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## Detection of in-cloud lightning with VLF/LF and VHF networks for studies of the initial discharge phase

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[1] Lightning initiation and the associated in-cloud parts of lightning flashes have been studied by comparing thunderstorm data from two independent networks, LINET and SAFIR-type systems, operating in the VLF/LF and VHF regime, respectively. The two networks respond to radiation pulses with different length scales; an event detected by VLF/LF must be hundreds of meters long. In all 12 storms studied, up to half of the first in-cloud events detected with the VHF networks were found to be closely time-correlated with the first VLF/LF signal. Range-normalized VLF/LF signal amplitudes of the time-coincident events (TCEs) are comparable to amplitudes of weak cloud-to-ground strokes. Without measured preparatory VHF emission activity, initial breakdown in TCEs seems to start directly with a strong discharge step producing signatures in VLF/LF records. The TCE data are consistent with lightning initiation via a runaway breakdown mechanism that extended over hundreds of meters. **Citation:** Betz, H.-D., T. C. Marshall, M. Stolzenburg, K. Schmidt, W. P. Oettinger, E. Defer, J. Konarski, P. Laroche, and F. Dombai (2008), Detection of in-cloud lightning with VLF/LF and VHF networks for studies of the initial discharge phase, *Geophys. Res. Lett.*, *35*, L23802, doi:10.1029/2008GL035820.

### 1. Introduction

[2] Lightning continues to be studied in many details, including open questions about fundamental processes of flash initiation, channel propagation, and cloud charge neutralization. Much effort (e.g., see recent review by *Rakov and Uman* [2003]) has been devoted to the study of cloud-to-ground (CG) and intracloud (IC) flashes, the latter defined as discharges that do not connect to ground. Since almost all flashes are initiated within clouds, the two types of lightning usually begin with an in-cloud charge movement which we will refer to as an in-cloud event. To date, no difference has been found between the in-cloud events that initiate CG and IC flashes, suggesting that both types of flashes may be inherently similar during initial breakdown and only later evolve, depending on the potential distribution, into either CG or IC flashes. The present paper utilizes

the first signals of flashes detected with different techniques and the time correlations between these signals to investigate initial breakdown mechanisms.

[3] During the beginning of CG and IC flash evolution certain discharge steps are typically detected by networks that exploit the VHF regime of electromagnetic emission [e.g., *Mazur et al.*, 1997]. According to general understanding, VHF radio signals are emitted during early phases of discharges, especially during the initial phase, because the early charge accelerations occur over short distances ( $\sim 10$  m or less). Subsequently, CG return strokes or strong IC current surges (e.g., streamers, K-processes) are easily detected in the VLF/LF spectrum, because the charge accelerations in these events covers distances of  $\sim 1$  km or more. Thus, in a typical CG flash the recorded VLF/LF signals occur many ms after the leader phase seen by VHF systems. Similarly, a typical IC flash shows substantial current pulses detected by VLF/LF sensors in later stages of the flash [e.g., *Shao and Krehbiel*, 1996; *Rakov and Uman*, 2003, chapter 9; *Betz et al.*, 2004, 2007]. Recently, *Nag and Rakov* [2008] examined preliminary breakdown pulses in negative CG discharges and noted that a small percentage of the pulses have fast-field amplitudes that exceed the amplitudes of subsequent return strokes. However, only a few comparisons have been made of the precise timing of events recorded in VLF/LF to those seen in VHF. *Maggio et al.* [2005] compared the first lightning events located by a VHF system (the Lightning Mapping Array or LMA [*Rison et al.*, 1999]) and fast field change data with a bandwidth covering most of the VLF/LF spectrum (similar in frequency response to individual LINET antennas). For 74 flashes over the LMA and 30 km from the fast field change antenna, *Maggio et al.* [2005] found 37 had no corresponding fast field change within 10 ms of the first LMA signal, 28 flashes had a fast field change that lagged the first LMA signal by less than 3 ms, and 9 flashes had a fast field change signal that preceded the first LMA signal by up to 1.7 ms. Thus, with the VHF system directly below the flashes (its most sensitive position), the VLF/LF data preceded the VHF data in  $\sim 10\%$  of the cases and slightly lagged the VHF data in  $\sim 40\%$  of the cases, so the overall coincidence rate was about 50%. Since the LMA runs continually and has essentially no dead time for low flash rates, there was no technical reason for missing an initial VHF event.

[4] The present paper examines the time difference between first signals from flashes concurrently recorded with VHF and VLF/LF networks during many storms in Poland and Hungary. An unexpected wealth of close coincidences is found, thereby supporting the finding of *Maggio et al.* [2005] that not only VHF- but also VLF/LF arrays exhibit

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sensitivity to processes directly associated with initial breakdown. The Maggio et al. study focused on determining how close (in time) the first LMA source was to the lightning initiation. We, instead, focus on the different length scales of events that are seen by sensors operating in different frequency bands (i.e., VHF and VLF/LF). In the VHF (30–300 MHz), sensors most easily detect charge acceleration over distances of a few meters, while VLF/LF (3–300 kHz) sensors most easily detect charge acceleration over distances of one or more kilometers. Thus, finding that the initial VLF/LF pulse is time-coincident with the initial VHF pulse suggests that the initial discharge length may be hundreds of meters or more, and this result has implications for lightning initiation mechanisms, which we discuss below. Interestingly, the coincidences are also found at the beginning of subsequent breakdowns during a flash.

## 2. Instruments

[5] In this study the first type of VHF data used are from commercialized versions of the SAFIR-systems (Surveillance et Alerte Foudre par Interférométrie Radioélectrique [Richard and Auffray, 1985]) in Poland (PERUN) and Hungary (HMS) with 9 and 5 VHF arrays for interferometric direction finding (DF), respectively. Each SAFIR sensor records lightning radiation at  $\sim 110$  MHz with a bandwidth of several MHz. These networks are operated in 2D mode and complemented by a LF sensor for CG stroke recording at each site. During charge accelerations over meters or tens of meters, e.g. channel formation, the VHF networks produce time and location for a ‘source train’ of 1 to  $\sim 100$  sequential radio source points with a time resolution of  $100 \mu\text{s}$ . During the evolution of a complete flash many different channels (and VHF source trains) are created, but due to technical limitations, not all the later source trains (after the first) are located and recorded.

[6] It must be noted that for VHF the time-of-arrival technique (TOA) gives more precise locations than DF [e.g., Thomas et al., 2004]. Interestingly, DF and TOA, though applied to the same VHF band, exhibit different sensitivity to the two types of signals that occur in unknown sequence during lightning discharges, namely isolated short radio pulses and longer pulse bursts [Mazur et al., 1997]. Mazur et al. [1997] compared a TOA VHF system (called LDAR, similar to the LMA) with a SAFIR-type system; the most significant finding for the present study concerned a comparison of three individual flashes. For two of the flashes both systems initially triggered at essentially the same time; but for the third flash the SAFIR-type system triggered 5–10 ms after LDAR. Because of the different sensitivities, the VHF system PROFEO (Programme Francilien d’Etudes des Orages), newly developed and deployed in the Paris area, utilizes both DF and TOA techniques; some preliminary results are shown below.

[7] The VLF/LF data for this study were taken from the new European lightning location network LINET (Lightning detection NETWORK) that has been developed at the University of Munich and exploits fast-field records with a bandwidth essentially covering the entire VLF/LF spectrum [Betz et al., 2004, 2007]. It operates in 18 countries, and 16 of its 90 sensors are positioned in Poland and Hungary, so that together with sites in surrounding countries, small

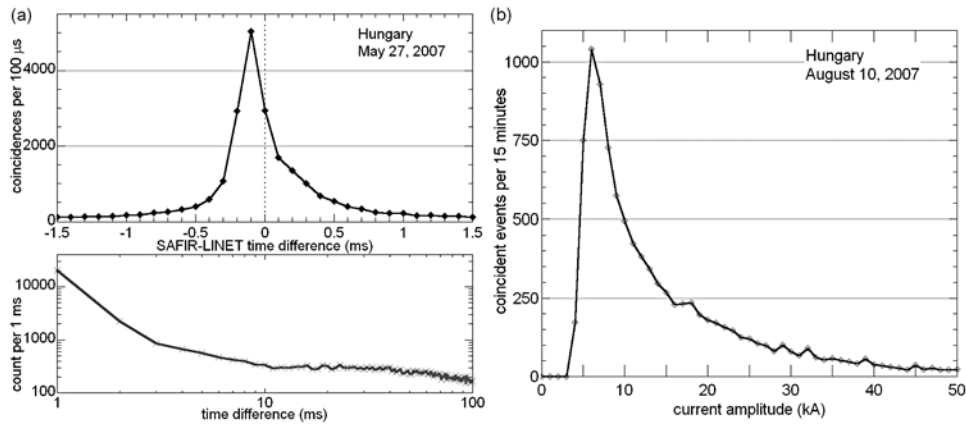
signals and, thus, copious in-cloud events can be captured, along with CG lightning data. Discrimination between IC and CG events is performed by means of a 3D-technique [Betz et al., 2004]; IC emission heights are also available, but the present comparison utilizes primarily time, location and strength of the events. Both LINET and SAFIR provide a GPS-controlled time basis of better than  $1 \mu\text{s}$ , sufficient for the comparison of event times.

## 3. Time-Coincident Lightning Data

[8] Lightning data are available from the above-mentioned networks for the entire 2007 season, and the twelve most intensive storm days during May–October have been analyzed. Total lightning counts of the SAFIR networks on these intense storm days (ranging from 1,000 to 25,000 flashes, and as many as 65,000 source trains) were ample to allow comparison of events that were detected by LINET in close time-coincidence. Since all systems use a precise time basis, coincidences can be investigated on a  $100 \mu\text{s}$  scale for both IC and CG events. Locating accuracy of all systems suffices for selection of those time-coincidences between SAFIR and LINET that identify pairs of physically related signals, originating from the same source area or discharge channel. The CG stroke locations derived from LF-sensors of PERUN and HMS agree well with LINET-derived results, and the average CG event-time differences are smaller than  $100 \mu\text{s}$ .

[9] A frequent and remarkable observation is this: when PERUN or HMS report a first source point, indicative of the beginning of in-cloud activity, LINET also records its first signal, often within  $100 \mu\text{s}$ . This kind of corresponding network response turned out to be quite typical for up to  $\sim 50\%$  of the flashes. As a quantitative example, let us consider the storm on October 5 in Poland: when one selects the first VHF signal of the 1014 source-point trains detected by PERUN, LINET reports 459 (585) coincidences within 1 ms (10 ms), corresponding to a coincident rate of 45% (58%), respectively. For a time coincident event (TCE) within 1 ms and initial leader speeds of  $1.6 \times 10^5 \text{ m s}^{-1}$  [Behnke et al., 2005], the current length would be  $< 160$  m if the flash developed via the usually presumed leader mechanism. A current length this short would probably not be detected by LINET. The observed close coincidences do not seem to depend on whether the flash subsequently developed into a CG or an IC flash. Figure 1a shows in more detail the time coincident events from another, more intensive storm system that occurred within the Hungarian network on May 27, 2007; we see that most of the TCEs occur within  $100\text{--}200 \mu\text{s}$  (corresponding to  $< 30$  m in length for the leader speed cited above), so development via an extending leader seems unlikely. Results were very similar in the other 10 storms investigated; a statistical analysis of signal occurrence and coincidences is planned for a follow-up article.

[10] Of course it is virtually certain that some of the TCEs were the result of the SAFIR systems missing the earliest VHF sources. However, it seems unlikely that all of the TCEs are a result of insufficient SAFIR sensitivity for the following reason. As discussed above, Mazur et al. [1997] showed that SAFIR was equally sensitive to the initial VHF radiation for two of three flashes when compared to the



**Figure 1.** (a) The top plot shows time delay of 2200 initial VHF event times, relative to time-coincident VLF/LF event times. Negative delay signifies that VHF signals are detected later than VLF/LF events; peak shows that LINET typically detects events 100–200  $\mu\text{s}$  before the VHF system. Total number of source trains (flashes) compared on this storm-day was 65150 (25200). The bottom plot shows magnitude of the time differences between the systems for all events on this day out to 100 ms. (b) Distribution of 9504 range-normalized (CG-equivalent) VLF/LF events that were time-coincident with initial VHF sources within 1.5 ms, as a function of current (bin size 1 kA). Not shown are 349 time-coincident events with current amplitudes of 51–100 kA. Total number of source trains (flashes) compared on this storm-day was 45730 (13300).

TOA LDAR system. With thousands of TCEs detected in the present study, a fraction of them must have occurred close enough to a SAFIR sensor for adequate sensitivity. Therefore, in spite of some variation in SAFIR sensitivity to initial VHF from the flashes, the data suggest that many lightning flashes (perhaps only 10%–50% as in the *Maggio et al.* [2005] data, or about 50% as indicated by the data presented herein) begin with a current surge detected at VLF/LF frequencies.

[11] The in-cloud event amplitudes from VLF/LF networks can be range-normalized as is customary for CG strokes; when this admittedly approximate procedure is applied to those in-cloud events that are coincident (within 1.5 ms) with the corresponding first VHF source time, one obtains a distribution depicted in Figure 1b. The polarity of the signals has been measured, but it is not differentiated here. The absolute currents cover a wide range and peak around 7 kA, a value that is close to the ones for CG strokes [e.g., *Rakov and Uman*, 2003]. Larger currents than the ones depicted in Figure 1b do occur; for example, the first signal of flash #4 in the October 5 storm was identified as an in-cloud event with a current of 65 kA. The largest values of comparable cases in the present data set of 12 storms are >100 kA. Of course, we have no reliable basis for using the procedure developed for CG strokes to convert the VLF/LF signal amplitudes from cloud events to currents. However, this procedure allows us to show that typical TCE signal amplitudes recorded by LINET are comparable with the amplitudes of weak CG strokes.

[12] During the ongoing PROFEO project, independent measurements have been obtained during storm activities in the area around Paris (France). Figure 2 depicts a concurrent observation from LINET and ONERA-VHF receivers at 114 MHz during one IC flash located 43 km away from the observation site. The first LINET event was sensed within 30  $\mu\text{s}$  of the earliest VHF pulse at the beginning of the flash. Note that this PROFEO data is from a single sensor, which

is a more sensitive way of looking at the VHF data than requiring 4 or 5 sensors to agree on the event time and position. Excellent correlations of signal-times are found for 78 other flashes (Figure 2c).

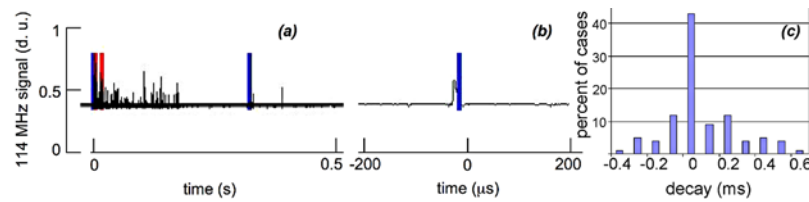
#### 4. Discussion

[13] To assess the significance of the relatively large number of time-coincidences between the initial VHF and VLF/LF signals, we briefly recall two contemporary hypotheses related to the initial discharge phase of lightning, conventional breakdown and runaway breakdown.

[14] Since lightning initiation via conventional breakdown requires a substantial electric field magnitude that has rarely, if ever, been observed inside thunderclouds [e.g., *Stolzenburg et al.*, 2007], it is typically assumed that conventional breakdown occurs only if hydrometeors locally enhance the field [e.g., *Crabb and Latham*, 1974; *Nguyen and Michnowski*, 1996]. Initiation in this case is hypothesized to be on a small scale ( $\sim 1$  m or less), followed by a stepped leader (with step lengths of tens of meters) that would extend the initial breakdown, followed in the case of CG flashes by a return stroke several km long. This overall process should first give rise to VHF emission measurable for  $\sim 10$  ms or more without any radiation in the VLF/LF spectrum (until the time of the return stroke). This model fits a large percentage of our data in which the first VHF sources occur 10 ms or more before the first VLF/LF current surge.

[15] However, hydrometeor-enhanced lightning initiation does not explain the numerous cases of TCEs reported above because it does not allow for an initial event with strong emission in the VLF/LF range. Lightning initiation via runaway breakdown [*Gurevich et al.*, 1992; *Gurevich and Zybin*, 2005] requires electric field magnitudes that have been observed [e.g., *Stolzenburg et al.*, 2007] and may explain the TCEs. For runaway breakdown the initial





**Figure 2.** (a) Data from ONERA VHF 114-MHz (black curve) and LINET (bars) recorded during an IC flash at 43-km distance from the observation site. (b) Zoom of 400  $\mu\text{s}$  time window centered around the first pulse detected by VHF system and first event detected by LINET in the same IC flash. (c) Distribution of event-time differences between the first VLF/LF events and coincident VHF signals from 78 flashes.

breakdown current is hypothesized to extend over hundreds of meters, long enough to produce significant VLF/LF radiation at the beginning of the flash. Observational evidence of the length of the initial breakdown current is not available for normal lightning flashes, but has been inferred for a relatively rare class of discharges called ‘narrow bipolar events’ (NBEs) [e.g., *Smith et al.*, 1999]. Just as in the TCE signals of the present study, NBEs have coincident VLF/LF and VHF radiation without noticeable precursory activity, and it has been suggested that NBEs are initiated by a runaway electron process [e.g., *Gurevich and Zybin*, 2005]. *Rison et al.* [1999] reported that many NBEs are the initial events of IC flashes. Estimated lengths of NBE currents include 600 m [*Watson and Marshall*, 2007], 300–1000 m [*Smith et al.*, 1999], and 3.2 km [*Eack*, 2004]. Figure 3 shows the observed and modeled NBE pulse (from *Eack* [2004] and *Watson and Marshall* [2007], respectively) and the frequency spectra. Since the spectra peak in the VLF/LF regime, LINET would easily detect the NBE radiation. This finding raises the possibility that the TCEs may be an indication of lightning initiation by runaway breakdown.

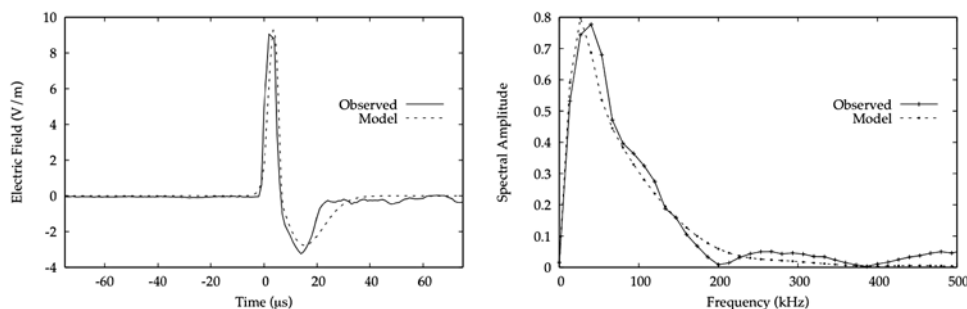
[16] On the basis of the above, the electromagnetic emission during the initial phase of a lightning flash might be described as follows. During the first few 100  $\mu\text{s}$  the initial breakdown produces dominantly VLF/LF, VHF, or both types of radiation. Depending on the initiation process, the initial breakdown can develop in two different ways. In one scenario the runaway breakdown mechanism prepares a channel and causes the appearance of both VHF activity and a VLF/LF pulse. Depending on the field and potential distribution, a stepped leader may begin and propagate

further, giving rise to subsequent VHF radiation while creating the conditions for either a CG stroke or an IC flash, or it may end as an attempted leader. In the second scenario the initiation process occurs over a short length, and the radiation is detected first in the VHF only.

[17] To the best of our assessment, this admittedly manifold picture of the initial discharge phase is in reasonable agreement with frequently reported results concerning both VHF and VLF/LF data, though the microphysical details of breakdown processes remain too intricate for satisfactory modeling. Clearly, the present data are not sufficiently complete to allow a clear and quantitative distinction between all the various discharge sequences.

## 5. Conclusions

[18] Comparison of experimental data from independent networks with the capabilities to detect in-cloud parts of lightning has revealed that a significant fraction of flashes start with a TCE: a time-coincident emission of VHF and VLF/LF radiation pulses. This finding is based on examination of more than 100,000 flashes on 12 storm-days. Our study has focused on the fact that the two different frequency regimes respond to radiation pulses with different length scales; in particular, an initial event detected by VLF/LF should be hundreds of meters long. Event-time coincidences of VLF/LF events with first VHF signals provide useful information about the lightning initiation process. The runaway breakdown mechanism [*Gurevich et al.*, 1992] is consistent with the TCE observations and, given the large percentage of flashes with TCEs (perhaps as many as 50%), may be responsible for far more lightning initiation than hitherto believed.



**Figure 3.** (left) Observed and modeled electric field change for a narrow bipolar event at 200 km range; observed data from *Eack* [2004], model parameters given by *Watson and Marshall* [2007]. (right) Frequency spectra for the observed and modeled NBE field change.

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