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Estimation of Building Form Factor and Calibration of ELF-MF Electric Field Antenna Dedicated to Lightning Measurements

Abstract. *This paper is aimed to obtain a calibration coefficient for lightning electric field antenna operating at the Lightning Research System of Rzeszow University of Technology. The measurement showed that the electric field at the antenna location was significantly increased in respect to the flat terrain. Verification of the calibration coefficient was done with application of the commercial lightning location system data. Comparison with previous research from high voltage laboratory showed that an open test site calibration is in better agreement with empirical formulas.*

Streszczenie*. Celem artykułu było wyznaczenie współczynnika kalibracji anten piorunowego pola elektrycznego pracujących w systemie rejestracji wyładowań atmosferycznych Politechniki Rzeszowskiej. Pomiar uwidocznił, że pole elektryczne w docelowej lokalizacji było znacząco zwiększone w odniesieniu do pomiaru na otwartej przestrzeni. Dokonano weryfikacji współczynnika kalibracji z wykorzystaniem danych komercyjnego systemu lokalizacji wyładowań. Metoda pomiaru w terenie okazała się być w większej zgodności z teorią niż w przypadku pomiaru laboratoryjnego.*
(Pomiar i analiza współczynnika odkształcenia budynku oraz współczynnika kalibracji dla anten piorunowego pola elektrycznego wykorzystywanych w systemie rejestracji wyładowań atmosferycznych Politechniki Rzeszowskiej).

Keywords: antenna calibration, lightning location system, electric field antenna, building form factor, spectrum analyzer
Słowa kluczowe: kalibracja anteny, system lokalizacji wyładowań atmosferycznych, antena pola elektrycznego, współczynnik odkształcenia budynku, analizator widma

Introduction

Calibration is an important task during the operation of different commercial and research lightning location systems [1,2]. The accuracy of the calibration has an influence on lightning flash parameters estimation regarding the distance and channel base current [3,4]. In case of systems operating for scientific purposes the calibration enables research centers to compare results each other. Moreover, it gives more analysis possibilities. Most models of lightning phenomena are based on idealized case where the lightning electromagnetic pulse (LEMP) propagates from the channel through the flat terrain. Therefore, registrations done with application of antennae located at urbanized terrain cannot be directly utilized in those formulas.

A problem of the calibration of antennae dedicated to lightning measurements is not very common in literature [5]. There are many different methods applied by lightning registration stations [6]. Some of them are based on setups composed of two parallel plates. In this case antenna is located between the plates in well-known electric filed (EF) generated by application of the voltage [7]. Unfortunately, this procedure is not accurate, and does not take into account the presence of the building. Antennas are often situated at the roofs of elevated buildings where the electric field distribution is different than in case of flat terrain. The influence of the structure which tells how much the field is amplified/attenuated is described by the form factor [8]. This factor is mainly dependent on the structure height and the location of the antenna at the roof. It might be significantly different when the antenna is placed near the edge or in the center of the roof. Therefore, the building form factor should be estimated for the normal operating position of the antenna.

Another type of calibration methods use computer simulation of electric field distribution [9]. The configuration of antenna and its surroundings have to be modeled accurately, otherwise, the results might be failed. In this case the problem is the time-consuming process of defining the system geometry and properties, the necessity of high computing power and relatively long time of the simulation. Therefore, in practice this method is often mixed with measurement techniques which can significantly reduce the complexity of the simulation model.

The third group of calibration methods is based on open test site measurements. The procedure was applied in this paper. This is the most accurate technique because the entire geometry of the system is taken into account. It utilizes two sets of similar sensors which are placed in normal operating location and at the flat terrain. Antennae are recording a reference signal which frequency should be within the antenna bandwidth. In most cases this is the radio station carrier wave. Signal have to be recorded simultaneously by the two setups. Ratio of results from electric field antennae enable to compute the building form factor. Additionally, the reference antenna is used in order to perform an absolute calibration. The major problem is to obtain calibration signal which should have stable parameters and was the same for both EF sensors. One of the most often used signals is the LF radio carrier wave. Despite the best accuracy from all calibration techniques the uncertainties are still at the level of several up to tens of percent [10].

Measurement Setup

There are two kinds of electric field sensors operating at the Lightning Research System of Rzeszow University of Technology. The ELF (slow) sensor, called the mill, is used for monitoring the field originated by the charge moving within the cloud. The second ELF-MF (fast) antenna is dedicated to recording major components of lightning.

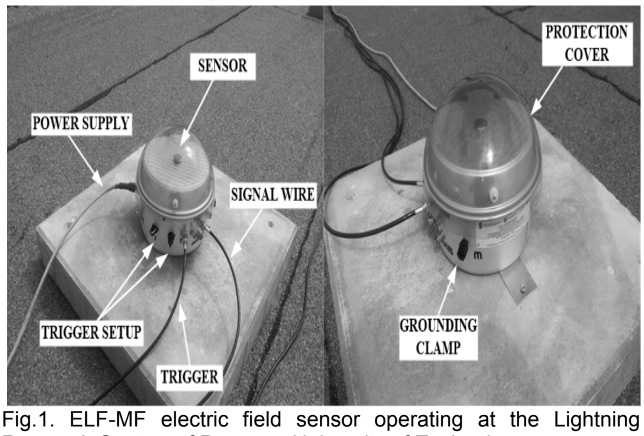

Fig.1. ELF-MF electric field sensor operating at the Lightning Research System of Rzeszow University of Technology

Calibration procedure presented in this paper was done only for the fast (ELF-MF) lightning electric field sensor (Fig.1). The slow sensor was calibrated with application of natural atmospheric electric field as a reference signal.

The fast EF sensor has a bandwidth from 0.5 Hz up to 3 MHz. It enables to record all major components of lightning like preliminary breakdown, leader, return stroke or continuing current. The antenna has a dedicated triggering circuit for cloud to ground (CG) lightning. Special polyethylene cover of the sensor ensures protection against rain and decreases the EF noise generated by charged rain drops falling on the antenna during thunderstorm. Antenna is connected with the ADC card with application of 10 m long BNC wires. The configuration of antenna connections was maintained during entire calibration procedure. The location of the sensor was the same as during normal operating mode.

Calibration setup consisted of two independent measuring points. One was at the roof of Rzeszow University of Technology building (50.0264900N, 21.9844829E). At the roof the fast lightning electric field antenna was located (Fig.2ab). The second measuring point have to be placed at a relatively flat terrain not so far from the Rzeszow University building (50.014552N, 22.022085E). Similar measurement setup was prepared in this case (Fig.2cd). The difference was a mobile power supply. It was important to give an additional power filter to improve S/N level of registration.

The straight distance between both points was about 3.02 km (Fig.3). It ensured that the calibrating signal was the same at both locations. The reference signal was a carrier wave of Polskie Radio I broadcasted from Solec Kujawski at 225 kHz.

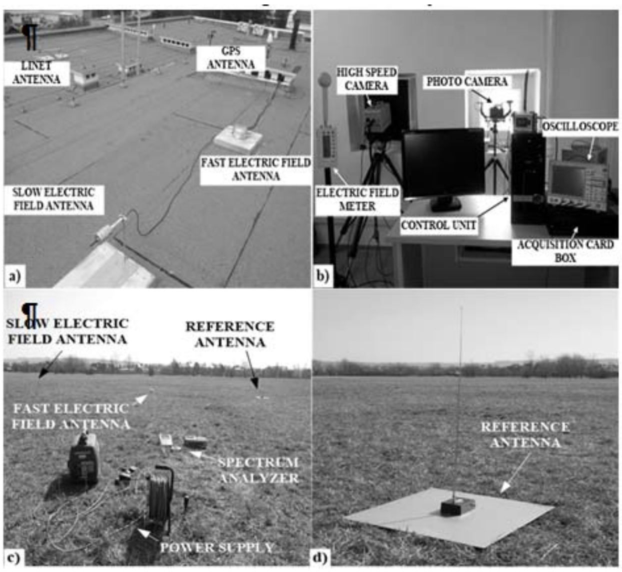

Fig.2. Measurement setup configurations. a,b) the first measurement point situated at the roof of Rzeszow University of Technology building; c,d) the setup located at the flat terrain

Measurement was done simultaneously with application of two spectrum analyzers. The first device was a Tektronix RSA5106A real-time signal analyzer. It visualized frequency spectrum from 1 Hz up to 6.2 GHz. The second was a handheld analyzer FSH4 manufactured by Rohde&Schwarz. It has a bandwidth from 9 kHz up to 3.6 GHz (Fig.4).

Measurements at the roof and flat terrain were done simultaneously in order to minimize the temporal variations of the carrier wave. The weather was good. There was no significant clouds and wind which could greatly change the distribution of LF radio signal. Additionally, to increase precision of measurement, results were averaged in similar time periods. This was done automatically by the software of spectrum analyzers. The level of input signal applied to analyzers was too high. Therefore, additional 10 dB and 20 dB attenuators were used. Using of attenuators force the necessity of additional calibration of both setups each other. In this case a reference generator of the harmonic signal was applied. This procedure enabled to take into account the influence of signal wires connecting antennae with analyzers. The settings of both analyzers were the same: RBW=30 Hz (Resolution Bandwidth), VBW=30 Hz (Video Bandwidth), SWT=11.1 s (Sweep Time). Total measurement time was about 111 s. This was a compromise between the duration of the measurement and resolution of the observed spectrum. In order to obtain absolute calibration the reference electric field antenna was used. It was SAS-550-1B with bandwidth from 9 kHz up to 60 MHz. The antenna factor was 0.1 dB/m.

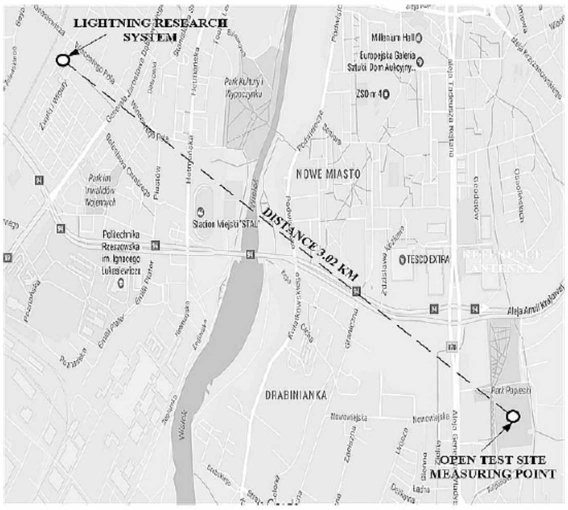

Fig.3. Map with given locations and the distance between two measurement setups used for calibration (Source: Google Maps)

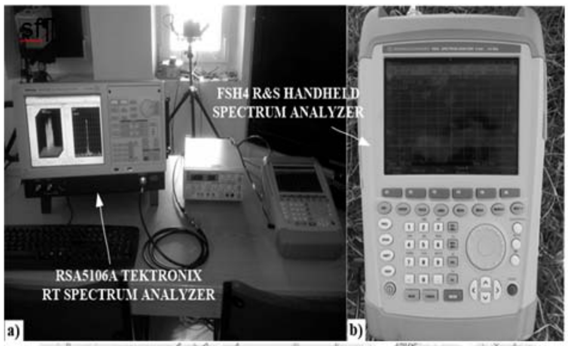

Fig.4. Spectrum analyzers used during calibration. a) RSA5106A RT Tektronix spectrum analyzer; b) FSH4 R&S handheld spectrum analyzer

Computing of Building Form Factor and Antenna Calibration Coefficient

The first step during the calibration was an estimation of the building form factor (Fig.5). This was done for the antenna located at the roof in the same manner like during the normal operating mode. Due to significant variations of the reference carrier wave signal the additional averaging of results was applied. This task was done fully automatically by the software of both analyzers. It greatly increased precision of measurement.

Fig.5. The Rzeszow University of Technology building for which the form factor was computed

The building increased the local intensity of electric field of about 2.53 times in respect do the flat terrain. This was within expected range. This showed that the antenna location has a high influence on registered lightning electric field waveforms and it could not be neglected during analysis. The precision of the estimation of the form factor was at the level of several percent. The main reason was the variation of the carrier wave amplitude. It was mainly due to variability of weather conditions between the transmitter located in Solec Kujawski distant by about 430 km from Rzeszow.

Next, the ELF-MF lightning electric field antenna calibration was done. The coefficient was computed on the basis of the building form factor and reference antenna recording. Considering the ADC card resolution of 12-bit and range ± 10 V, obtained calibration coefficient was 1.13 (V/m)/Bit.

In order to verify this result the commercial lightning location system – LINET data was used [1]. The calibration coefficient was computed with application of formula (1) describing the amplitude of lightning current as a function of magnetic field [4].

(1) $$I = 2\pi RBc/(v_{RS}\mu_0)$$

where: I – amplitude of lightning current given from LINET, R – the distance from the strike point obtained from LINET, B – registered magnetic field, v_{RS} – velocity of the current wave in the lightning channel, μ_0 – magnetic permeability of vacuum

This equation is correct only for radiated component of observed magnetic field. Applying this formula for vacuum impedance related to electromagnetic field (2), the equation (3) for the calibration coefficient was obtained.

(2) $$Z=E/H$$

where: Z – impedance of free space, E – electric field, H – magnetic field

(3) $$k=(v_{RS}\mu_0 I)/(2\pi RE_{ADC})$$

where: k – calibration coefficient, E_{ADC} – registered electric field amplitude given in ADC bits

Application of (2) forced to consider only far lightning events [Fig.6]. Therefore, the registrations with distance above several tens of kilometers were included in the analysis. For those recordings the radiated component of electric field was dominating. The empirical calibration coefficient computed from (3) was 1.81 (V/m)/Bit. It was close comparing to the open test site results. The better agreement of results is difficult to obtain in practice. Among main reasons there are simplifications made in the theoretical model. Especially, the constant value of the return stroke current wave speed, and absence of electrostatic and inductive components of electric field influence.

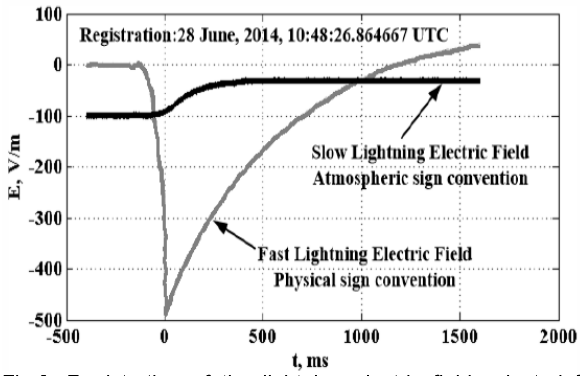

Fig.6. Registration of the lightning electric field selected for the computation of the calibration coefficient

Comparison with the laboratory calibration results

Comparison of open test site results with laboratory method of calibration was presented. The laboratory calibration was done in the high voltage laboratory of the Rzeszow University of Technology [7]. The measurement setup consisted of two metal plates forming a kind of capacitor [Fig.6]. Plates were situated in parallel. The sensor was located at the center of the bottom plate. The impulse voltage was applied from the generator between both plates. Voltages up to 3 kV were used. Electric field was computed with application of a simple formula (4).

(4) $$E=U/d$$

where: U – voltage applied from generator, d – distance between plates

The spacing of plates was 1 m therefore voltage could be easily converted to electric field units. The calibration coefficient was computed in almost the entire range of the ELF-MF antenna. The coefficient was observed to be stable. Small variations of this parameter were only for the lowest electric fields generated by the setup.

The calibration coefficient was obtained to be 0.78 (V/m)/Bit. It was about 30 % lower than from the open test side method. Despite this, the range of both results was comparable. It states that the laboratory method can be interpreted as measurement of the calibration coefficient in respect to the flat terrain. It can be seen that this method do not take into account the building form factor. Therefore it cannot be used for the lightning location systems operating in urbanized areas.

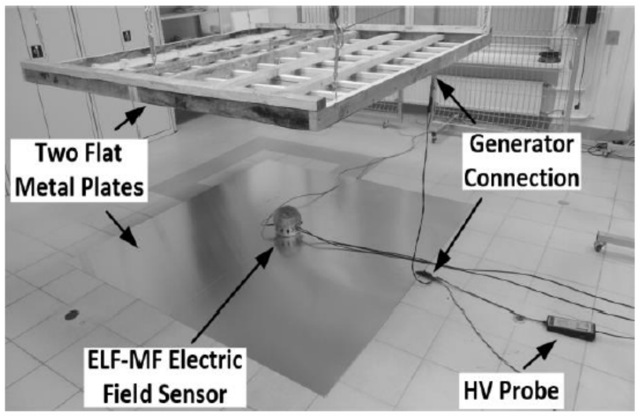

Fig.7. Measurement of the calibration coefficient at the high voltage laboratory

Conclusion

Research was aimed to obtain a calibration coefficient for lightning electric field antenna operating at the Lightning Research System of Rzeszow University of Technology. Additionally, the building form factor describing the modification of the lightning electric field due to presence of building was estimated. It was a continuation of previous research regarding a calibration in the high voltage laboratory. The open test site method was selected for the computation of the calibration coefficient. Measurements were done with application of two similar setups composed of ELF-MF antennae and spectrum analyzers. There were no close elevated objects which might influence the local electric distribution. Measurement of reference radio-wave signal was done simultaneously with application of two spectrum analyzers. The research showed that the electric field at the roof was significantly increased in respect to the flat terrain. The main reason was the presence of the building structure where antenna was located. Research showed that the building influence have to be taken into account during conversion between ADC units and electric field. The calibration coefficient was computed on the basis of the building form factor and reference antenna registration. Empirical verification of this coefficient done with application of commercial lightning location system data showed good agreement of results. Comparison with previous research regarding calibration setup consisted of two metal plates showed that the open test site calibration was in better agreement with results obtained from empirical formulas but the range of results obtained from both methods was similar. This value of the calibration coefficient was implemented in algorithms of the Lightning Research System in Rzeszow.

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