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Instrumentation and data analysis process at the new lightning research station in Poland

Abstract. *In this paper we have presented an analysis of the functionality of the new lightning research station to be installed at Rzeszow University of Technology for determining the parameters of the lightning electromagnetic field and the current flowing in the lightning channel. The instrumentation and data analysis process of the slow and fast electric field components measured during thunderstorm condition along with the fast video simultaneous recordings are also described. Some current and prospective capabilities of the experimental setup and dedicated software tools are considered. This modern lightning station is developed at the University of Technology in the cooperation with the Institute of Geophysics, Polish Academy of Sciences, and the Institute of Electronic Systems, Warsaw University of Technology, where the electric field sensors have been constructed.*

Streszczenie*. W niniejszym artykule dokonano analizy funkcjonalności nowej stacji do badania wyładowań piorunowych pod kątem wyznaczania parametrów piorunowego pola elektromagnetycznego i prądu płynącego w kanale wyładowania atmosferycznego. Przedstawiono oprzyrządowanie oraz proces analizy danych wolnozmiennego i szybkozmiennego pola elektrycznego mierzonego w warunkach burzowych oraz jednoczesnych rejestracji fotograficznych rozwoju czasowego kanału wyładowania wykonanych za pomocą szybkiej kamery wideo. Opisano aktualne i przyszłe możliwości układu pomiarowego i dedykowanych narzędzi programowych. Stacja wyładowań atmosferycznych jest rozwijana w Politechnice Rzeszowskiej wspólnie z Instytutem Geofizyki Polskiej Akademii Nauk. Anteny do rejestracji pola elektrycznego skonstruowano w Instytucie Systemów Elektronicznych Politechniki Warszawskiej. (****Oprzyrządowanie oraz proces analizy danych w nowej stacji do badania wyładowań piorunowych rozwijanej w Polsce****).*

Keywords: lightning research station, lightning current, electric field, fast video recording, lightning protection
Słowa kluczowe: stacja do badania wyładowań piorunowych, prąd piorunowy, pole elektryczne, szybka rejestracja wideo, ochrona odgromowa

Introduction

One of the most dangerous effects of lightning are electric and magnetic fields generated by the return stroke current. The fast components of these fields may have destructive influence on electric and electronic devices even up to several kilometers from the striking point. Overvoltages induced in long transmission lines and loops created by different electrical installations are often the major cause of important data loss and energy supplies stoppages which generally can be costly. Moreover, the droughts and increasing storm activity observed recently are often behind the damage to forests caused by fires initiated by high-energetic lightning flash component called the continuing current (CC) [1, 2].

The electric and magnetic fields of the lightning flash can be considered as an important source of information about the physics of lightning and the lightning location. In fact, data contained in a single lightning waveform can be used for detailed analysis of the lightning current and are crucial for algorithms implemented in lightning location systems (LLS). In addition, fast video recordings simultaneous with the electric and magnetic field measurements can be useful for further investigations of the evolution of different lightning processes [3]. There are many various LLS systems working operationally in Europe and all over the world nowadays. The largest systems, such as NLDN (North America) or LINET (Europe) and smaller ones like the SAFIR/PERUN in Poland, are equipped with multiple sensors able to locate lightning discharge strokes and estimate their peak currents, and even to distinguish between cloud-to-ground (CG) and intra-cloud flashes (IC) [1,4,5]. Over recent times, LLS, and besides, lightning warning systems (LWS), have become more common and are now extensively used by fire departments and airports for different lightning protection tasks [1]. A few years ago the Local Lightning Detection Network (LLDN) was developed and installed for research purposes in the Warsaw region in Poland [6]. The main aim of the LLDN system was to provide complementary lightning data which were used to obtain 3D locations of regions with negative and positive charges formed inside thunderstorm clouds [7].

Measuring Setup of the Lightning Research Station in Rzeszow

One of the most important goals of the ongoing development of lightning detection and location methods is to improve their numerical algorithms, the main task of which is to properly recognize and identify all main stroke components of CG lightning flashes, i.e., the return stroke (RS) and continuing current (CC) stages, from the parameters of recorded waveforms of the lightning electric and magnetic field. It is believed that such improvements of the LLS systems currently used can be achieved only if an accurate and relevant set of lightning parameters is obtained from direct measurements of slow and fast components of the electric and magnetic fields radiated by CG lightning.

A study into possible improvements concerning LLS is planned in the Lightning Research Station in Rzeszow (LRS), currently being developed by the Rzeszow University of Technology in Poland. The general set-up of the entire LRS system is shown in Fig.1.

The station is situated on the roof of Rzeszow University of Technology building (50º1'37''N 21º59'4''E). The LRS is equipped with two different sensors for the electric field measurements during thunderstorms, both built at the Institute of Electronic Systems, Warsaw University of Technology. Additionally, the high-speed camera Photron SA5 will be used simultaneously at the station to record optically the time development of lightning flash channels with the resolution of up to 7500 fps in HD video quality. The first electric field sensor, i.e., the electric field meter with a rotary dipole, is dedicated for the monitoring of thunderstorm electric field slow variations in the frequency range from DC to 10 Hz. The second one is a flat plate antenna that can be used for measurements in 5 Hz – 3 MHz frequency range of fast electric field changes during the observed lightning flash incidents. This antenna was preliminary calibrated using the MIG0618SS generator typically applied in aviation to perform the immunity tests of avionics according to the standard DO-160. The so-called waveforms 6.4/70 μs (WF1) and 40/120 μs (WF4) generated by the MIG0618SS were delivered to two-wire

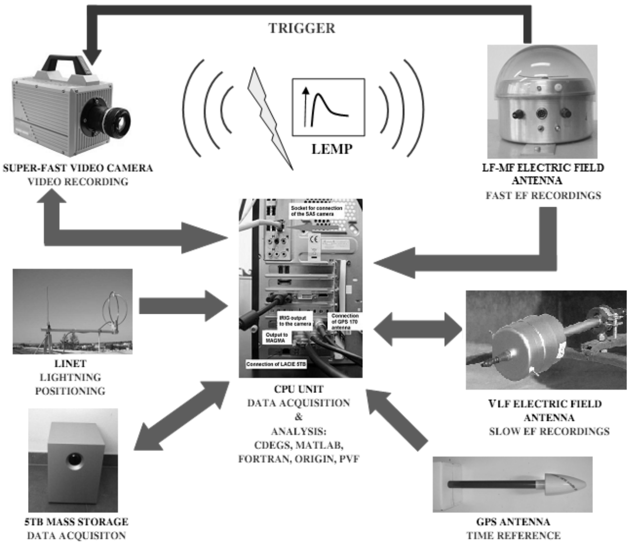

Fig.1. The Lightning Research Station configuration developed at Rzeszow University of Technology.

system serving as a source of the electric field pulse. For comparison, further calibration of such electric field sensor using different methods is required. More information about the details of the LRS performance is presented in [8,9].

Data acquisition and their processing

At the start the collaboration between Rzeszow University of Technology and the Institute of Geophysics, Polish Academy of Sciences, was focused on the research related to the analysis of dynamic spectra of different types of electric field waveforms of lightning CG strokes that were detected and registered during summer thunderstorms in the Warsaw region [6,7]. The analyses have shown that the power spectrum density (PSD) of lightning electric field changes can be effectively used for proper discrimination between the return stroke (RS) and CC components of CGs. A thorough analysis of the PSD spectrograms was possible by the Matlab module dedicated to the PSD evaluation, supported by our own software tool created in the Matlab environment. Our intention was to develop and improve computation capabilities in order to perform more effective analyses of the electric field waveforms of a RS or CC in the time and frequency domains.

In the coming summer thunderstorm season of 2013, using the experience gained during lightning electric field recordings campaign run in Warsaw and in Gainesville at the University of Florida, our first measurements are planned to be performed at the Lightning Research Station in Rzeszow. The diagram of data acquisition and analysis using our dedicated software tools is shown in Fig.2.

The entire pre-analysis process is possible without any user interaction and a short report with general statistical information about the lightning electric field waveforms is generated. Moreover, the specific waveforms of particular lightning flash strokes including their parameters can be presented in the same report. Among the typical parameters are: (1) initial electric field peak, (2) opposite-polarity overshoot, (3) ratio of the initial electric field peak to the opposite polarity overshoot, (4) zero-to-peak rise-time, (5) initial half-cycle duration, (6) opposite polarity overshoot and (7) distance from the lightning striking point. Such information is completed during each lightning CG flash event detection and its preliminary more advanced analysis due to continuous and large lightning data set accumulated at the computer system is possible to be performed. The lightning location data delivered by the

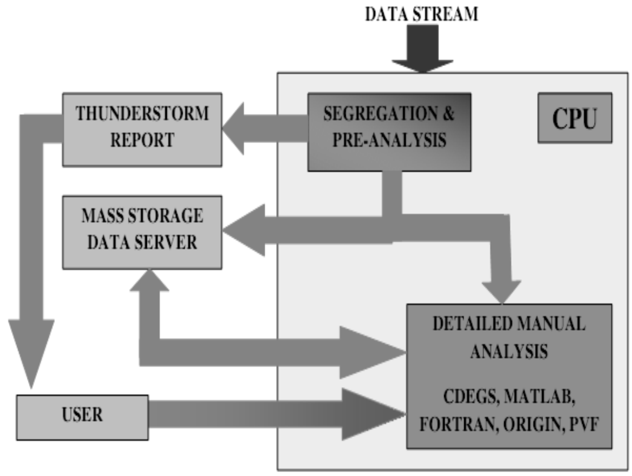

Fig.2. Data acquisition and analysis using dedicated software tools at the Lightning Research Station in Rzeszow.

SAFIR/PERUN or LINET networks will be correlated simultaneously with the electric field measurements through the use of the GPS time synchronization of 200 ns precision. Therefore, it will be possible to fit electric field waveform signatures to the corresponding lightning stroke events, and then, to compute the lightning current parameters based on the mathematical models of the considered lightning CG flash discharge.

Lightning Electric Field Propagation Analysis and Inverse Solution

The lightning electric field can be derived for the perfect conducting ground from Maxwell equations and is usually separated into three components: electrostatic, induction and radiation field components as follows [1,10]:

$$E_z(\rho,z,t)=\frac{1}{4\pi\varepsilon_0}\cdot\int_{-H}^{+H}\left[\begin{array}{l}\dfrac{2(z-z')^2-\rho^2}{R^5}\displaystyle\int_0^t i(z',\xi-R/c)\,d\xi+\\+\dfrac{2(z-z')^2-\rho^2}{cR^4}i(z',t-R/c)-\\\dfrac{\rho^2}{c^2R^3}\dfrac{\partial i(z',t-R/c)}{\partial t}\end{array}\right]dz' \quad (1)$$

$$E_\rho(\rho,z,t)=\frac{1}{4\pi\varepsilon_0}\cdot\int_{-H}^{+H}\left[\begin{array}{l}\dfrac{3\rho(z-z')}{R^5}\displaystyle\int_0^t i(z',\xi-R/c)\,d\xi+\\+\dfrac{3\rho(z-z')}{cR^4}i(z',t-R/c)+\\\dfrac{\rho(z-z')}{c^2R^3}\dfrac{\partial i(z',t-R/c)}{\partial t}\end{array}\right]dz' \quad (2)$$

where: ρ – the distance from the lightning channel base, t – time, R – the distance from the specific segment along the channel, z – the height above the perfect conducting ground, z' – the height along the vertical channel, H – the total channel height, ξ– auxiliary integration variable, c – the speed of light in vacuum, ε_0 – the electric permittivity of the vacuum (approximately equal to the air permeability), i – the lightning current.

The electrostatic, induction and radiation components of the electric field radiated by lightning CG discharge change respectively as inverse of the third, second and first power of the distance. Therefore, at distances longer than 50 km from the lightning CG channel the electrostatic and induction components can be neglected. It is worth noting that analytical formulas (1) and (2) enable to analyse each electric field component separately and the total electric field waveform can be computed independent on the distance from the lightning striking point determined by the SAFIR/PERUN or LINET system. This feature will help to undertake the more detailed analysis of some physical processes involved in CG discharges taking place in the Rzeszow region.

Additionally, analysis of the lightning CG channel geometry based on registration made by the fast video camera (FVC) is planned to be carried out. Thus it will be possible to verify the theoretical model of the lightning corona sheath dynamics developed at the Rzeszow University of Technology and at the University of Florida in Gainesville during our long-term collaboration [11].

Possible charge transfer and slow changes of electric field occurring just before and after a particular lightning flash can be monitored by using the electric field meter working in the VLF range. In cases where the lightning CG channel will not be perpendicular to the ground surface, hypothesis on the superposition of two electric waves, i.e., the direct and reflected waves from the ionosphere, will be verified [12].

Access to the LINET database gave a good opportunity to evaluate accuracy of the formula adopted in [13]:

(3) $$D = 2R_e \sin^{-1}\sqrt{\sin^2\frac{(\theta_{LO}-\theta_e)}{2} + \cos\theta_{LO}\cos\theta_e\sin^2\frac{(\phi_{LO}-\phi_e)}{2}}$$

where: D – distance from the lightning channel R_e – the Earth radius, θ_{LO} – the latitude of the lightning observatory, Φ_{LO} – the longitude of the lightning observatory, θ_e – the latitude of the lightning striking point, Φ_e – the longitude of the lightning striking point.

Note that the distance and the latitude as well as the longitude are considered in kilometers and degrees respectively. The parameters D, θ_e, Φ_e can be obtained directly from the LINET database. When the peak value of the electric field and distance from the lightning channel are known the peak current during the return stroke can be estimated from the empirical formula [14]

(4) $$I = 1.5 - 0.037 \cdot D \cdot E$$

where: I – estimated peak current in kA, D – distance in km from the lightning channel, E – peak value of electric field waveform. Equation (4) was derived based on triggered lighting data, and, in fact, it has direct application only to the subsequent strokes, although, it is sometimes applied to the first return stroke estimation as well. Additionally, the electric field measurements made at the Lightning Research Station in Rzeszow enable to compare the peak lightning currents computed from Eq. (4) with corresponding data obtained from the LINET system. The simultaneous time and position reference are ensured automatically by GPS receiver build-in the system.

Software Package for Analysis of Lightning Electric Field Data

As mentioned in the previous section, the electric field radiated by a CG flash consists of three components. The contribution of each of them to the final result of the recorded change in the electric field due to the flash depends on the distance of the observatory from the lightning striking point. To conduct some preliminary analysis of the electric field waveform signatures of some chosen RSs or CCs, the LightViewer, a dedicated Matlab program developed at the Rzeszow University of Technology, has been used.

For illustration an example of three RS waveform signatures of one multiple CG flash collected in the Warsaw region [6] has been converted in the LightViewer interface and shown in Fig.3. Different shapes of the falling slopes after the first RS of the considered multiple flash distinctly seen in Fig.3 were caused by different distance of the first RS from each LLDN measuring station.

Lightning electric field variations can be measured at the LRS station simultaneously with the video recordings of the lightning channel development time. Hence both kind of data, i.e., electric field waveforms and video stream can be visualized by the Photron Fastcam Viewer as it is shown in Fig.4.

Simultaneous data concerning the same CG flash, obtained from one of the electric field antennas and the FVC, allow verify the influence of the lightning channel development on the shape of the lightning electric field signature observed at different distances. Moreover, some phenomena as downward and upward leader or attachment process may be also analyzed with megapixel image quality at 7500 fps during the planned field campaign.

The Power Spectrum Density (PSD) spectrograms have been used by us to discriminate between different stages of multiple CGs detected by the LLDN in the Warsaw region [7]. An example of typical RS electric field waveforms of the detected multiple CGs with its dynamic spectrum calculated using the Short Time Fourier Transform (STFT) is shown in Fig.5. The upper panel of Fig.5 presents another kind of the LightViewer module visualization ability - some of the STFT parameters such as the adjustable window size, the number of overlap probes or the FFT length can be easily changed and adjusted in this data processing program. Moreover, the non-linear frequency axis in the form of given vector is possible to be applied. The analysis of the PSD spectrograms is an interesting alternative to the time domain analysis. Such spectra enable to obtain

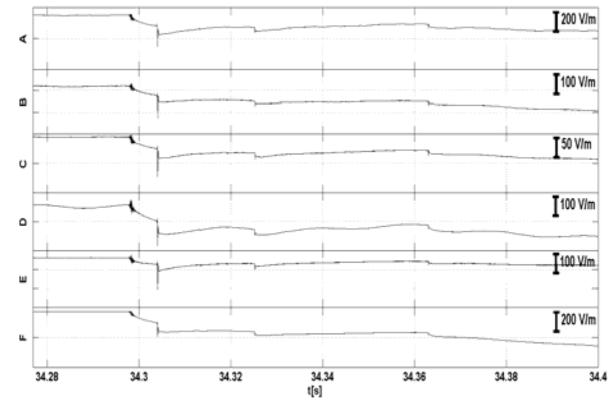

Fig.3. The dedicated LightViewer program showing the same first RS stage of a one multiple CG flash recorded by six various LLDN stations in the Warsaw region.

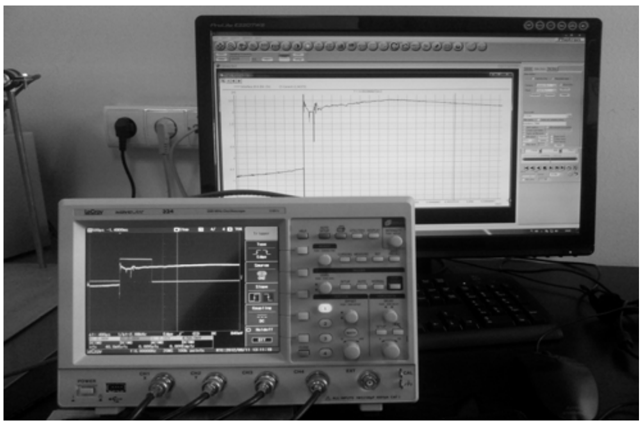

Fig.4. The Photron Fastcam Viewer presenting its recording ability during calibration process performed at the LRS setup.

unambiguous information about the RS and CC stages of detected multiple CGs. In particular, the energy of each particular stage can be computed, followed by risk level estimation.

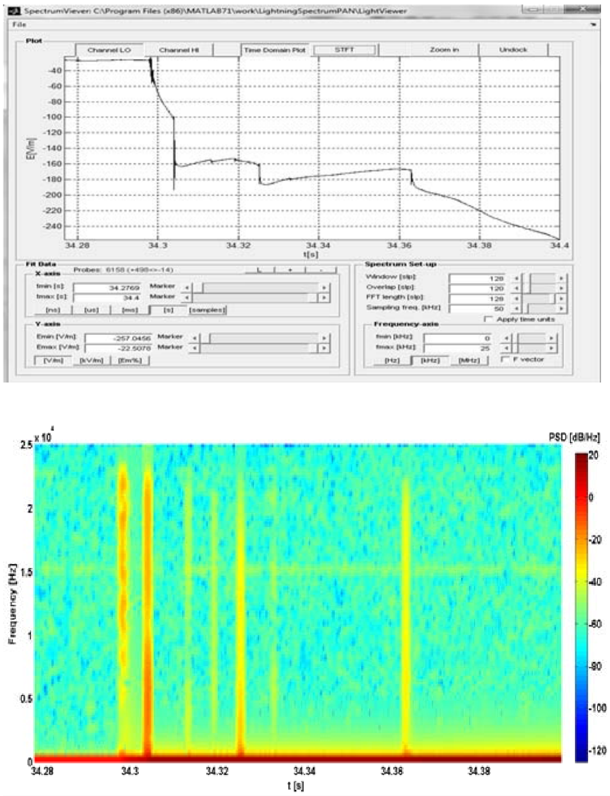

Fig.5. An example of the PSD dynamic spectra analysis used in discrimination of different stroke stages of CG multiple flash. The upper panel – shows a general view of the LightViewer PSD computing interface depicting one of the considered electric field waveforms of multiple CG flash recorded by station F (Fig.3). The bottom panel – gives an example of relevant PSD print-out obtained from the implemented computer data processing.

Conclusions and final remarks

The Lightning Research Station in Rzeszow is able to measure and store simultaneously different kind of lightning data sets, namely, lightning electric field measurements with their DC and AC variations, and high speed video recordings. Lightning data obtained from the slow electric field meter and fast electric field antenna together with the fast video camera recordings of lightning channel development give us a unique possibility to perform detailed analysis and comparison of the different time development of various stages of CG lightning flashes taking place in the Rzeszow region.

Our numerical procedures used for lightning data analysis are based on the built-in Matlab algorithms from the Image Acquisition and Processing Libraries and the Photron Fast Viewer implementation delivered by the camera manufacture company. In addition, part of the lightning electric field waveform analysis is supported by our own software tool developed in the Matlab environment.

The LRS measuring setup is designed to investigate and provide the PSD discrimination of the return stroke and continuing current stages of lightning CG discharges. Moreover, analysis of lightning channel geometry recorded by the fast video camera (FVC) can be applied to verify the theoretical model of the lightning corona sheath dynamics. Launch of LRS field campaign is planned in 2013 summer thunderstorm season.

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