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Characteristics of return stroke electric fields produced by lightning flashes at distances of 1 to 15 kilometers

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Ė-signals from single and multiple lightning strokes measured at the lightning research station of the University of the Federal Armed Forces near Munich in 1989 are presented. For about 25% of all acquired waveforms, produced by return strokes, stepped leaders or intracloud discharges, type and distance of the signal source are known from the observations by an all sky video camera system.

The analysis of the Ė-waveforms in the time domain shows a significant difference in the impulse width between return stroke signals and those of stepped leaders and intracloud discharges. In addition the computed amplitude density spectrum of return stroke waveforms lies by a factor of 10 above that of stepped leaders and intracloud discharges in the frequency range from 50 kHz to 500 kHz.

Introduction

In the past a lot of electric field derivative measurements of return strokes, stepped leaders and intracloud discharges in the near distance range were made [e.g. 1, 2]. However often difficulties remain in determining distance and type of the signal source. Hence in the case of single station measurements the recording of optical and acustical lightning signals by using various video cameras [3] or a so called all sky video camera system is necessary.

Only if type and distance of the signal source are certainly established criterions can be worked out derived from the measured electric data to discriminate signals from return strokes from other signals. To achieve this aim analysis in the time domain, as well as in the frequency domain down to low frequencies of 50 kHz, are performed.

Experiment

The fully automatically working measuring station consists of two components, firstly the measuring devices for obtaining the electrical signals of a lightning discharge and secondly the so called all sky video camera system. Figure 1 shows a overview of the measuring station with the HP 9836 computer as the controller.

The electric field derivative Ė is registered by a capacitive 0.5 m rod antenna with a spherical termination at the top. Combined to a coaxial cable with a surge resistance of 50 Ω it leads to a bandwith of at least 50 MHz. Using a digital storage oscilloscope LeCroy 9450 with a sample rate of 10 ns it is possible to record at maximum 20 Ė-waveforms of 20 μs duration, which are separately to be triggered, within one lightning event.

As it is reported from near field measurements [1, 2, 4, 5] the interesting Ė-signals of return strokes which are of main interest show a typical bipolar impulse with dominant frequencies up to a few MHz. To avoid triggering on very fast impulses, e.g. produced by stepped leaders, an external trigger generator in combination with a separate similar rod antenna is used. It works as a bipolar trigger with an upper cutoff frequency of 5 MHz.

A DSO GOULD 4072 samples at a rate of 1 ms both the electrostatic field measured by a slow field mill (bandwidth = 10 Hz) and the maximum Ė-signals using peak detection during 1 sec. A positive change of the electrostatic field points at a negative flash, a negative change at a positive flash, if it is produced by a cloud-to-ground flash. The peak detection of the Ė-signal over a time period of 1 sec gives informations about the duration of one whole event and the maximum amplitudes of the electric field derivative.

The second essential part of the station is represented by the all sky video camera system. The simultaneous storing of the video camera output together with the mixed in date and time signal of a video timer and the signals of two thunder microphones enables the operator to estimate the distance to the striking point by the time difference between thunder and optical signal. Similar to the photoelectric detector described by Uman [6] a video camera is mounted in vertical position below a convex mirror in a height of about 6 m above ground (Fig. 2). The rotationally symmetrical aluminium mirror (Fig. 3) is optimized to wavelengths of 380 nm to 780 nm. A distance of about 350 mm between mirror and camera objective results in an elevation angle of 60° and an azimuth angle of 360°. According to the weather conditions lightning flashes in a range up to 15 km are recognizable as cloud-to-ground (Fig. 4a), resp.

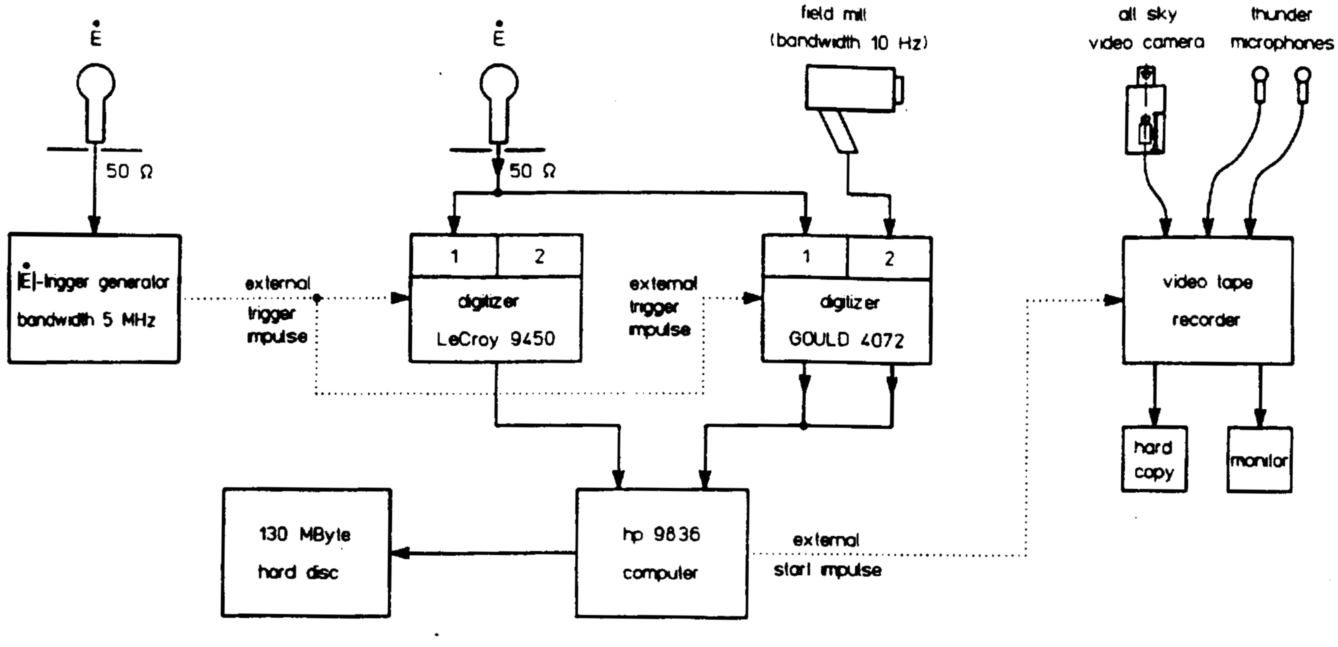

Fig 1: Block diagram of the automatically working electric field measuring station used in 1989.

cloud-to-cloud discharges (Fig. 4b). Thereby the horizon appears as the inner circular disk surrounded by the sky as an englightened annular ring. With the video image repetition rate of 40 ms it is possible to resolve even subsequent strokes. During the automatic operation the computer starts the video recorder after the first trigger impulse and stops it 7,5 min after the last trigger impulse in order to make the most of the video tape with a recording time of 180 min.

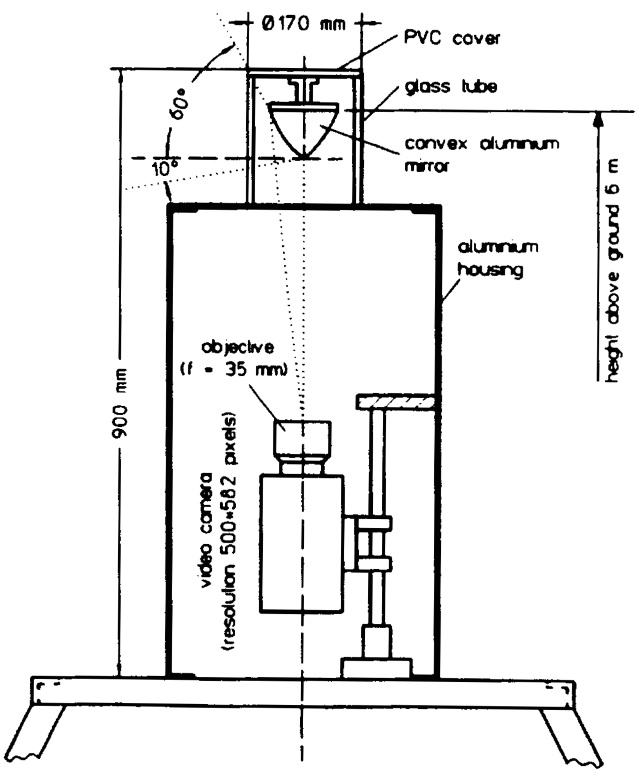

Fig. 2: All sky video camera system with an azimuth angle of 360° and an elevation angle of 60°

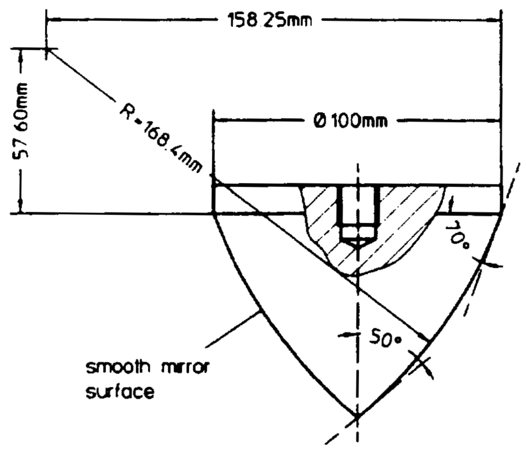

Fig. 3: Convex aluminium mirror used in the all sky video camera system for wavelengths of 380 nm to 780 nm.

Measurements

In 1989 of altogether 604 lightning flashes creating 5044 $\dot{E}$-signals 111 flashes with 1219 $\dot{E}$-signals were registered on video tape (Table 1). Triggering to a certain threshold of the $\dot{E}$-signals explains the relatively small number of 54 obtained return stroke waveforms compared to 2165 single impulse waveforms produced by stepped leaders and intracloud discharges. In the following $\dot{E}$-signals are examined with a single characteristic impulse within 20 μs. Figure 5 shows the interesting parameters, that is the impulse width (T_{50}) and the maximum peak of the $\dot{E}$-signals ($\dot{E}_{max}$), resp. the initial peak of the computed electric field (E_{max}). 2813 $\dot{E}$-waveforms without a regular structure or with multiple characteristic impulses within 20 μs are ignored.

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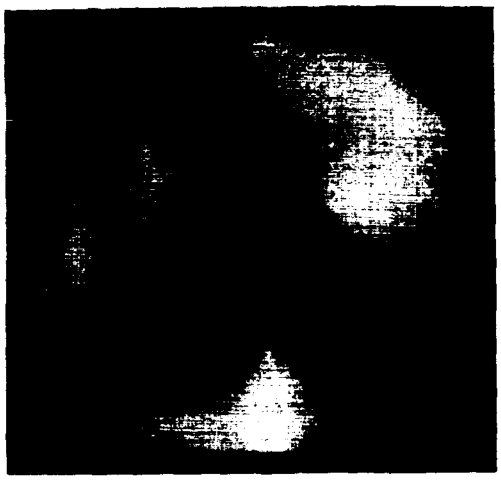
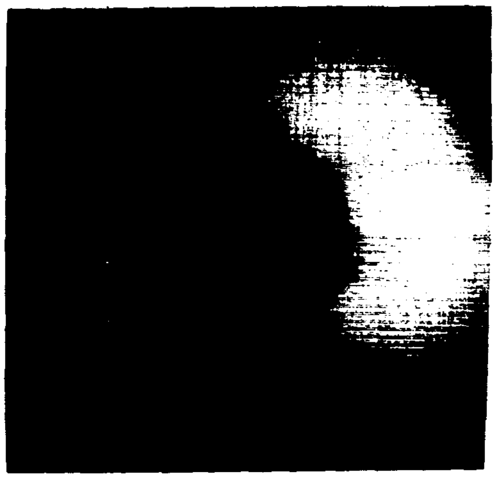


a) Cloud-to-ground lightning channel



b) Cloud-to-cloud lightning channel

Fig. 4: Video images of a cloud-to-ground (a), resp. cloud-to-cloud (b) lightning channel observed by the all sky video camera system.

	All measured data	Data with determined distances
Multiple characteristic impulses or amorphous signals	2825	704
Negative single impulses of stepped leaders and intracloud discharges	973	233
Positive single impulses of stepped leaders and intracloud discharges	1192	271
Neg. impulses of return strokes	7	3
Pos. impulses of return strokes	47	8
Σ	5044	1219

Table 1: Overview of 5044 Ė-signals (20 µs, 10 ns sample interval) in 604 flashes, resp. 1219 Ė-signals in 111 flashes with determined distances measured in 1989.

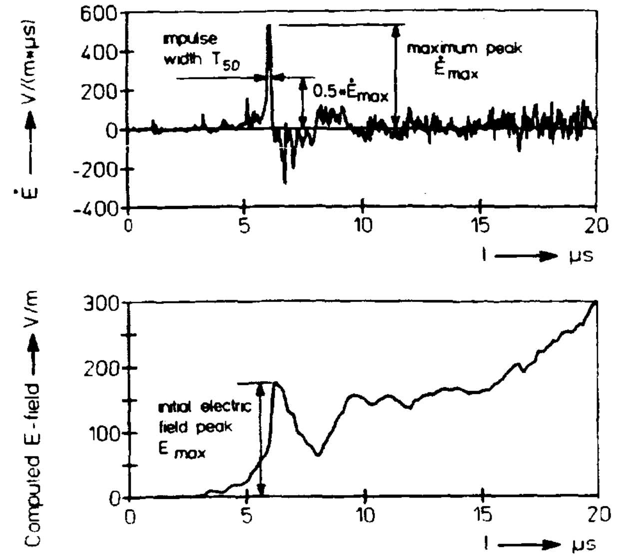


Fig. 5: Example of field derivative Ė and computed E-field waveforms of a return stroke in a distance of 2 km. The impulse width T_{50}, the maximum Ė-peak $\dot{E}_{max}$ and the electric field initial peak E_{max} as the interesting parameters are shown.

Results

In agreement with former measurements [1] the maximum peaks of the electric field derivative $\dot{E}_{max}$ with a mean value of 128 (V/m)/µs for all measured data of stepped leaders and intracloud discharges, resp. 7.59 (V/m)/µs for determined distances normalized to 100 km by the inverse distance relationship, lie in the same order as those of return strokes with a mean value of 109 (V/m)/µs for all data, resp. 5.53 (V/m)/µs for determined distances normalized to 100 km (Fig. 6).

Against that the electric field initial peaks E_{max} differ with a mean value of 4.82 V/m for all measured stepped leaders and intracloud discharges, resp. 0.247 V/m for determined distances normalized to 100 km, from return strokes electric field initial peaks with a mean value of 88.6 V/m for all data, resp. 3.95 V/m for determined distances normalized to 100 km (Fig. 7). The mean value of 3.95 V/m for Emax of return stroke waveforms normalized to 100 km is also found in [3] and [7].

The comparison of T_{50} shows the most obvious difference between stepped leaders and intracloud discharges on the one hand with a mean value of 26.2 ns for all acquired data, resp. 23.1 ns for determined distances, and return stroke signals on the other hand with a mean value of 606 ns for all data, resp. 564 ns for determined distances (Fig. 8).

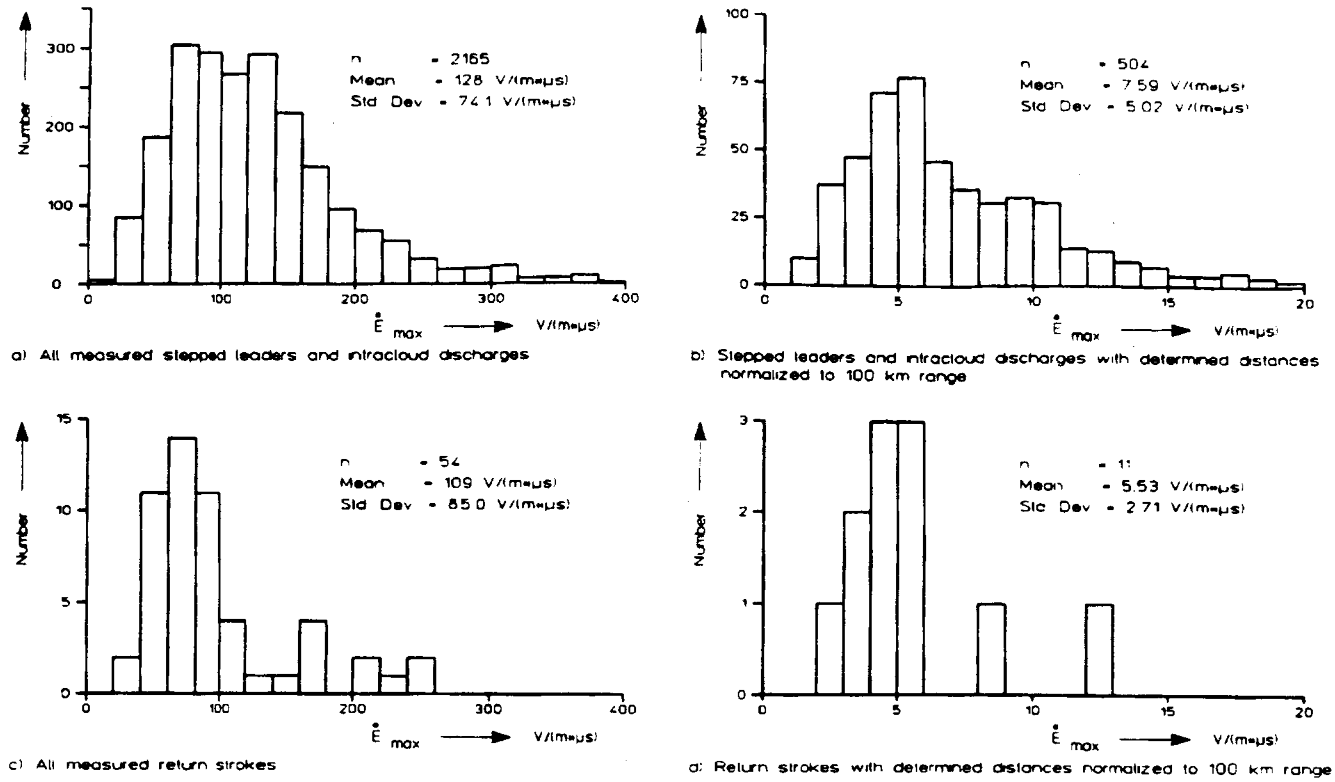


Fig. 6: Histograms of maximum peaks $\dot{E}_{max}$ (pos. and neg.)

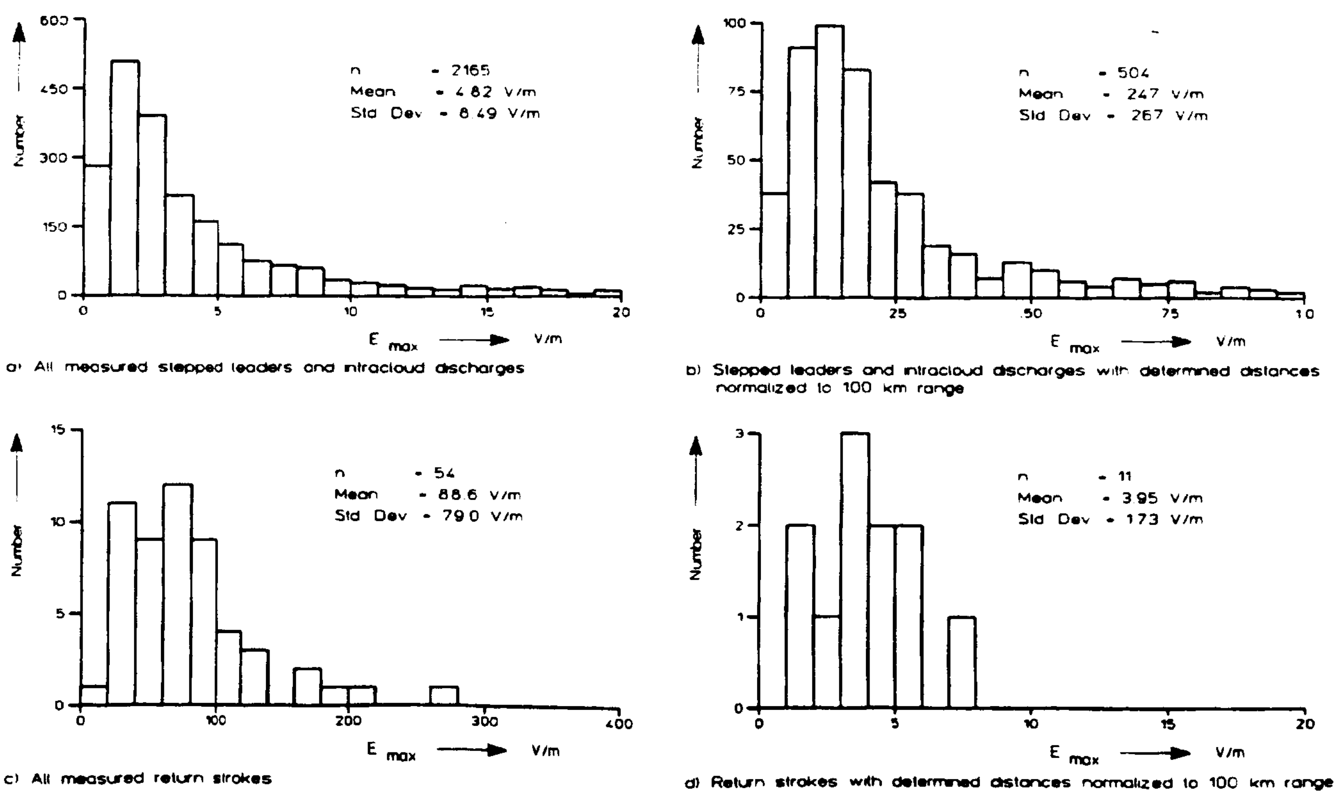
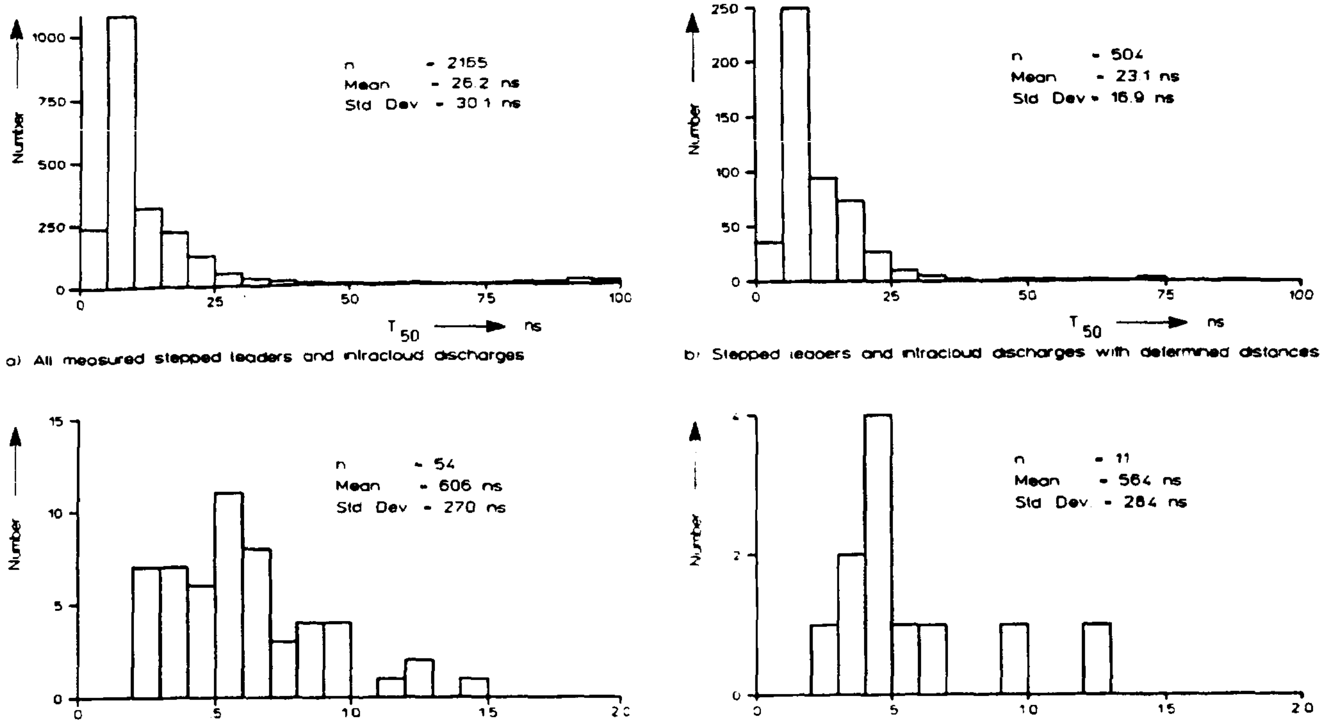


Fig. 7: Histograms of electric field initial peaks E_{max} (pos. and neg.)



a) All measured stepped leaders and intracloud discharges

b) Stepped leaders and intracloud discharges with determined distances

c) All measured return strokes

d) Return strokes with determined distances

Fig. 8: Histograms of impulse widths T_{50}

Discussion

The results show, that for the discrimination of electric field derivative signals of the return strokes from those of stepped leaders and intracloud discharges in the range to 15 km both the impulse width and the electric field initial peak by a factor of 15 seem to be appropriate criterions. The evident difference of T_{50} in the time domain points at a significant difference also in the frequency domain.

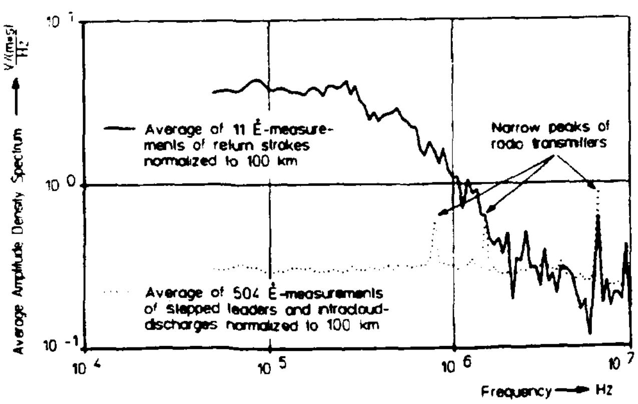


Fig 9: The means of amplitude density spectra for return strokes, resp. stepped leaders and intracloud discharges both normalized to 100 km, recorded at distances up to 15 km.

In Fig. 9 the two average amplitude density spectra of the Ė-waveforms produced by return strokes (solid) resp. stepped leader and intracloud discharges (dotted) are presented [8]. Before computation of the Discrete Fourier Transform in the frequency range from 50 kHz to 10 MHz is performed the data are normalized to 100 km. Up to frequencies of 500 kHz the average amplitude density spectrum of 11 Ė-signals originating from return strokes lies by a factor of 10 above that of 504 Ė-signals produced by stepped leaders and intracloud discharges. For frequencies higher than 2 MHz no such difference is recognizable as also reported in [9]. This correponds to the relatively long T_{50} of return strokes, which is caused by the massive removal of charge from the lightning channel at the beginning of the return stroke phase.

Deduced from Fig. 9 a bandwidth limitation of the Ė-measuring system, that means of the trigger device, by a lowpass filter with a cutoff frequency of 500 kHz leads to an appropriate discriminator for return stroke signals produced by cloud-to-ground flashes in the 15 km range.

In order to eleminate strong stepped leader pulses of near cloud-to-ground discharges or signals of cloud-to-cloud discharges the Ė-signals filtered by a 4th order Butterworth lowpass filter with a 3 dB cutoff frequency of 500 kHz is compared to the unfiltered Ė-signals. Fig. 10 shows the ratios of the maximum peaks within the 20 µs time window of the filtered and unfiltered Ė-signals

($\dot{E}_{max/500kHz}/\dot{E}_{max}$) produced by return strokes. The 4th order Butterworth lowpass filter was simulated by a digital recursive filter using the bilinear transform. For all return stroke signals the ratio is greater than 25% with a mean value of 61.2%, resp. 57.8% for signals with determined distances. Against that the ratio for all other acquired signals lies under 35%.

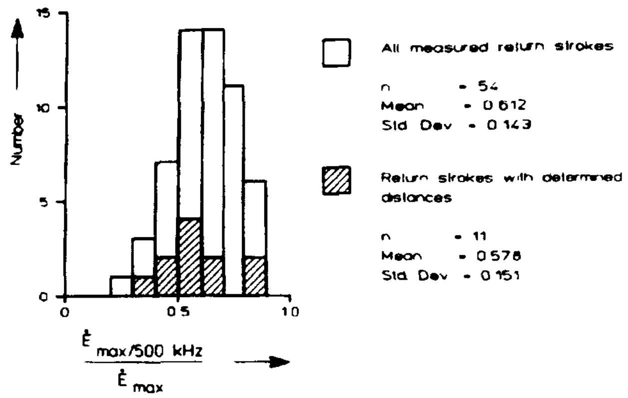


Fig. 10: Histograms of ratios of maximum peaks of filtered $\dot{E}$-signals $\dot{E}_{max/500\ kHz}$ (4th order butterworth lowpass-filter with a 3 dB cutoff frequency of 500 kHz) and of corresponding unfiltered $\dot{E}$-signals $\dot{E}_{max}$.

Conclusion

The comparison of $\dot{E}$-signals with determined distances by the use of the all sky video camera system results in significant differences both in the time and the frequency domain for return strokes on the one hand and all other signal sources on the other hand.

To achieve the discrimination of return stroke signals in the 15 km range two criterions have to be fullfilled. First the $\dot{E}$-signal filtered by a 4th order lowpass filter with a cutoff frequency of 500 kHz must exceed a certain level, which affects the effective range of the measuring system. Second the ratio of the maximum peaks of the filtered and unfiltered $\dot{E}$-signal ($\dot{E}_{max/500kHz}/\dot{E}_{max}$) has to be greater than 35% in order to register at least 90% of the return stroke $\dot{E}$-signals (first and subsequent) in the 15 km range and to exclude predischarges, stepped leader and cloud-to-cloud pulses.

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