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Modern Lightning Detection and Implementation of a New Network in Germany

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Summary

During the past 20 years lightning detection networks have been positioned in many countries of the world and operate quite successfully. For surveillance of large areas VLF/LF techniques are preferred while special monitoring of thunderstorms, especially activities within clouds, can be traced by means of VHF methods with limited range. In Germany commercial lightning detection service is provided utilizing the combination of data from VLF/LF networks in Germany (BLIDS by Siemens) and surrounding countries (especially ALDIS, Austria, and EUCLID = European combined lightning detection). Initially, these networks were designed to report cloud-to-ground strokes (CG) in order to locate damage on the ground. Lately, meteorological applications received interest as well, pointing to the importance of intracloud lightning (IC); examples are early warning features, recognition of severe weather conditions and cell-tracking of thunderstorm cells. In most existing networks, sensor technologies and data processing have been regularly updated so that there appeared no reason for further basic changes. Nevertheless, this paper demonstrates that significant improvements are feasible.

The Munich research group developed an independent VLF/LF network and – in cooperation with the German and Austrian network operators – compared the results with BLIDS/ALDIS-data. Detailed evaluations in 2003 and 2004 revealed that our new network exhibits three advantages: high detection efficiency with the inclusion of low-amplitude discharges, few locating errors, and reliable CG-IC discrimination.

All three features represent useful progress compared to existing technologies, which is important not only for scientific reasons, but also for most of the practical data applications. We attribute the high performance of our network mainly to its modern design

with respect to all influential components, including software procedures. Some details are presented below and more specific results from the lightning data are given in a separate contribution.

Lightning Detection Networks

Detection and counting of lightning has a long history and numerous methods have been developed for quantification. Overviews can be found in Uman (1987) and Rakov and Uman (2003). During the past two decades electromagnetic techniques have been improved, based on fundamental aspects of lightning sources radiating in both the VLF/LF (atmospherics, Volland 1982) and the VHF regime (Krehbiel et al., 1999). Let us first comment the low-frequency solutions which are attractive due to relatively long ranges of the signals. For example, in 1987 the largest VLF/LF network was set up in the U.S. (National Lightning Detection Network, NLDN) which comprises more than 100 sensors (Orville et al., 2002) with average sensor-spacing of some 300 km. Once commercially available, systems of this type were set up in many other countries. In general, electric and/or magnetic fields are measured by means of conventional rod and crossed-loop antennae, respectively. Two different locating methods are employed, partly in combination, namely direction finding (DF) and time-of-arrival (TOA). Output quantities are event time, location, amplitude including sign, and – to a varying extent – classification as either CG or IC lightning.

Initially, the most important aim of traditional networks was to determine occurrence of CG strokes in conjunction with reporting points of damage (failure of power lines). It is not for too long that meteorological applications have become increasingly important in connection with now-casting and combination of meteorological data sources (radar + lightning). Necessarily, report of CG strokes requires suppression of IC discharges; this task is performed by means of waveform discrimination. Network flash detection efficiencies reach values as high as 90%, but it should be emphasized that this is true only for amplitudes above some 5 kA (peak current in the lightning channel). Lower amplitudes can not be denied to exist but are thought to be rare. Under favorable conditions locating errors are as low as 500 m, as could be verified by observation of triggered lightning and strikes into instrumented towers.

VHF networks have been developed for both scientific exploration and commercial applications, utilizing both DF and TOA. Since short wave lengths are measured, short discharge steps of the order of 100 m can be traced, providing a very detailed picture mainly of IC-lightning. Meanwhile, the complete evolution of a lightning event can be mapped by resolving thousands of data points as a function of time and three-dimensional coordinates (Thomas et al., 2004). By comparison, during such a process a VLF system reports at best a single data point (return stroke or recoil streamer).

Due to the relatively short range of VHF signals, limited by the line of sight, high complexity and large data rates, coverage of very large areas has not been attempted.

There is still a basic lack of understanding: to what extent are VLF/LF and VHF methods overlapping and complementary? In other words: which steps of an entire discharge process are seen by VLF/LF sensors and which steps are missed by VHF observation? We can not yet answer the question whether, under which circumstances, or to what extent VLF/LF techniques allow representative measurements of ‘total’ IC activity. Simultaneous operation of the two efficient types of networks could provide clarification.

New VLF/LF Network in Southern Germany

Technical Aspects

An independent VLF/LF lightning detection network was developed and set up in Southern Germany. The starting motivation was advancement of early thunderstorm detection and, thus, several requirements had to be met: high efficiency of the sensor stations and the entire network with respect to weak signals, improved treatment of complex impulse waveforms, and handling of high data rates. Besides, modular and economic design, use of modern components, and digital lay-out were imperative.

A passive sensor for magnetic field components (two crossed loops, module 1) was constructed which contains no electronics and, therefore, needs no power supply. The components $B_x(t)$ and $B_y(t)$ of the magnetic flux are measured independently and serve to infer both amplitudes and bearing angles by the well known DF method. It must be pointed out that sensor system parameters are chosen in a particular way which allows – in contrast to procedures in other systems – direct measurement of true wave forms B(t), rather than time derivatives dB/dt of the magnetic flux with the need for subsequent integration. In this way significant advantages can be exploited in connection with the detection of very weak signals in the frequency range of interest. Though the antenna shows receiving capability up to about 1 MHz, an upper limit is set to 400 kHz in order to serve anti-alias properties, and a digital filter can be adjusted in the range 100-400 kHz in order to reduce influence of radio signals; the wave form distortion due to the actually chosen band-width limitation remains acceptable for the present purposes.

Signal timing is achieved by means of a separately mounted commercial GPS clock with an accuracy of 100 ns (initially 300 ns, module 2). Special measures are taken to transport this level of basic accuracy as far as possible to the actual event timing. Signal amplification, filtering, AD-conversion and data processing are performed with a single plug-in card (module 3) in a remotely positioned standard PC (module 4).

The effective sampling rate was set to 1 MHz and incoming signals are recorded with 14 bit resolution in a continuous mode. Triggered events are transferred to and processed in a parallel unit so that no data loss occurs and no allowance for rearm time must be provided (zero deadtime). Signal rates of up to approximately 1 kHz can be handled. Each station collects data and transmits packets of condensed information to the central station at Garching. Depending on the type of chosen line-connection this transmission can take place immediately after completion of an individual signal analysis, or within pre-selected time intervals for a group of signals which has been accumulated within this interval. Due to transmission line band width the transfer is presently limited to some 100 signals/s which is plenty even during strong thunderstorm activity. Nevertheless, a buffer is provided for handling of occasional overload. The complete data sets including full wave forms are stored locally and transmitted only on specific demand. All station software modules and operational parameters can be loaded and set remotely from the centre at Garching. Central processing takes place by means of a customary PC which handles and organizes incoming data. Locating is performed and results are transferred to a server for storage and availability for secondary off-line jobs.

In 2003 and 2004 the network operated with six sites and an average distance between neighbouring sensors of some 115 km. Extension to a twelve-sensor network is completed and begins operation in 2005, covering Southern Germany.

Signal Treatment at the Sensor Level

The continuously recorded digitised data stream is inspected for threshold crossing of either sign; upon triggering the pulse will be subjected to a detailed analysis. At present, we define somewhat arbitrarily that a single signal from a lightning discharge (stroke) may last up to 512 μs, i.e. we do not carry out a search for more than 1 event within this time period. Overlap of signals within this time span is rare and will be disentangled by future software-developments. In order to discriminate false signals a fast Fourier analysis is performed which helps to identify signals from radio transmitters and other sources of technical origin. Signals with spectra far from the range of acceptable patterns are eliminated. Depending on the sensor site several types of technics may show up which display a signature similar to the one of true lightning pulses and cannot be sorted out at once; these false signals are eliminated by time coincidence and shape considerations in the central processing software.

Particular care was taken to record weak signals. In particular, any wave form is accepted no matter how complex it may be. It would not represent a goal oriented procedure to require predefined patterns or shapes. In fact, one observes a very wide variation of signal forms. Therefore, all prominent peaks are identified and time-tagged; in addition, peak widths and B_x/B_yratios are determined. A concentrated data package containing characteristic signal features is assembled and transmitted to the central processing unit. At the sensor level, no attempt is made to discriminate CG from IC discharges. For scientific reprocessing purposes and optimisation of analysis procedures the full wave forms are stored locally and can be transferred on demand for later use, because they are not needed for the standard network output.

Central Data Analysis

All sensor stations send data on-line to the central processing unit. Incoming data packages are sorted according to event time and enter into a locating routine within pre-selected time intervals. Here, care is taken to correlate those events which truly belong to the same lightning discharge. Both event time control and pulse shape comparisons are utilized; for example, a single peak pulse and a multi-peak pulse will not be considered correlated even when the event time suggests so. In this way a maximum of realistic signal groups can be attained. TOA fitting is exploited for efficient locating, aided and controlled by DF.

According to established standards, stroke amplitudes are calculated for a normalized range of 100 km by means of the propagation law, $\sim$ 1/R, where R signifies the distance between the lightning and the respective sensor site, followed by conversion into the corresponding current in the lightning channel. Assignment of a sign is straight forward in case of unipolar pulses; it turns out, however, that a substantial fraction of discharges exhibits complex wave forms which make sign assignments somewhat arbitrary.

CG-IC discrimination is carried out by means of a recently described direct 3D-technique (Betz et al., 2004). This entirely new method exploits differences of signal travel-times between radiation source points within the clouds (IC) and close to ground (CG, return stroke), respectively. In a sufficiently dense network with relatively small distances between the point of lightning and the next (closest) sensor site (preferably $<$ 100 km) no adjustable parameter of any kind is needed to perform the discrimination; emission heights are quantitatively extracted with an accuracy of a few kilometres.

Prominent Network Features

A detailed two-year study of the output from the new network revealed remarkable features. Backed up by radar and other meteorological observations the usefulness of the results could be established. Most important, by courtesy of, and in co-operation with BLIDS/ALDIS an extended comparison with data from the commercial network operating in the same area could be carried out (Schmidt et al., 2004). Particular progress was achieved in three directions:

Detection of low-amplitude discharges:

For high-amplitude strokes very little differences were found between the networks. Below approximately 8 kA, however, the new network detects up to 10-times the number of events reported by BLIDS/ALDIS. The additional locations lie well within verified storm cells and signal parameters, except for the magnitude, do not indicate a different class of events.

Few locating errors:

Comparison of locations determined by the two networks for time-coincident events yields, in the majority of cases, differences of less than some 500 m. A significant fraction, though, differs greatly. Systematic inspection of the contours observed for storm cells, especially of low- or no-activity areas between storm tracks, shows that BLIDS/ALDIS produces diffuse cell borders while the new network delivers more concentrated cells with sharper border areas.

New CG-IC discrimination:

When lightning occurs in the central area of the network the new 3D-discrimination techniques works excellently and yields emission height distributions which peak between 7 and 10 km. On the average, we find an IC fraction of 30-50%, but it varies depending on the type and life cycle of cells. Agreement with BLIDS/ALDIS assignments is very poor so that it remains to be clarified under which conditions the two methods, 3D- and waveform discrimination, provide reliable results.

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