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The time and power spectrum density analysis of different lightning components based on electric field waveforms from 2014 thunderstorm season recorded in the south-eastern part of Poland

Abstract. *This paper is focused on the Power Spectrum Density analysis of the lightning electric field signatures collected in Subcarpathian part of Poland, in 2014. Lightning records were carried out in two different ways. The slow electric field sensor (TLF-ELF), the mill, was used for observation of lightning activity during entire thunderstorm lifetime. The second recording mode was the acquisition of fast electric field changes (0.3 Hz to 3 MHz) associated with different types of cloud-to-ground (CG) and inter-, intra-cloud (IC) type discharges. The registration process was synchronized with microsecond time precision. This allowed to relate lightning stroke detections to these reported by the LINET, the commercial lightning location system. Different lightning stroke components, as e.g. the preliminary breakdown (PB), the return stroke (RS) and the continuing current (CC) were identified with application of the Short-Time Fourier Transform. The spectral analysis might be adapted to improve in future some detection algorithms used in lightning location systems. Such lightning CG stroke discrimination is not applied as yet by any lightning location system routinely operated in Europe.*

Streszczenie. *W artykule skupiono się na analizie spektrogramów widmowej gęstości mocy wyznaczonych dla różnych przebiegów piorunowego pola elektrycznego zebranych w południowo-wschodniej części Polski w 2014 roku. Dane zostały zebrane z wykorzystaniem dwóch sensorów pola elektrycznego. Sensor pola elektrycznego pracujący w zakresie TLF-ELF umożliwił obserwację aktywności burzowej w długofalowym okresie czasu. Drugi typ rejestracji obejmował akwizycję szybkich zmian pola elektrycznego (0.3 Hz do 3 MHz) pochodzących of różnych typów wyładowań doziemnych oraz wewnątrz-, między-chmurowych. Proces rejestracji został zsynchronizowany z mikrosekundową precyzją. Pozwoliło to na porównanie własnych rejestracji z detekcjami LINET-u – komercyjnego systemu lokalizacji wyładowań. Różne składowe wyładowania takie jak wyładowania wstępne, udar główny oraz prąd długotrwały zostały zidentyfikowane z wykorzystaniem krótkoczasowej transformaty Fouriera. Analiza spektralna może w przyszłości zostać wykorzystana w usprawnieniu algorytmów detekcji wyładowań. Taki rodzaj identyfikacji wyładowań doziemnych nie został jak dotąd zaimplementowany w żadnym systemie lokalizacji wyładowań atmosferycznych pracującym regularnie w obszarze Europy.* ***(Czasowa oraz widmowa analiza różnych składowych wyładowania atmosferycznego w oparciu o przebiegi pola elektrycznego zebrane w południowo-wschodniej części Polski w 2014 roku).***

Keywords: lightning electric field, thunderstorm, lightning location system, short-time Fourier transform, power spectrum density
Słowa kluczowe: piorunowe pole elektryczne, burza, system lokalizacji wyładowań, krótkoczasowa transformata Fouriera, spektralna gęstość widmowa mocy

Introduction

Presently, there are many different types of lightning location systems continuously operated all over the world [1, 2, 3]. These systems were designed to warn against lightning events dangerous for the electrical installations, buildings, forests and human beings. A continuous stream of data containing parameters of lightning strokes is saved and stored for present and future use. These parameters can be divided into two groups. The first group is connected with determination of the exact time occurrence and spatial coordinates of the recorded/detected lightning incident and the second one is represented by physical parameters of this event, as e.g. lightning current and electric field amplitude, polarity and type of lightning stroke. Full set of these parameters is important for overvoltage protection purpose and in order to classify if a such particular lightning incident is dangerous or not for protected object or place. Unfortunately, in many cases there is hard to identify if a lightning stroke was a cloud-to-ground (CG) or an intracloud (IC) type [4, 5]. There is a noticeable underestimation of CG stroke events that are reported by the commercial lightning location systems in Europe. It seems to be the result of difficulties to obtain an efficient discrimination procedure of the preliminary stages and main components of lightning CG flashes only on the base of the electromagnetic field lightning parameters evaluated from the time domain records. To the best knowledge of the authors, there is no lightning location system operated in Europe as yet that could be able to deliver/report besides RS change detections during CG flashes also the occurrence and parameters of their CC components. Determination of the extreme value of lightning parameters of particular CG strokes are essential for any effective lightning protection action. However, the full knowledge of the time sequence of RS and CC strokes in CG flashes is also very important to estimate the total heat impact effect that is introduced by them to any installation/device which protected object from lightning strike. It is worth to note that the resulted effect of lightning current distribution in any kind of the protection system will be more dangerous in the case of multiple CG flashes, because more energy can be injected then to it. Therefore there is strong necessity to group particular RS and CC lightning stroke events into one multiple CG flash incident. One of possible way to effectively perform such task is using the power spectrum density (PSD) analysis for the examination of electric field signature of RS or CC changes recorded during CG flashes. This approach is based on the short-time Fourier transform (STFT) application to conduct the discrete-time signal processing [6, 7]. Such PSD algorithm enables us to move any recorded lightning electric field waveform from the time-domain to the time-frequency domain consideration and to obtain more transparent and straightforward spectral analysis used for proper identification/differentiation of any kind of lightning pulse incidents, as e.g. components of the preliminary breakdown (PB), stepped-/dart-leader (SL/DL), return stroke (RS), continuing current (CC) or intracloud (IC) changes occurring during different lightning discharge processes.

Measurements of lightning electric field during thunderstorm development

Our lightning E-field measurement campaign was carried out at Bezmiechowa Gorna located about 80 km to the south from Rzeszow. This research action was arranged with the cooperation of three institutions: the

Rzeszow University of Technology, the Institute of Geophysics of Polish Academy of Sciences and the Warsaw University of Technology. Lightning activity from passing thunderstorms was recorded by our E-field sensors only from 19 to 23 May 2014. There the most intense and close lightning activity was observed just in 20 May 2014. The measuring setup used by us for lightning E-field recordings at Bezmiechowa Gorna is shown in Fig. 1. More detailed description of the E-field sensors presented in Fig. 1 one can find in the following papers [8, 9, 10]. The main aim of our measurement action was to compare both E-field flat plate antennas used for lightning detection in Rzeszow and Warsaw and to check their performance contrary to the LINET lightning detection results in Subcarpathian part of Poland used by us for further the post-time analysis.

The slow lightning electric field variations were recorded in the TLF-ELF frequency range from 0 Hz to 10 Hz with using the field mill with rotated dipole and digital oscilloscope. Due to this we were able to observe time development of the total lightning activity and the electric structure of thunderclouds approaching or moving away from our measuring site. The fast lightning electric field changes in the frequency range from 0.5 Hz to 3 MHz was gathered from the dedicated flat plate E field antennas prepared by the Warsaw University of Technology. Both slow and fast lightning E field signatures were recorded accordingly to UTC time with the 200 ns GPS time precision with the 12-bit ADC resolution and the speed of 50 MS/s. Additionally the long-term variations of atmospheric electromagnetic field (EM) was recorded by the Maschek ESM-100 device in the frequency range from 5 Hz to 400 kHz. By that means three coordinates of electric and magnetic field were measured for the one-day period.

The high-speed camera Photron SA-5 was used for anticipated lightning CG flash video acquisition. This camera can record lightning channel development at the 7000 fps and with 1024x1024 pixels resolution. However, in contrast to the automated video recordings at Rzeszow measuring site, this time the fast camera was triggered manually.

Additionally, the DSLR camera Nikkon D7100 was configured and prepared to image the 2D geometry of a possible channel development of nearby CG stokes with the resolution of the order 24 Mpix. Our photo equipment was installed at the lookout tower just over the roof of the AOS building and therefore its view area was relatively large.

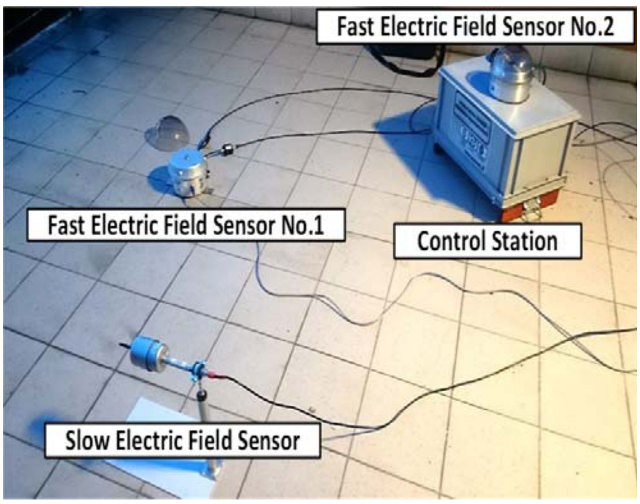

Fig.1. The electric field sensors setup located at the roof of Academic Gliding Center (AOS) in Bezmiechowa Gorna

Time- and time-frequency domain analysis of lightning electric field

We have analyzed our recorded file containing the fast E-field signatures of lightning flashes both in time- and time-frequency domain. We have obtain 134 lightning events that were archived in 48 files. All registration statistics is given in Table 1.

Table 1. The parameters of the sensor

Type of event	*No. of events*	*Comments*
Total	134	
CG	127	1 negative hybrid CG consisted of 5 RS 3 negative CG consisted of 3 RS 19 negative CG consisted of 2 RS 1 bipolar CG consisted of 2 RS 93 single stroke flashes
IC	7	

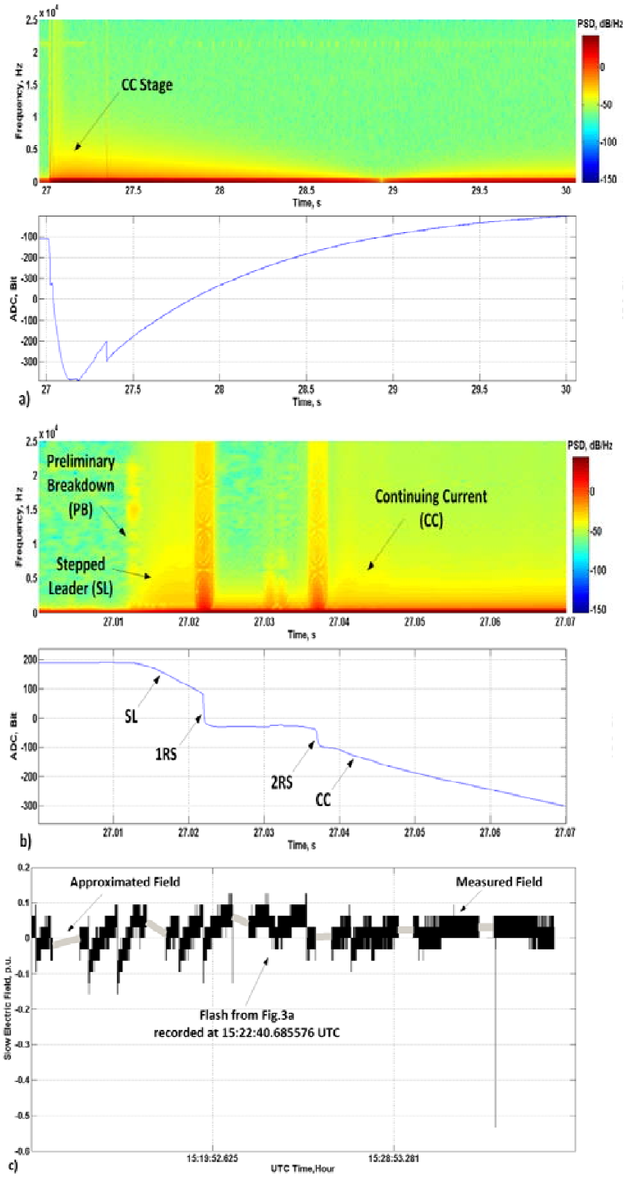

Fig.2. The time- and time-frequency domain analysis of E-field of multiple negative CG recorded in Bezmiechowa 20 May 2014. a) the time E-field course (bottom panel) and the corresponding PSD (upper panel) of the whole CG flash; b) the falling slope of E-field of CG flash presented in the part a); c) the slow E-field variations just after and before the CG events shown in the part a). Note that the STFT parameters for the parts a) and b) are as follows: window=128 samples, overlap=120 samples and FFT length=128 samples with fs=50 MS/s

The exemplary two selected episodes with IC and multiple CG flashes are considered in more detail below. The first case is multiple CG flash event recorded on 20 May 2014 at 15:09:27.021718 UTC and presented in Fig. 2. This CG flash consists of two RS's and one CC component that are preceded by the distinct stepped leader stage. The phase of continuing current is initiated by the second RS [see Fig. 2b].

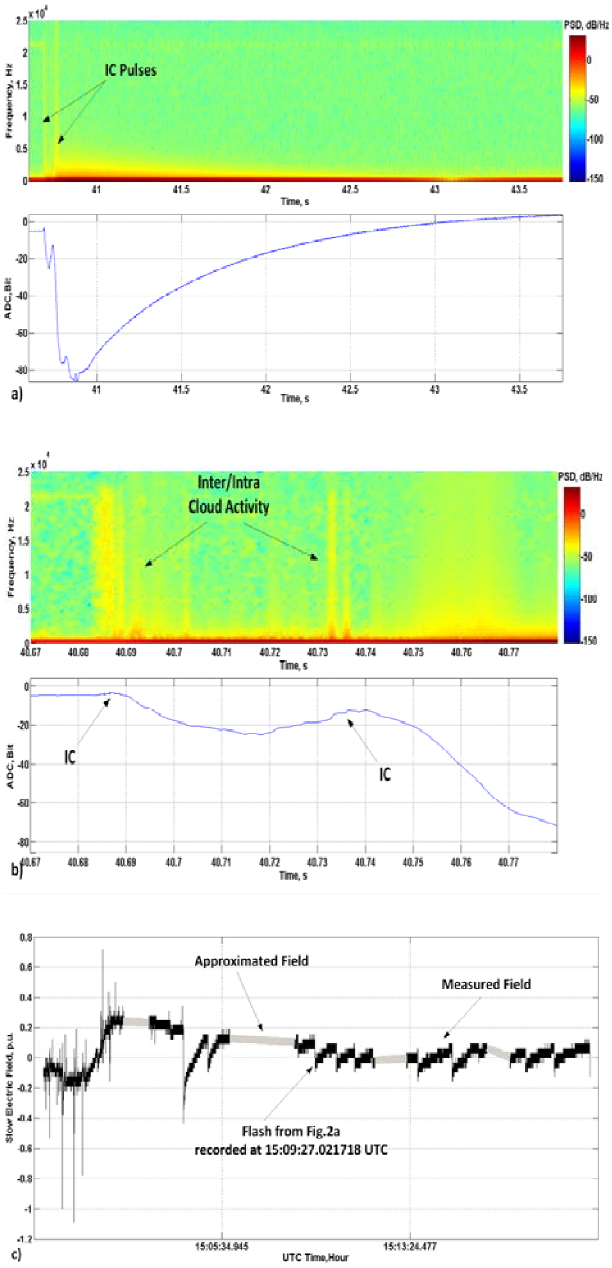

Fig.3. The PSD analysis of IC discharge lightning event recorded in Bezmiechowa 20 May 2014. a) the time E field plot of the entire IC discharge (bottom panel) and the corresponding its PSD spectrogram (upper panel); b) the falling slope of E field from IC discharge incident presended in the part a); c) the long lasted slow lightning E field variations after and before the IC episode shown in part a). The parameters of the STFT are the same as in Fig. 2

Additionally, we have shown in Fig. 2c the characteristic and lasting longer slow thunderstorm E-field variations that is related to the CG flash incident presented in the upper part of Fig. 2. On the other hand, in Fig. 2b we have presented in one panel all possible components of the considered negative CG flash and resulted from the relevant PSD analysis. The time sequence of the particular episodes of this CG flash starts from the preliminary breakdown stage and then the distinct phases of stepped leader with two RS changes are following. But, after the second RS the long continuing current begins to flow in the lightning channel. The direct comparison of the time-domain lightning E field plots with these panels depicted the conducted PSD analysis has exhibited the pronounced time correlation of the spectral PSD lines with the time derivative of the lightning CG waveforms recorded only in the time-domain. We can see that when the more rapid lightning E-field change is recorded during CG incident then the stronger PSD spectrum activity is obtained. On the other hand, the slower components of CG flash, like as the SL or CC changes, can be identified by the long lasted PSD activity in the lower frequency range. However, the faster components, like the PB or RS stage, are presented by the relevant PSD spectrogram as the narrow strips which frequency is reaching up to several kHz. The similar relationships were also observed during some previous PSD analyzes and obtained from lightning E-field measurements in different parts of Poland [11,12,13].

The second lightning discharge case selected to our PSD analysis presented here is obeying the time sequence of distinct IC train pulses recorded on 20 May 2014 at 15:22:40.685576 UTC and presented in Fig. 3.

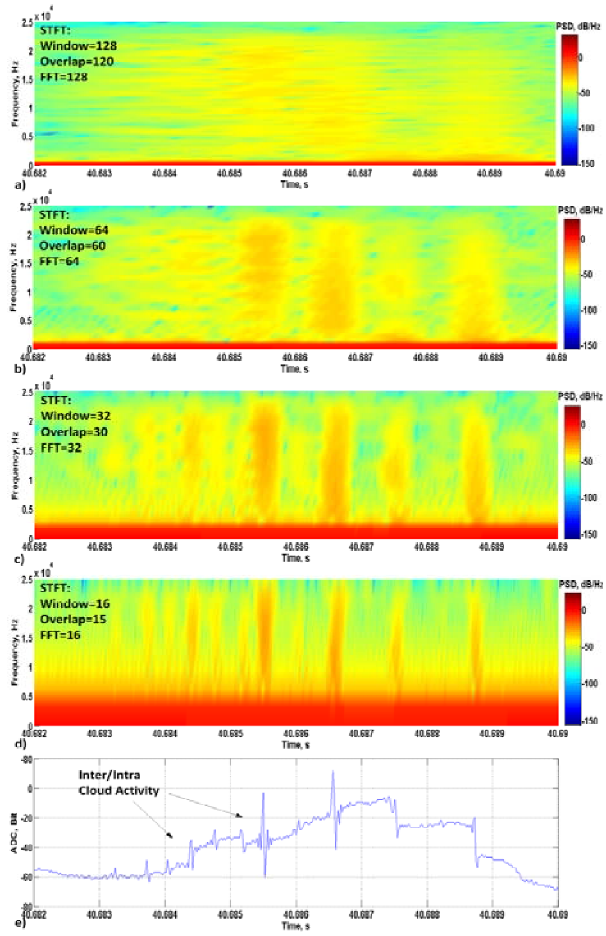

Fig.4. Four examples of the PSD analysis of the seleted part of IC discharge train pulses and for different parameters of the conducted STFT procedure(upper panels a-d). These parameters are given in the left upper corner of each (a-d) panel. Additionally, the corresponding plot with the considered time-domain lightning E field IC signatures is presented in the e panel at the bottom

We can note that the PSD spectrograms presented in Fig.3a and Fig.4a are similar to each other. But, the time extension of the corresponding falling slope of their lightning E-field results in the completely different structure of the obtained PSD spectra. For the selected part of IC lightning incident presented in Fig.4 we can only differentiate some characteristic time sequence of different train pulses. Hence, there are some PSD strips, similar to that for the PB stages and presented in Fig.2b. However, these PSD strips that are shown in Fig.3 and Fig.4 are randomly distributed and corresponded to greater lightning E-field changes as compared to those obtained for the PB stage from the considered CG flash.

The choice of the different STFT parameters on the obtained PSD strip structure is presented in Figs.4a-d. To this comparison was only taken the beginning part of the lightning E-field IC signatures (see Fig.4e). Four sets of three different parameters for the used STFT window were applied as follows: for the window of 128 samples we have Δt=2.56 ms and $1/\Delta t \approx 0.391$ kHz, for the window of 64 samples we have Δt=1.28 ms and $1/\Delta t \approx 0.781$ kHz), for the window of 32 samples we have Δt=0.64 ms and $1/\Delta t \approx 1.562$ kHz, and for the window of 16 samples we have Δt=0.32 ms and $1/\Delta t \approx 3.125$ kHz. Thus, the PSD time axis resolution becomes more accurate when the STFT window length is also more narrow and the obtained PSD strips corresponding to different IC pulses are well distinguishable. However, the resolution of the PSD frequency axis is simultaneously decreased. This is the consequence of the Heisenberg-Gabor limit [14]. Better frequency resolution with wider STFT window or better time resolution with narrower STFT window force one to assume a compromise in order to obtain the reliable PSD representation of the considered IC or CG lightning flash components.

Conclusion

The proper selection of the STFT parameters is the key task to obtain reliable algorithms for their identification and discrimination. The conducted comparison of our identification of CG or IC flash incidents gave us some important information about performance of our recording system regarding to its detection efficiency and E-field sensor sensitivity range. Moreover, it has shown that there are still CG flash events that are not correctly recognized by the commercial lightning location systems and therefore their discrimination algorithms used for lightning detection should be improved. Particularly the proper identification of lightning CG components as like the preliminary breakdown or the continuing current stage is strongly desired and not yet fully attained. Thus, the PSD analysis could be used to recognize these components and compute their characteristic parameters. The time- and frequency-domain analysis with application of the Short-Time Fourier Transform is preferred to fulfill such need. The parameters of the STFT procedure can be adjusted to distinguish any different stages of IC or CG flashes in proper way. The results of our PSD analysis have shown that for the case of the fast components of CG incidents as like the preliminary breakdown or return stroke stage the better choice for their reliable discrimination is the narrow STFT window. On the other hand, for the stepped leader or the continuing current stage two to four times the wider STFT window should be used.

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REFERENCES

[1] Rakov V. A.: Electromagnetic Methods of Lightning Detection, Surv. Geophys., 34, 2013, s. 731–753
[2] Betz H., Schmidt K., Laroche P., Blanchet P., Oettinger W., Defer E., LINET – A New Ligthning Detection Network in Europe, 13-th International Conference on Atmospheric Electricity, 2007, Beijing, China
[3] Loboda M., Betz H.D., Baranski P., Wiszniowski J., Dziewit Z., New Lightning Detection Networks in Poland – LINET and LLDN, The Open Atmospheric Science Journal 01/2009, 3:29-38
[4] MacGorman, D.R., Rust W.D.: The electrical nature of storms, Oxford University Press, New York, 1998, s. 49-53
[5] Rakov V.A., Uman M.A., Lightning: Physics and Effects, Cambridge Univ. Press, 2003, New York
[6] Oppenheim, Alan V., Ronald W. Schafer, and John R. Buck. Discrete-Time Signal Processing. 2nd Ed. Upper Saddle River, NJ: Prentice Hall, 1999
[7] Rabiner, L.R., and R.W. Schafer, Digital Processing of Speech Signals, Prentice-Hall, Englewood Cliffs, NJ, 1978
[8] Maslowski G.: Lightning E-field measurement and fast video recordings station at the Rzeszow University of Technology, Poland, Konferencja: 21st International Conference on Electromagnetic Disturbances EMD 2011, Białystok 28-30.09.2011, s.181-182
[9] Baranski P., Loboda M., Wiszniowski J., Morawski M. (2012), Evaluation of multiple ground flash charge structure from electric field measurements using the Local Lightning Detection Network in the region of Warsaw, Atmospheric Research, 117, 99-110, doi: 10.1016/j.atmosres.2011.10.011
[10] Karnas G., Maslowski G., Baranski P., Berlinski J., Pankanin G.: Instrumentation and data analysis process at the new lightning research station in Poland, Przegląd Elektrotechniczny, ISSN 0033-2097, R. 89 NR 6/2013, s. 217-220
[11] Maslowski G., Baranski P., Karnas G., Electric Field Frequency Spectra of Multiple Cloud-to-Ground Lightning Flashes Recorded in the Warsaw Region by Local Lightning Detection Network, XIV International Conference on Atmospheric Electricity, 2011, Rio de Janeiro, Brazil
[12] Masłowski G., Barański P., Karnas G.: Spectral characteristics of the electric field related to the preliminary breakdown stage of cloud-to-ground lightning flashes, Proceedings of the 15-th International Conference on Atmospheric Electricity, ICAE 2014, Norman, Oklahoma, USA
[13] Karnas G., Maslowski G., Preliminary measurements and analysis of lightning electric field recorded at the observation station in the South-east part of Poland, Przeglad Elektrotechniczny, ISSN 0033-2097, R.90, no.4, 2014
[14] Oliveira P.M., Barroso V., Uncertainty in the Time-frequency Plane, Statistical Signal and Array Processing, Proceedings of the Tenth IEEE Workshop, 7803-5988-7/00/$10.00, pp.607-611, 2000