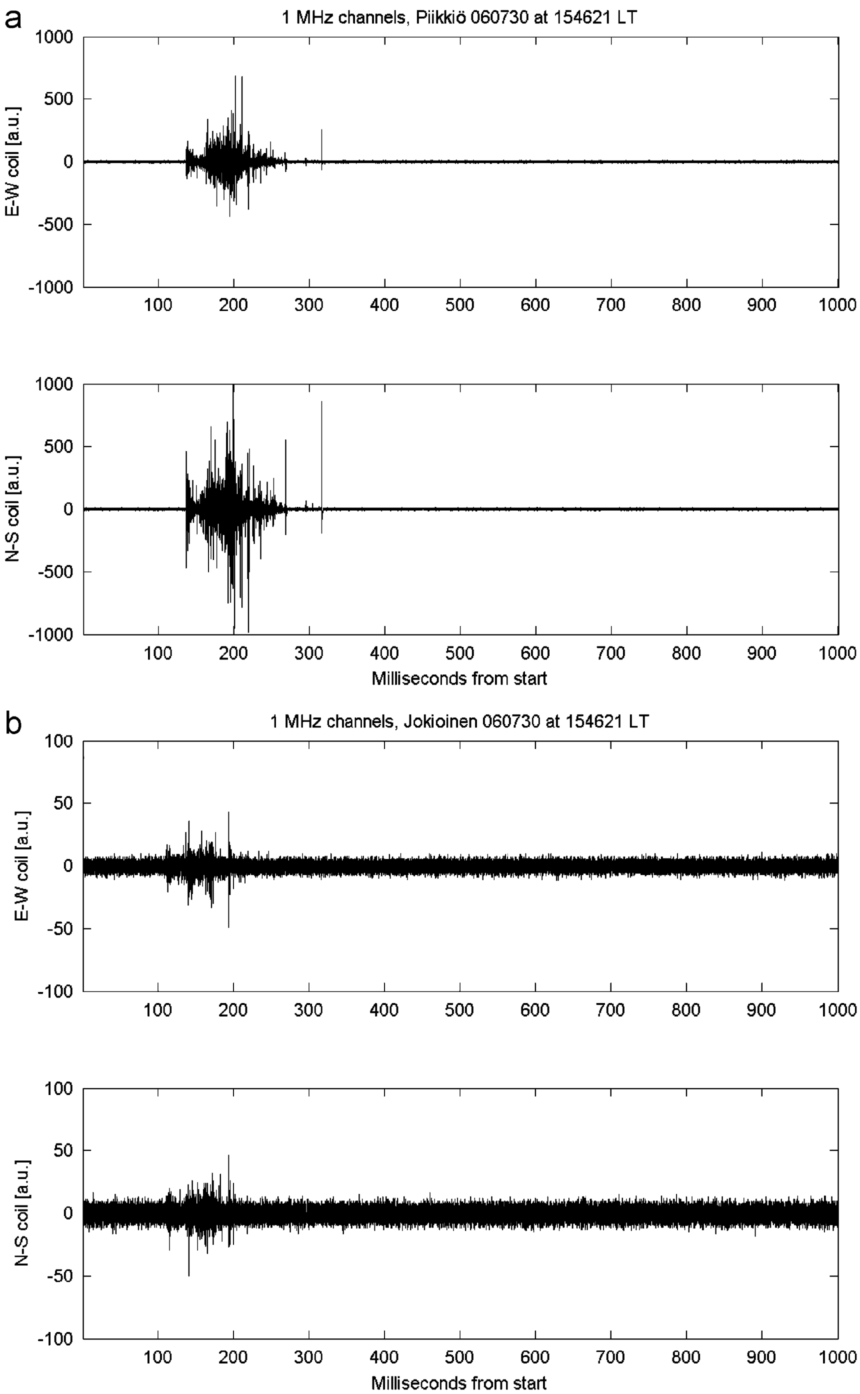


Fig. 2. Cloud-to-ground flash close to Piikkiö with single return stoke and strong preliminary breakdown, seen in both stations.

data. At D there is a return stroke that is seen in all devices. However, the intensities of the narrowband peaks at and before the return stroke appear random. A dart leader and return stroke occurred at time E, causing a strong response in all instruments, and was almost symmetric in both narrowband channels. Between E and F, there is a series of weak pulses only barely visible in the flat-plate

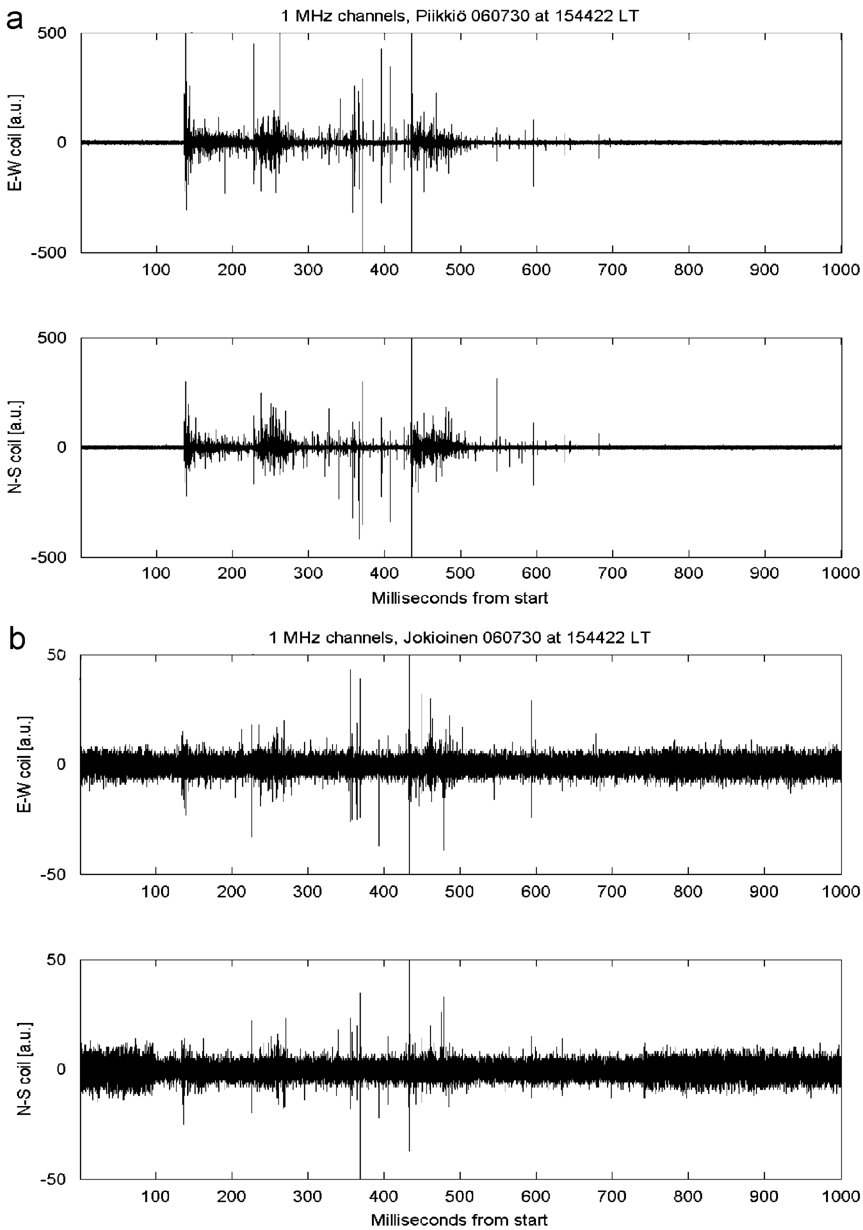


Fig. 3. Probable intra-cloud discharge close to Piikkiö, seen in both stations. Note factor 10 difference between vertical scales.

antennas but strong in the narrowband signal. The response to the return stroke can have opposite polarity in the two narrowband channels, as at F.

Fig. 5 shows the detailed system response at sub-millisecond time scales. The first breakdown-return stroke sequence is shown at high time resolution. The top panel shows the intensity from the narrowband coil (top) and the voltage output from the flat-plate antenna, smoothed with 100-point moving average to distinguish relevant details. The units are arbitrarily normalized and shifted for clarity. The bottom panel shows the broadband electric field in V/m. The broadband electric field data are saturated at both the top and the bottom. The preliminary breakdown did not in this case begin with a well-defined high-intensity pulse sequence, but rather there was continuous activity starting at 324.5 ms, changing into a stepped-leader phase at around 348.5 ms, with a return stroke at 349.5 ms. It can be seen that the narrowband system

Table 1
Information on the sample flash

| Stroke # | Time (UTC) | Latitude | Longitude | Intensity (kA) |
|---|---|---|---|---|
| RS1 | 132249.3809 | 61.3246 | 24.2389 | −17.1 |
| RS2 | 132249.4043 | 61.326 | 24.2359 | −28.6 |
| RS3 | 132249.4433 | 61.3233 | 24.2409 | −53.4 |
| RS4 | 132249.5022 | 61.3297 | 24.2587 | −20.3 |
| RS5 | 132249.5282 | 61.3284 | 24.2359 | −10.4 |
| RS6 | 132249.7775 | 61.3284 | 24.2504 | −20.6 |
| RS7 | 132249.8368 | 61.3272 | 24.2395 | −11.6 |
| RS8 | 132250.0975 | 61.3263 | 24.2389 | −9.2 |

responds to the same impulses as the HF antenna, but the response is randomized so that the amplitude of individual peaks in the narrowband data is not well correlated with the amplitude in the flat-plate data. At the stepped leader and return stroke, the flat-plate reacts very intensely, but the amplitude of the coil signal is lower than for some of the earlier pulses. The results show that the narrowband system is best suited for capturing continuous processes that have time scales of a few milliseconds. For highly impulsive events, the response becomes garbled, but because of the high gain, a signal is nevertheless detected. Return strokes that are preceded by dart-stepped leaders (such as D and E) are thus likely to be captured. Thus, even if the response to such fast events is unpredictable, no significant lightning processes appear to be completely missed by the system.

## 5. Results

A subset of the narrowband data was chosen for which lightning location data existed at the same instant. The real distance to the flash was therefore known. The intensity was measured both as the glitch energy and as the highest peak in the 1-s signal. Fig. 6 shows both the glitch and peak energies as a function of distance. With both methods, the data become essentially noise above 100 km, but below 100 km there is a correlation between distance and measured intensity. The measured intensity of course is a function of both source intensity and distance; however, there are no existing measurements of the distribution of HF emission intensities at the lightning source. Although it is clearly incorrect to assume that the intensities would be identical for all flashes, it is feasible to assume that the distance effect dominates in our data set, which has more than an order of magnitude difference between the shortest and longest distances. With this assumption, a log-log fit was made to determine the best estimate for the exponent. Both the peak and glitch energy were found to follow approximately a $1/R^3$ distribution dependence on distance, although with significant amounts of scatter. Fig. 7 finally shows the best fit obtained by assuming that the measured glitch energy $E$ has a distance dependence of the type $E(R) = a + (b/R^3)$. The fit is far from perfect, as shown by the deviations from the least-squares fit (solid line). In particular, above 50 km the ranging becomes quite inaccurate. The scatter is predominantly within 10 km of the real distance.

Two orthogonal coils can in principle be used for direction-finding. However, downmixing loses the phase information, and thus the angle is projected to the first quadrant. The coils were assumed to have ideal angular response $G(\varphi) = \cos^2(\varphi)G_0$, where $G_0$ is the gain along the main axis. The arctangent of the signal intensities thus gives the angle. Fig. 8 shows the correlation between the measured and actual angles to two perpendicular coils, restricting the range so that only flashes within 100 km are included. The correlation is $r = 0.83$, which is statistically significant. More usefully, the squared sum of the orthogonal signal intensities eliminates the cosine term, and gives a better estimate of the real intensity value. When this value is used to estimate the distance, the scatter is reduced considerably, as seen in Fig. 9. The light gray dots show the distance derived from a single coil; the black dots show how the accuracy improves when both coils are used. The use of two coils thus almost doubles the useful ranging distance from about 50 to about 100 km.

Overall system performance is shown by analyzing a sample case. A series of small storm cells formed almost overhead the Piikkiö station on July 30, 2006 after 15 local time (12 UTC). Again, only those flashes were chosen which had a corresponding CG signal in the lightning location system. The distance to each flash was estimated using the above method. The distance as a function of time is shown in Fig. 10. The top panel shows the distance to each flash calculated from the lighting-location data; the bottom panel shows the distances estimated from the glitch energy. There is scatter in the results, but overall there is a reasonable correlation between the real and measured distance. The approach of the storm before about 17 LT can be seen quite clearly.

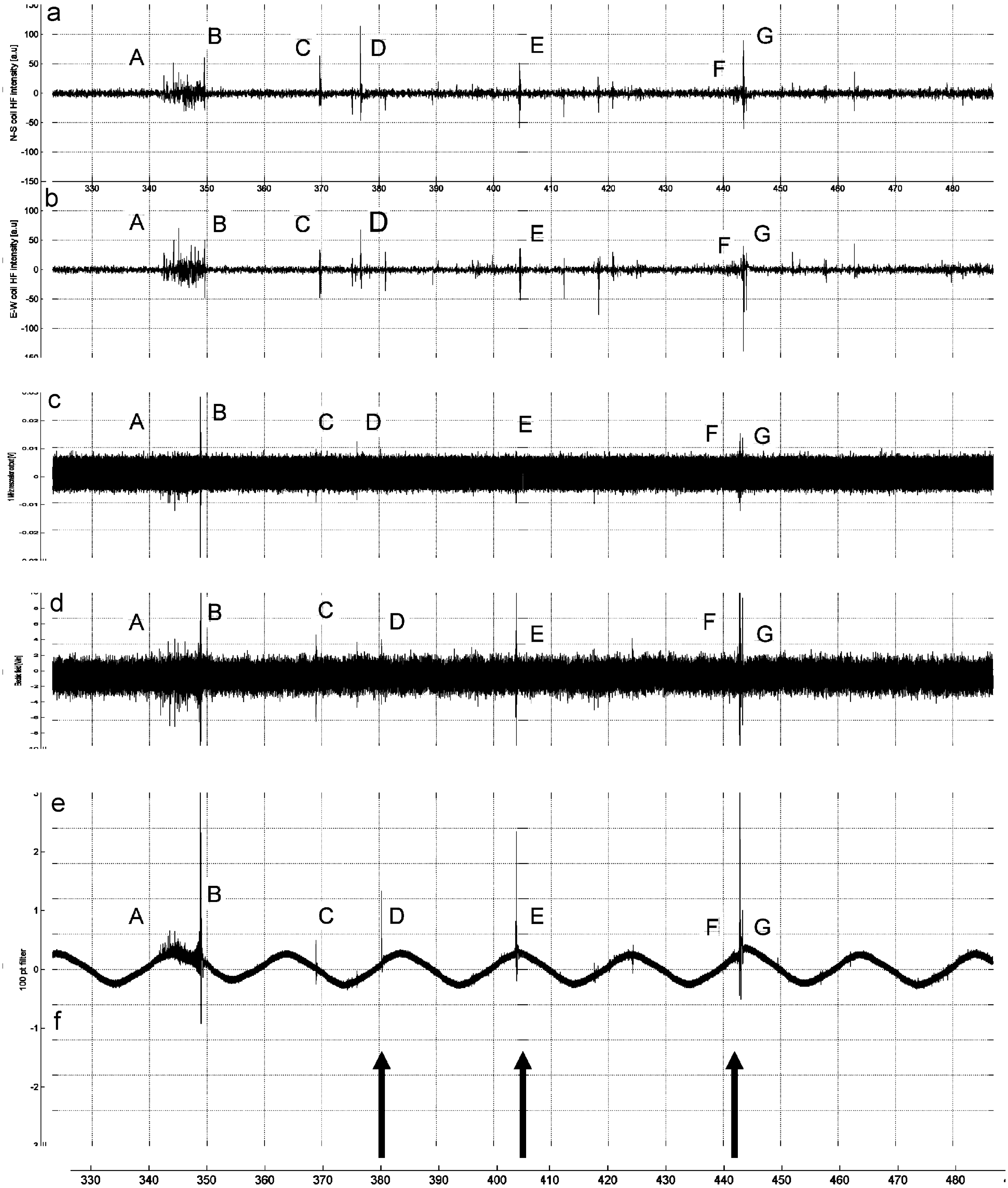


Fig. 4. Comparison to reference data. A 160 ms sample is shown. Top panel shows output from the 1 MHz resonator oriented in the E–W direction; second panel is a 1 MHz resonator in the N–S direction; third panel is raw output from parallel plate antenna resonating at 1 MHz; fourth panel is the output from panel 3 filtered with a 100-point floating average; fifth panel is the broadband reference as described in the text. The thick arrows point to return strokes identified by the lightning location system; note that the first return stroke has not been identified in the lightning location data. The letters A–G point to the most important points of correspondence discussed in the text.

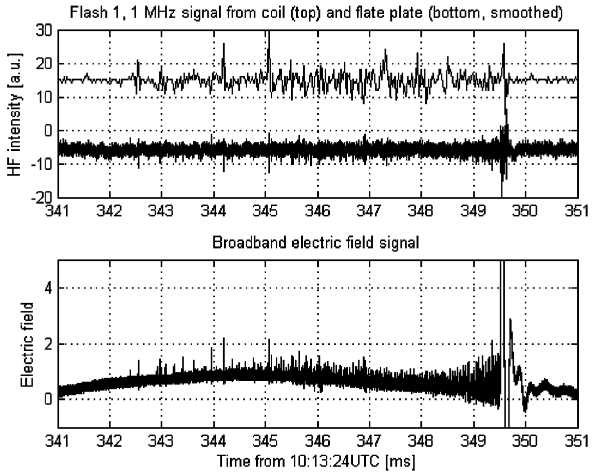


Fig. 5. Breakdown and return stroke sequence at sub-millisecond resolution.

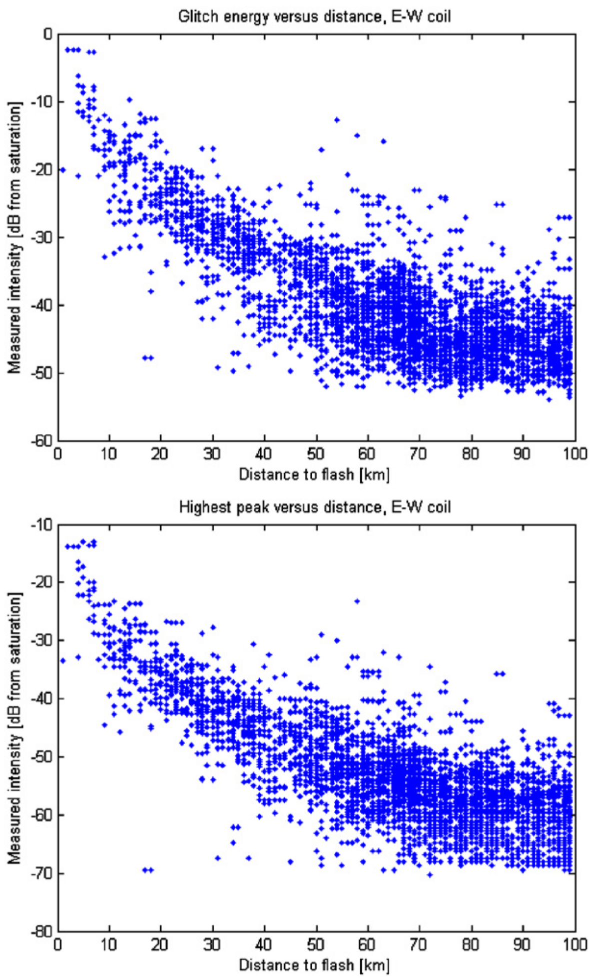


Fig. 6. Glitch energy (top panel) and highest peak (bottom panel) versus distance for flashes within 100 km.

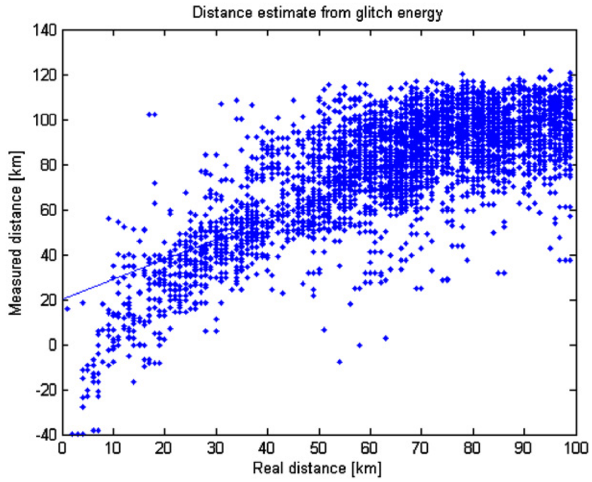


Fig. 7. Best-fit estimate of distance as a function of glitch energy, using a function of type $E(R) = a + b/R^3$. The fit is most accurate below a distance of about 50 km.

## 6. Discussion

Our results show that narrowband methods can in principle be used for low-resolution ranging of CG lightning, even when the signal is downmixed. It was shown that the system produces signals that are compatible with reference broadband and HF resonator data. Peaks in the broadband signal were also seen in the downmixed narrowband data, though with randomized amplitude. The intensity of any single peak is therefore not a reliable estimate of the energy emitted during that process. Physical details of the fastest processes are lost so that for example the stepped leader–return stroke process is essentially transformed into a single composite signal. However, longer-lasting processes such as the preliminary breakdown are reproduced more faithfully in our system.

The time-domain signal was reduced to a single parameter to represent the intensity of the flash. Two parameters were tested: the highest peak in the 1-s signal and the glitch energy of the full 1-s signal (essentially the RMS energy, as defined e.g. in Mäkelä et al., 2007). It is trivially clear that whatever intensity parametrization is used, the measured signal will drop as a function of distance. However, the measured intensity also depends on the intensity of the signal at the source. No measurements of the source intensity exist in the literature, and such measurements are not straightforward even with our measuring devices and do not fall within the scope of this paper. However, our

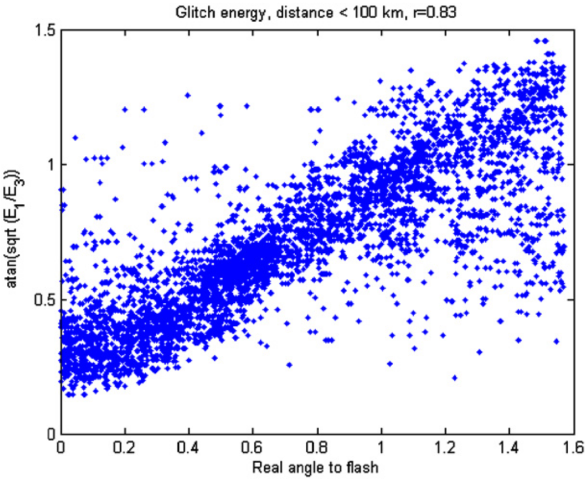


Fig. 8. Calculated angle from glitch energy, using only flashes within 100 km.

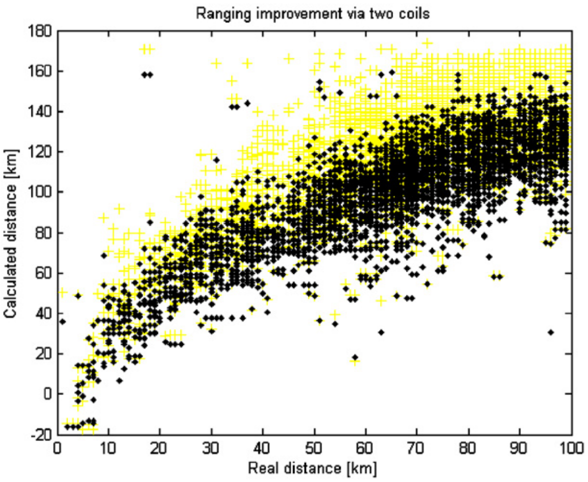


Fig. 9. Effect of using squared sum of orthogonal coils. The values from a single coil are shown in gray; the value of the squared sum of the orthogonal coils is shown in black.

approach is valid if the intensity variations between individual flashes can be considered a second-order phenomenon compared to the distance. That is indeed empirically seen to be the case in Fig. 7, where the distance effect predominates and other phenomena cause scatter in the data. The scatter is further reduced by using orthogonal coils (Fig. 9). Overall, the scatter can be estimated to cause an uncertainty of about 10 km even in the statistical ranging. This is sufficient for tracing the development and movement of active storm cells (Fig. 10).

The physical reason for the rapid intensity drop ($1/R^3$ or faster) is currently not known. For a vertically oriented single radiation source, the

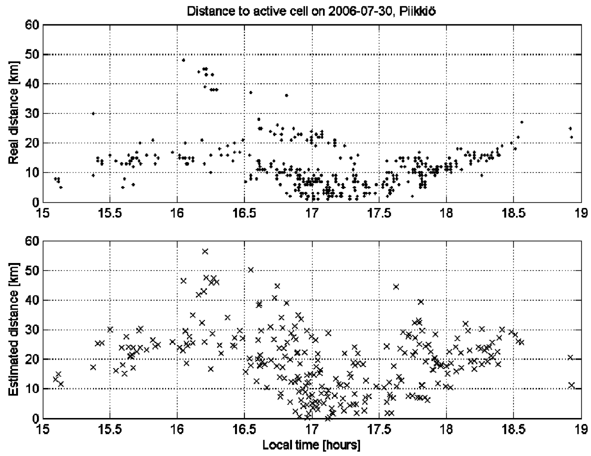


Fig. 10. July 30 storm, real distance from Piikkiö (top panel) and calculated distance (bottom panel).

intensity should drop more slowly as $1/R^2$. However, our system does not have a preferred polarity, and will also pick up the signal from horizontally extending sources that may be associated with in-cloud processes. Over an ideally conducting plane, the mirror current from such a source will cancel out the effect of the horizontal source; however, when the ground is not ideally conductive, some signal will propagate at least short distances. This hypothesis is at present tentative.

Some fundamental restrictions can be seen based on the results presented in this paper. Even if a good CG/IC differentiation can be made, for any individual flash either the distance or the intensity remains ambiguous. A statistical approach is however possible, and it is possible to track the development, distance, and approach speed of an electrically active storm cell. The downmixing system does not preserve phase information, and hence the system presented here is not suitable for genuine direction finding. With separate orthogonal coils, it is possible to determine the angle to a given flash projected to one quadrant, but the value of such information is somewhat limited. At a general level, a system of this type could have potential to function as a flash counter, with a limited ranging accuracy, and in particular estimation of storm approach speeds. The main advantage of such a system is that it could be made physically very small as well as electronically simple. A fully functioning device would not have to be physically larger than a portable AM radio, especially since the algorithms used in this paper could be easily implemented with a small modern digital signal processor.

The results presented show that there is general validity of narrowband ranging, but do not yet constitute a validation of a genuine lightning detection system. Such a system requires an accurate and reliable method to distinguish between CG and IG flashes; in our data set, the distinction was made by the lightning location system. The time-domain plots (Figs. 2 and 3) point to qualitative differences in the time-domain signals of CG and IC flashes, but so far the differences have not been quantified or parameterized in a simple manner. Therefore, it is still an open question whether the differences can be calculated on the basis of a simple metric like the full-flash energy described here, or whether a full time-domain signal analysis is needed (in which case the system can lose much of its simplicity). A clear next step would be to use the same parameterizations for IC flashes to estimate whether cell ranging is still possible. However, such an analysis is not straightforward, since there is no unambiguous reference against which the range estimate could be compared. In principle, isolated single-cell storms (identified by radar as well as lightning location data) could be used, but there were too few such storms in the summer of 2007 to do this reliably. Further measurements and analyses are ongoing.

On a global level, system performance in tropical environments is an open question because there are significant differences in preliminary breakdown intensity at different locations on earth. In particular, Gomes et al. (1998) observed almost no breakdown in tropical lightning in Sri Lanka, but essentially always observed strong breakdowns in high-latitude lightning in Sweden. In semi-tropical Florida, breakdowns do not seem to have a consistent structure (Beasley et al., 1982). This is in contrast to the signatures from return strokes, which do not appear to be significantly different at these three locations (Cooray and Jayaratne, 1994). Since the breakdown contributes a significant proportion of the full-flash HF energy at least in our data set, this is a possible source of error which will require measurements at different locations.

## 7. Conclusions

First results were presented for a simple system which utilizes narrowband measurements for lightning ranging, using a single parameter for the composite energy of the flash. This type of solution would have the advantage of small size and simplicity, and could be realistically implemented in the size scale and complexity of a handheld AM radio. Similar devices already exist on the market, but have not been scientifically validated. The system measures electromagnetic disturbances at about 1 MHz, and downmixes the signal to audio frequencies, simplifying the data analysis dramatically. The downmixing introduces randomization in the signal which limits the system accuracy. The system automatedly measured lightning flashes over one summer in Finland. A best-case analysis was performed that was restricted to flashes which were identified as ground flashes by a lightning location system. Two simple parameterizations were used to estimate flash energy: the peak signal intensity and the integrated full-flash signal intensity. It was empirically found that the full-flash energy statistically drops as approximately $1/R^3$ of the distance to flash. This means that although the method cannot range individual flashes with useful accuracy, statistical estimates of overall cell range could be possible within approximately a 50–100-km radius, with a distance accuracy of 10 km. A functioning system would require distinguishing between IC and CG flashes, but at present it is not known whether this can be done using a single parameter.

## Acknowledgments

We thank Tapio Tuomi at the Finnish Meteorological Institute for access to the lightning location data, and Vernon Cooray and Mahesh Erdilisinghe at the University of Uppsala for guidance on the broadband reference system. We also wish to thank the three anonymous reviewers for suggestions which improved the paper considerably. The research was funded by Nokia Oyj, Finland. Some applications that may be derived from the research are protected under patents granted and pending.

## References

American Meteorological Society, 2002. Updated recommendations for Lightning Safety—2002, available from 〈http://www.ametsoc.org〉.

Anderson, R.B., van Niekerk, H.R., Prentice, S.A., Mackerras, D., 1979. Improved lightning flash counters. Electra 66, 85–98.

Beasley, W.H., Uman, M.A., Rustan, P.L., 1982. Electric fields preceding cloud to ground flashes. Journal of Geophysical Research 87, 4883–4902.

Cooray, V., Jayaratne, K.P.S.C., 1994. Characteristics of lightning flashes observed in Sri Lanka in the tropics. Journal of Geophysical Research 99 (D10), 21051–21056.

Cooray, V., Perez, H., 1994. HF radiation at 3 MHz associated with positive and negative return strokes. Journal of Geophysical Research 99 (D5), 10,633–10,640.

Cummins, K.L., Murphy, M.J., Bardo, E.A., Hiscox, W.L., Pyle, R.B., Pifer, A.E., 1998. A combined TOA/MDF technology upgrade of the US National Lightning Detection Network. Journal of Geophysical Research 103 (D8), 9035–9044.

Edirisinghe, M., Mäkelä, J.S., Montaño, R., Fernando, M., Cooray, V., 2006. Signatures of the lightning HF radiations at 10 MHz, 5 MHz and 3 MHz associated with leader and return stroke processes. In: Proceedings of the International Conference on Lightning Protection, Kanazawa, Japan, 2006.

Gomes, C., Cooray, V., Jayaratne, C., 1998. Comparison of preliminary breakdown pulses observed in Sweden and Sri Lanka. Journal of Atmospheric and Terrestrial Physics 60, 975–979.

Jayaratne, K.P.S.C., Cooray, V., 1994. The lightning HF radiation at 3 MHz during leader and return stroke processes. Journal of Atmospheric and Terrestrial Physics 56 (4), 493–501.

Krider, E.P., Weidman, C.D., Noggle, R.C., 1977. The electric fields produced by lightning stepped leaders. Journal of Geophysical Research 82, 951–1060.

LeVine, D.M., 1980. Sources of the strongest RF radiation from lightning. Journal of Geophysical Research 85 (C7), 4091–4095.

LeVine, D.M., 1987. Review of measurements of the RF spectrum of radiation from lightning. Meteorology Atmospheric Physics 37, 195–204.

Le Vine, D.M., Krider, E.P., 1977. The temporal structure of HF and VHF radiations during Florida lightning return strokes. Geophysical Research Letters 4 (1), 13–16.

Mackerras, D., 1985. Automatic short-range measurement of the cloud flash to ground flash ratio in thunderstorms. Journal of Geophysical Research 90 (D4), 6195–6201.

Mäkelä, J.S., Edirisinghe, M., Fernando, M., Montaño, R., Cooray, V., 2007. HF radiation emitted by chaotic leader processes. Journal of Atmospheric and Solar-Terrestrial Physics.

Nanevicz, J.E., Vance, E.F., Hamm, J.M., 1987. Observation of lightning in the frequency and time domains. Electromagnetics 7, 267–286.

Taylor, W.L., 1973. Electromagnetic radiation from severe storms in Oklahoma during April 29–30, 1970. Journal of Geophysical Research 78, 8761–8777.

Tuomi, T.J., 2003. IMPACT–SAFIR comparisons in Finland. In: Proceedings of the 12th International Conference on Atmospheric Electricity, 9–13 June 2003, Versailles, France, pp. 657–660.

Weidman, C.D., Krider, E.P., Uman, M.A., 1981. Lightning amplitude spectra in the interval from 100 kHz to 20 MHz. Geophysical Research Letters 8 (8), 931–934.

Willett, J.C., Bailey, J.C., Krider, E.P., 1989. A class of unusual lightning electric waveforms with very strong high frequency radiation. Journal of Geophysical Research 95, 16,255–16,267.

Willett, J.C., Bailey, J.C., Leteinturier, C., Krider, E.P., 1990. Lightning electromagnetic radiation field spectra in the interval from 0.2 to 20 MHz. Journal of Geophysical Research 95 (D12), 20,367–20,387.