SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 11, No. 4 (special issue), December 2014, 629-647

UDC: 621.316.933:551.596.5(497.11)"2008-2013" **DOI: 10.2298/SJEE1404629J**

Flash Density Maps of Serbia for 2008-2013

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Abstract: Two sensors of the European lightning detection network (LINET) were installed in Serbia and included into this system in 2008. Besides getting various LINET results for lightning discharge characteristics over the six-years' period, the first accurate flash density maps of Serbia are obtained and given in this paper. Such maps are nowadays preferable for the design of lightning protection system. Principles of LINET system and its possibilities are also presented in this paper. Current amplitude distributions, stroke rates for 24-hours and lightning strokes maps for some lightning days in Europe are given, so as flash density maps of Serbia for each year from 2008 to 2013, along with the map of accumulated data for that period.

Keywords: Current amplitude distribution, Flash density, Lightning detection network, Lightning discharges, Stroke rate.

1 Introduction

In many years of studying lightning discharges, different techniques and methodology for detecting, measuring and recording their characteristics have been used in order to understand lightning phenomena. This approach was necessary for providing better design of lightning protection for electric power systems, objects, electronic equipment and devices, and for reducing dangerous effects of lightning discharges on people and animals.

Registration of the intensity and waveform of a lightning discharge current is performed by recording the voltage over resistor through which the current is flowing, or by recording the discharge current in the coil of the special measuring high-frequency transformer, so-called Rogowski coil, which is often set at the bottom of high tower and allows measurements in a wide-frequency range. In addition to measuring natural lightning discharge parameters, measuring is also performed on discharges artificially initiated by rockets launched to thunder clouds either from the fixed platforms or moving vehicles. Measured intensity and waveform of lightning electric and magnetic field at chosen distances is used for verifying lightning discharge models.

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Due to sudden changes in electromagnetic field radiated from lightning discharges, they may be registered at certain distances e.g. by lightning flash counters. Counters characteristics were standardized in order to enable comparison of results recorded in different countries, but there are two basic difficulties that cause uncertainty in the results: discharges of greater current intensities may be registered from far distances whereas those of smaller intensities just from near distances, and counters don't make distinction between cloud-to-ground and intra-cloud discharges. It is therefore necessary not only to perform calibration of counters, but to detect and evaluate the part that belongs to cloud-to-ground discharges which is more important for the design of lightning protection systems. In order to overcome the difficulties many other ways are used for registering lightning activity: satellite and radar monitoring of thunderstorm clouds, visual, acoustic and electromagnetic observation and available lightning detection networks.

There are international lightning detection systems [1 – 3] which require setting up the network of stations arranged at needed distances, so to cover the desired area and to satisfy the requested accuracy of detection. These stations provide information about location of lightning discharges, intensity and waveshape of the discharge current, and changes in electromagnetic field. In each station, the sensor is set up at a location with as small electromagnetic disturbances as possible e.g. on roof tops of suitable facilities. In case of LINET, the field sensor consists of two orthogonal crossed loops that record the changes in magnetic field which induces electromotive force and a GPS antenna for precise measuring of the event time. A processor for data acquisition is placed near the antenna. Induced signals are processed and compact data are sent to the central computer, connected to all the stations of the lightning detection network. Each station provides a time stamp. On the basis of the measured differences in time of propagation of electromagnetic wave from the lightning discharge position to a certain sensor station, the central computer determines the location of the discharge (TOA, time-of-arrival). In addition, the bearing angles are determined in order to verify the TOA solution. The locating analysis is performed with 5 or more time stamps so that unusual location accuracy of the order of 150 m is obtained. Lightning discharges radiate in a wide frequency range. Lightning detection systems can record very high frequency (VHF) or low frequency (VLF/LF) contents of signals. Using the VHF band lightning channels can be observed in more details, especially the process of forming leaders, whereas other phases of a discharge such as return-strokes emit dominantly VLF/LF radiation (Fig. 1). While VHF detection is limited to smaller distances from lightning discharges, signals in the VLF/LF range have longer wavelengths and can be registered from greater distances. Of course, inside clouds one finds also VLF/LF strokes, detectable with VLF/LF networks, and VHF leader steps extend down to ground, detectable with VHF systems from very short distances and undisturbed sight.

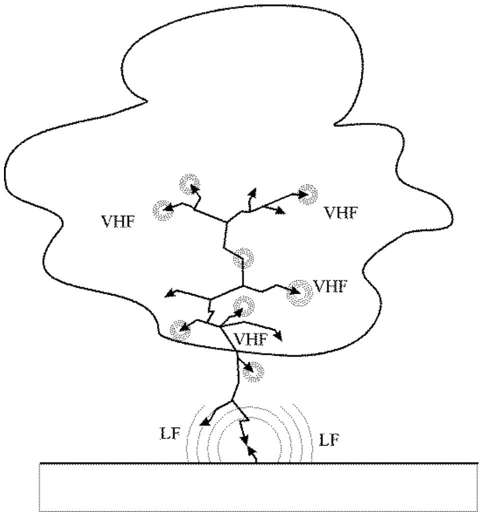


Fig. 1 – *Simplified VHF and VLF/LF radiation during a lightning discharge.*

In the past twenty years, systems for the detection of lightning discharges have been installed in many countries. There are some countries where several lightning detection networks have been set up. For example, in Poland on finds PERUN (VHF), CLDN (Central Lightning Detection Network), LINET, and a local scientific network (LLDN) in the region of Warsaw. LINET system proved to be very effective in the analysis, if compared to other networks, as well as to radar systems results.

LINET employs crossed loops for measuring the magnetic flux, bearing angles, and polarity of lightning signals, though locating employs only TOA techniques. Twenty years ago, the Physics Department of the University of Munich started research in atmospheric electricity and developed this lightning detection network. The system was tested first in the area of Munich, then in South Germany, and results were compared to other systems operating in Europe. In South Germany, LINET was intensively checked by DWD in comparison with lightning data from EUCLID [3]. Due to the improved features of LINET (designed, set up, and operated by nowcast GmbH), it became used by the German Weather Service since 2006, with renewed commissioning. Many independent installations were made in campaigns all around the world, e.g. in Darwin (North Australia), Benin (West Africa), Bauru (Brazil, South America) and Florida (USA, North America). LINET started with 60 sensors in Europe in 2006, improved steadily (Fig. 2), and nowadays it has about 140 sensors.

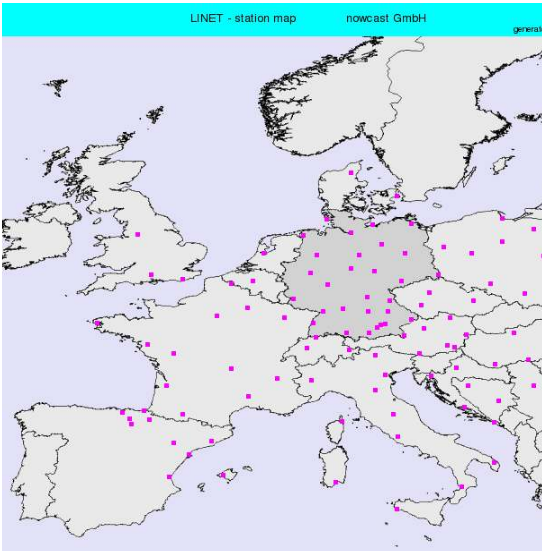


Fig. 2 – LINET *sensors in Europe* (2009).

Fig. 3 – LINET *sensor in Niš.*

Fig. 4 – *Cross-loop and GPS antenna in Niš.*

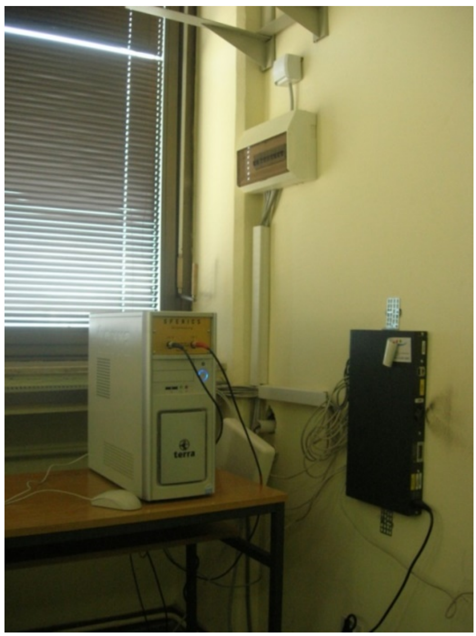


Fig. 5 – *Terra computer for LINET station in Niš.*

The reasons to install this system also in Serbia (Fig. 3) were high detection efficiency, the ability to report very weak strokes, particular location accuracy, the 3D feature that allows reporting of the altitude of cloud strokes, its simple design, low cost, quick and easy installation and operation.

2 LINET Background

Two LINET sensors were installed in Serbia in 2008, one at the Faculty of Electronic Engineering in Nis, and the other one at Republic Hydrometeorological Service of Serbia in Belgrade. Optimal coverage of the territory requires the presence of LINET sensors at distances not greater than 250 km, which was fulfilled by placing these two sensors in addition to already placed sensors in the surrounding countries. It was the first installation of sensors in Serbia for an international lightning detection system. Results are available online and can be used for scientific purposes, analysis of lightning discharge characteristics, but also for meteorological and practical needs, e.g. for the alert at airports and for power systems protection, as well as for other vulnerable thunderstorm-dependent installations. Together with the other network sensors in the region (Fig. 2), this configuration provides efficient data acquisition for the whole area of South-Eastern Europe.

LINET detects the VLF/LF part of the spectrum for both cloud-to-ground (CG) and intra-cloud (IC) flashes. In the VHF range (from 30 MHz to 300 MHz) the wavelengths (10 m to 1 m) are short compared to the lightning channel length, so that the channel can be observed in great structural detail and imaged in three dimensions. Especially, formation of the leader can be followed, but other phases of a flash like return strokes and slower pulse processes are emitting more pronounced in the VLF/LF range. Whereas VHF detection is confined to relatively short distances from the sources (line of sight), longer wavelengths of the VLF/LF range can be observed at much larger distances. Thus, VLF/LF is more efficient for the ground-strike-point determination in large areas.

Lightning location is performed by an analysis in the central processing unit, using sensor data from at least five stations that are located nearest to the lightning discharge event. TOA techniques are used for locating the 2D-position of lightning strokes; the 3D location is provided for IC strokes. Since abundant IC events are located, an effective discrimination against CG is required. The chosen solution consists in the employment of a new 3D-technique [5], which is independent of any specific lightning signal parameters.

Each individual station comprises an antenna with of two vertical and orthogonal loops with planes oriented N-S and E-W for measuring the magnetic field vector, and a GPS antenna for measuring a precise (<100 ns) time reference (Fig. 4). A field processor for data acquisition is placed inside a near building (Fig. 5). All received and pre-processed data are locally stored and transferred by internet to the processing centre operated by nowcast GmbH. It can be assumed that the lightning channel is oriented vertically so that the radiation is such that the magnetic field lines are horizontal circles, coaxial around the source. The output voltage of a loop antenna is proportional to the cosine of the angle between magnetic field vector and normal vector to the plane of the loop, according to the induction law. Hence, a loop with the plane oriented N-S receives maximum signal if the source is North or South of the antenna, whereas an orthogonal E-W loop receives no signal in that case. The signal in the N-S loop is proportional to the cosine of the angle between North and the source, as viewed from the antenna, and in the E-W loop to the sine of the same angle. Hence, the ratio of two antenna signals is proportional to the tangent of the azimuth angle to the source [2].

The strength and polarity of the lightning discharge can be determined from the values and signs of the measured field components. As regards CG-IC discrimination, traditional methods use the rate of change in electric or magnetic fields, based on the assumption that discharges into the ground are characterized by pulses with relatively slow decay ("peak-zero" time), while IC pulses are characterized by narrower waveforms. Due to insufficiencies of this method, LINET employs a newly developed 3D technique. It relies on the fact that CG radiates most strongly near the earth's surface, whereas IC radiates necessarily from higher altitudes; as a consequence, the sensor arrival times from IC lightning strokes are slightly delayed as compared to CG emission from the same 2D position of the considered stroke. This method has advantages because it does not depend on the shape or amplitude of the signal. Thus, LINET avoids the "traditional method" to distinguish IC from CG. Thus, discrimination of small-current signals becomes more reliable [3]. Still, 3D stroke-type identification becomes difficult or fails when signal shapes are extremely complex, or when the stroke-sensor distances becomes too long.

In the given network geometry strokes with amplitudes down to ~5 kA can be efficiently recorded and located with LINET system. This implies that a substantial fraction of cloud strokes can be reported, yielding so-called total-lightning capability, meaning both cloud-to-cloud and cloud-to-ground lightning are reported [6]. Relatively small baselines and other system settings result in low signal thresholds, thus guaranteeing high detection efficiency. As most CG currents have amplitudes above the network threshold, high CG efficiency is achieved. As regards IC detection efficiency, LINET reports a representative fraction, but a definite percentage cannot be given because the "100%-level" is unknown. LINET also reports all the usual stroke parameters, such as date, time, position, current, polarity, stroke type, error, and – depending on the demand – a variety of other characteristic pulse and stroke parameters.

3 Lightning Discharge Maps

On August 8th, 2014, there was a strong lightning activity in the region of Niš, which could be recorded by LINET system giving precise locations of CG discharges in the city map, as depicted in Fig. 7. Severe weather occurred in the whole central Balkan region.

LINET lightning activity maps are given in Fig. 6 for August 21st, 2014, for 24 hours of this day (UTC). Fig. 7a gives information about the type of discharges (CG denoted red, IC green). Fig. 7b shows storm activity in time intervals: 10 colours are used for a 24-hours period divided into 10 intervals of 2 hours and 24 minutes each, starting at midnight of that day (with the most intensive green colour), and ending at midnight (with the most intensive red colour). This visualization shows the movement of the storm and lightning discharges during this day. Fig. 7c displays current amplitudes, and Fig. 7d presents IC altitudes. The stroke-rate distribution for the same area is given in Fig. 8, showing that the most intensive lightning discharges of this day occurred between 10:30 and 16:30 UCT.

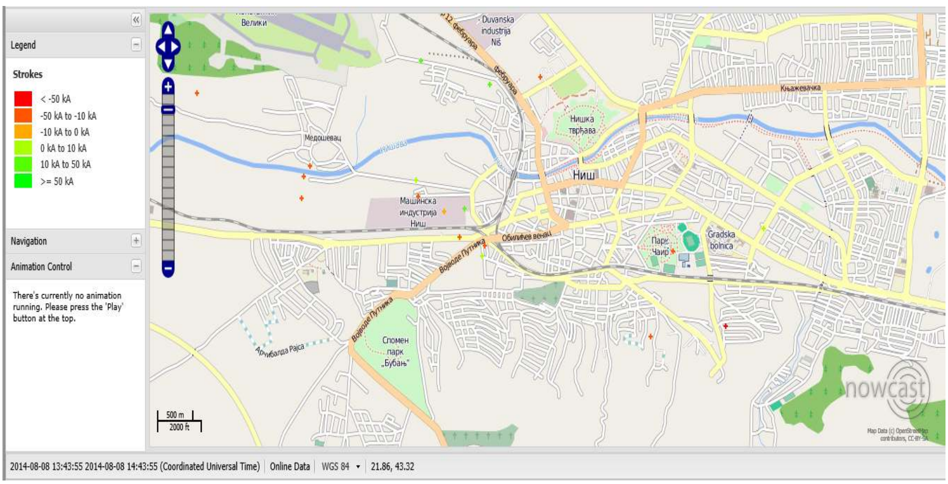
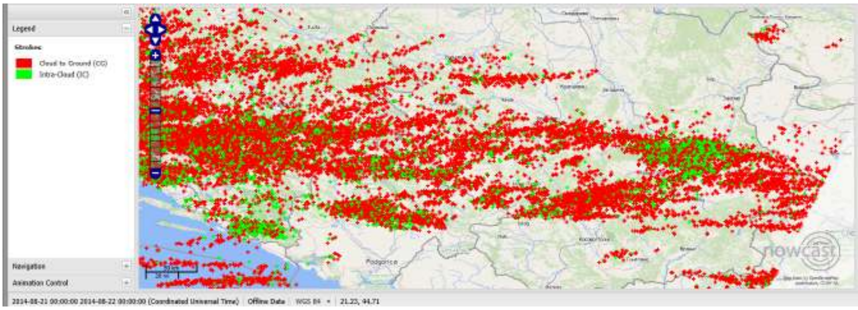


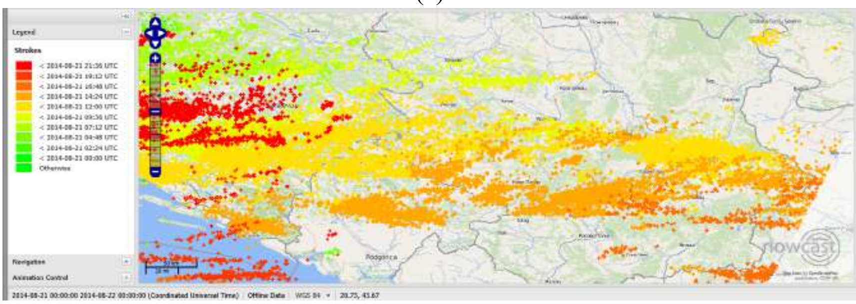
Fig. 6 – *Lightning discharges in Niš on August 8th, 2014, during one hour from 13:43:55 to 14:43:55 UCT.*

For the chosen dates with lightning activities (June 18th, 2010, May 17th, 2011, June 24th, 2011, and July 20th, 2011), LINET maps of Europe are given in Figs. 9 – 12, each for 24 hours. In these figures CG are denoted in green and IC in red. Current amplitude distributions and stroke rates for the same date and the same area are given in Figs. 12 – 19.

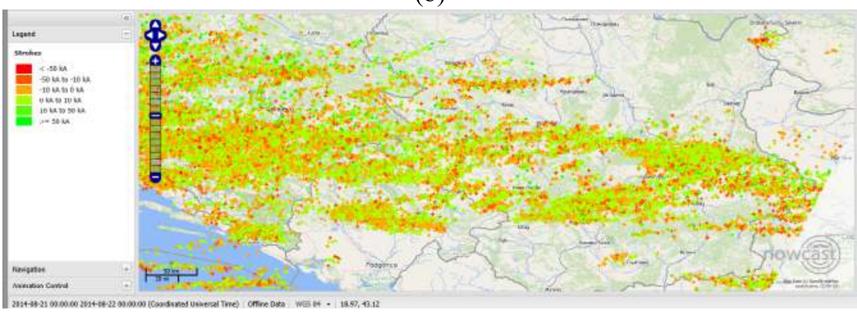
All results refer to the area 17 – 24°/41°– 47°N. It can be noticed that most of the CG strokes have current amplitudes from 5 to 10 kA.



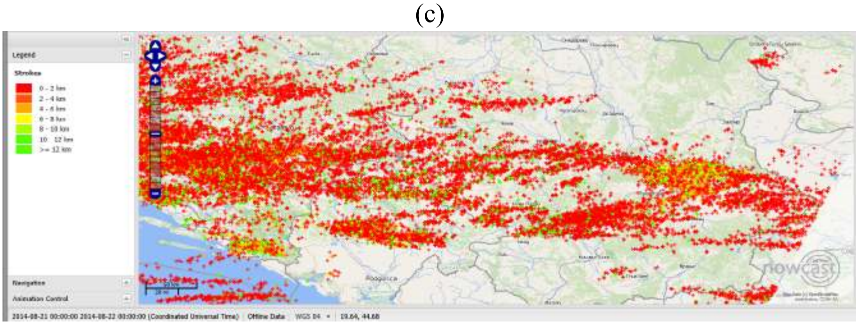
(a)



(b)



(c)



(d)

Fig. 7 – LINET *view of lightning activity for 24 hours on August 21*[st]*, 2014.*
The colour codes distinguish: (a) type CG or IC; (b) *event time*,
(c) *current amplitude*, (d) IC *emission altitudes.*

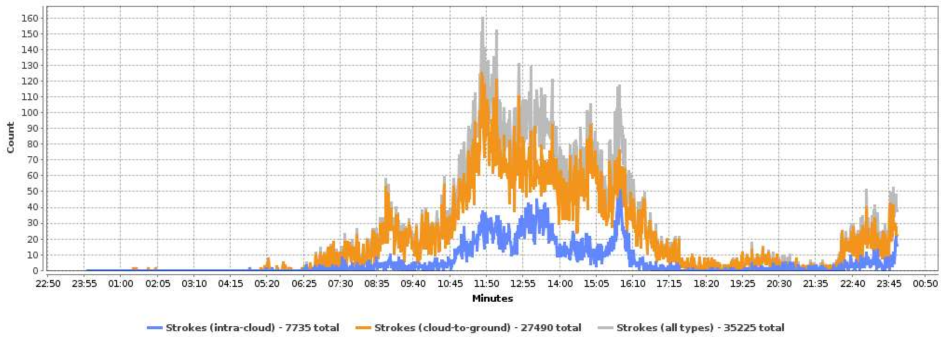


Fig. 8 – *Strokes distribution for 24 hours on August 21st, 2014, for the area given in* Fig. 7.

On June 18th, 2010, the stroke rate was up to 3000 within 10 minutes, and on July 20th, 2011up to 8000/10 min. It is interesting that May 17th, 2011, is a spring day with strong lightning activities in the Balkan area. The depicted storm days were selected according to intensive lightning activities in the South-East of Europe [7].

On June 24th, 2011, there were severe storms with hail in the South-East of Serbia and a large number of lightning discharges occurred in the whole region. The direction of storm displacement in the South-East of Europe was from North to South.

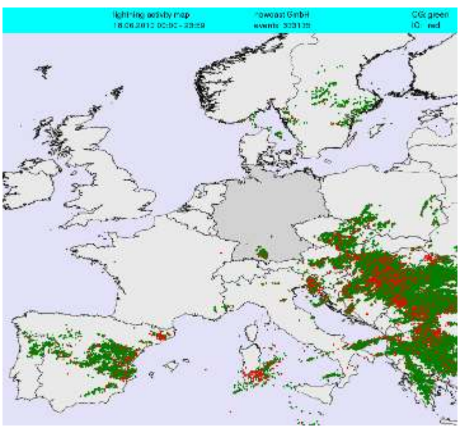


Fig. 9 – *Lightning activity map for June 18th ,2010, 333,135 events, CG denoted green, IC red.*

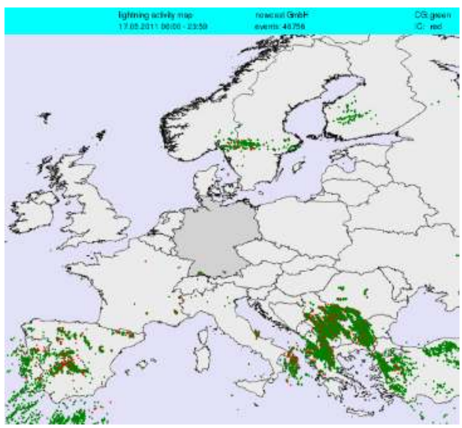


Fig. 10 – *Lightning activity map for May 17h , 2011, 46,756 events, CG denoted green, IC red.*

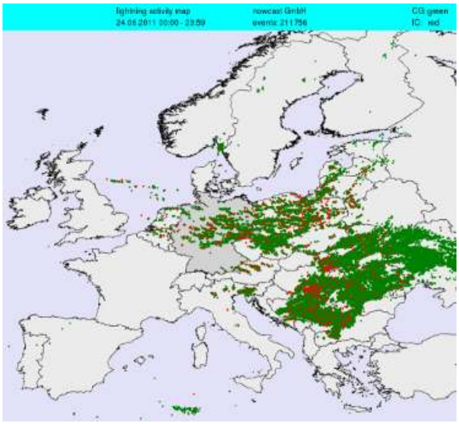


Fig. 11 – *Lightning activity map for June 24th, 2011, 211,756 events, CG denoted green, IC red.*

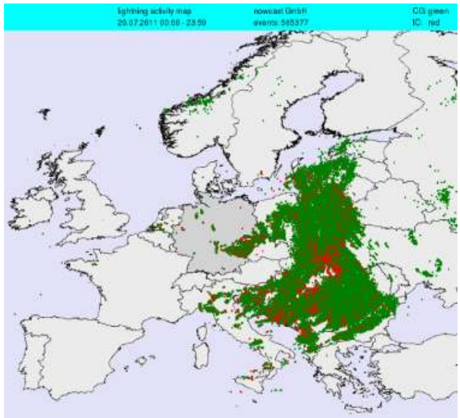


Fig. 12 – *Lightning activity map for July 20th, 2011, 565,377 events, CG denoted green, IC red.*

The European lightning activity on July 20th, 2011, is presented in Fig. 12. On that day, the registered number of lightning strokes by LINET within 24 hours was 565,377. The direction of storm movement in the South-East of Europe was from West to East. Stroke rates during this day were also very high. However, distributions of the registered lightning stroke currents have similar maximum values of about 10 kA for all these days.

Different thunderstorm development and directions of movement of thunder-clouds across South-Eastern Europe (SEE) over 24-hours' time can be noticed in the depicted maps. From activities in successive time intervals it is obvious how the cells moved and where the storms developed during these days [8].

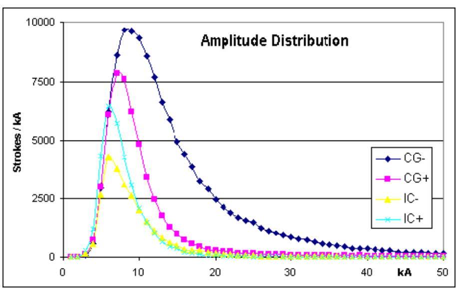


Fig. 13 – *Amplitude distribution for June 18th , 2010, for the area* 17°-24°E/41°-47°N.

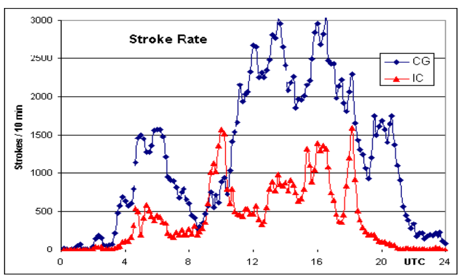


Fig. 14 – *Stroke rate for June 18th, 2010, for the area* 17°-24°E/41°-47°N.

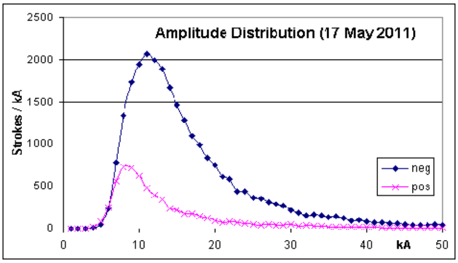


Fig. 15 – *Amplitude distribution for May 17^h, 2011, for the area* 17°-24°E/41°-47°N.

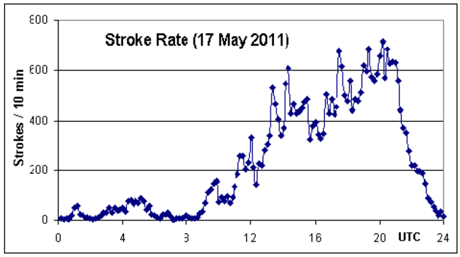


Fig. 16 – *Stroke rate for May 17^th, 2011, for the area* 17°-24°E/41°-47°N.

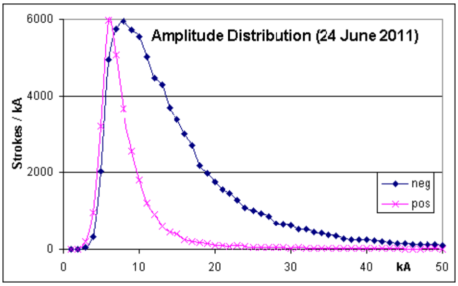


Fig. 17 – *Amplitude distribution for June 24^th, 2011, for the area* 17°-24°E/41°-47°N.

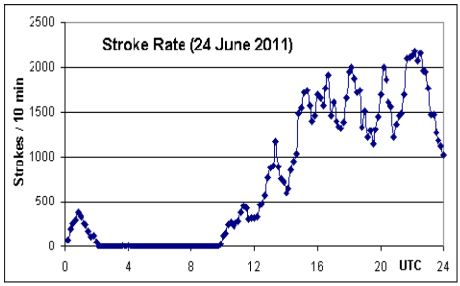


Fig. 18 – *Stroke rate for June 24^th, 2011, for the area* 17°-24°E/41°-47°N.

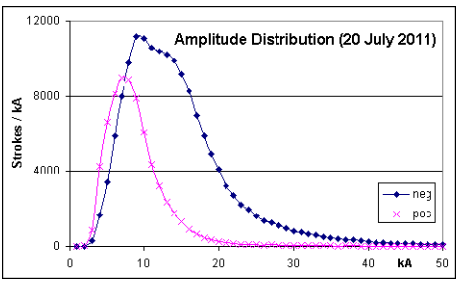


Fig. 19 – *Amplitude distribution for July 20^th, 2011, for the area* 17°-24°E/41°-47°N.

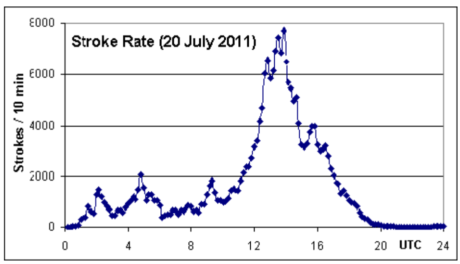


Fig. 20 – *Stroke rate for July 20^th, 2011, for the area* 17°-24°E/41°-47°N.

3 Isokeraunic Levels Versus Flash Density Maps

Isokeraunic maps are often used to represent lightning activities in some parts of the world (Fig. 21) where average number of thunder days per km^2 and per year are given.

Such a map is available for Serbia and Montenegro for the period 1951-1980 (Fig. 22). It is a part of the Serbian standard on lightning protection SRPS N.B4.803:1996 [9]. Although this kind of data is frequently in use, counting thunder days based on thunder sound (roar) depends on the equipment used for registration and its sensitivity, and on the distance of a station from the lightning discharge point. Thus, such maps became non-comparable and not reliable for use in design of lightning protection systems, except for rough estimation. Naturally, modern lightning detection systems are superior because they are usually capable of registering flashes more efficiently and distinguish the stroke currents.

If T_d, the number of thunder days per km^2 and year (isokeraunic level) for some area is taken from the isokeraunic map, then flash density N_g per square kilometre and year in that area is estimated from the expression

$$N_g = 0.04 T_d^{1.25}\,\mathrm{km}^{-2}\mathrm{year}^{-1}, \tag{1}$$

but it has different constants – depending on climate conditions in the area. For countries as Brasil, Colombia and Indonesia, or areas as North Australia, Central and South Africa, lightning flash density is $N_g = 8 \div 15\,\mathrm{km}^{-2}\mathrm{year}^{-1}$, and it is corresponding to the number of thunderstorm days T_d from 70 to 115 (Fig. 21). E.g. if $T_d = 30$ is taken from the isokeraunic map, then $N_g \cong 2.8\,\mathrm{km}^{-2}\mathrm{year}^{-1}$ is calculated according to (1). However, it is better if more accurate flash density data is obtained for some region as a statistical result of the lightning detection system.

For the calculation of an average number of flashes to a common object, N_d, the following expression is used

$$N_d = N_g A_e 10^{-6}, \tag{2}$$

where N_g is the lightning ground flash density per square kilometre and per year. A_e is the collection area of the object in square metres. It is equal to the ground surface collecting the same number of flashes as the object and may be estimated as $A_e = A_S C_S$, where A_S is the collection area of an isolated object and C_S is the relative location coefficient of the object, depending on the appearance of the terrain and other objects in its vicinity. Collection areas of the surrounding objects are overlapping, thus reducing the individual collection area. If it is surrounded by higher objects or trees $C_S \cong 0.25$, if they are not higher than the object, but of similar height, then $C_S \cong 0.5$. If the object is in the flat terrain with no other objects in the vicinity $C_S = 1$, and if the object is isolated on the top of a hill or knoll $C_S \cong 2$.

The collection area of an isolated parallelepiped object having length L, width W and height H at the flat terrain is

$$A_S = WL + 6H\left(W + L\right) + 9\pi H^2 . \tag{3}$$

There are also approximate graphical methods to determine A_e for objects at a non-flat terrain and/or in the presence of other objects.

A critical number of flashes to an object, N_C, is used for checking if the object needs to be protected at all. If $N_d > N_C$, then the design of lightning protection system for the object is necessary. This critical number of flashes is adopted based on the object's value, importance and construction, people, animals, equipment and materials inside it, vicinity of other potentially dangerous objects, or the demand of investor. Of course, special objects as those of heights above 60m, very important objects, power systems, telecommunication lines, objects with explosive materials and flammable liquids, nuclear plants, gas pipelines, reservoirs with biochemical substances, historical objects, etc., should be much better protected than the common objects.

For Serbia, flash density maps are given in Figs. 23 – 28 for each year from 2008 to 2013. From the map in Fig. 29 for the accumulated results over six-years' period and from the annual maps, the average flash density for Serbia is $N_g \cong 3 \div 4\,\text{km}^{-2}\text{year}^{-1}$.

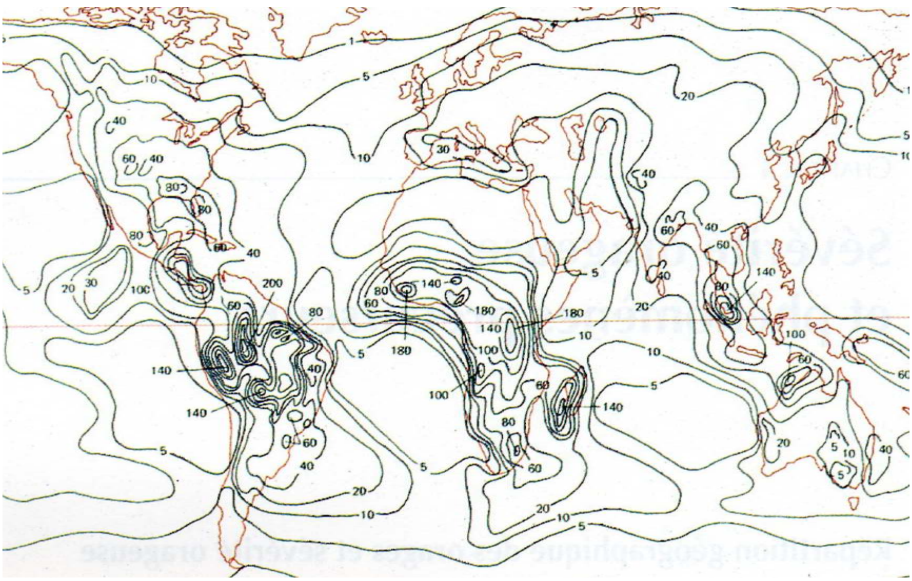


Fig. 21 – *Isokeraunic map of the world.*

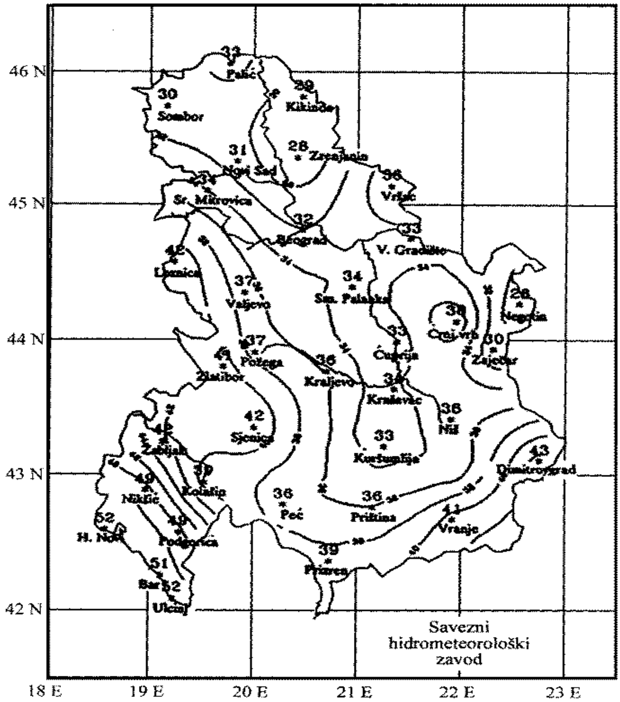


Fig. 22 – *Isokeraunic map of Serbia and Montenegro from SRPS N. B4.803:1996.*

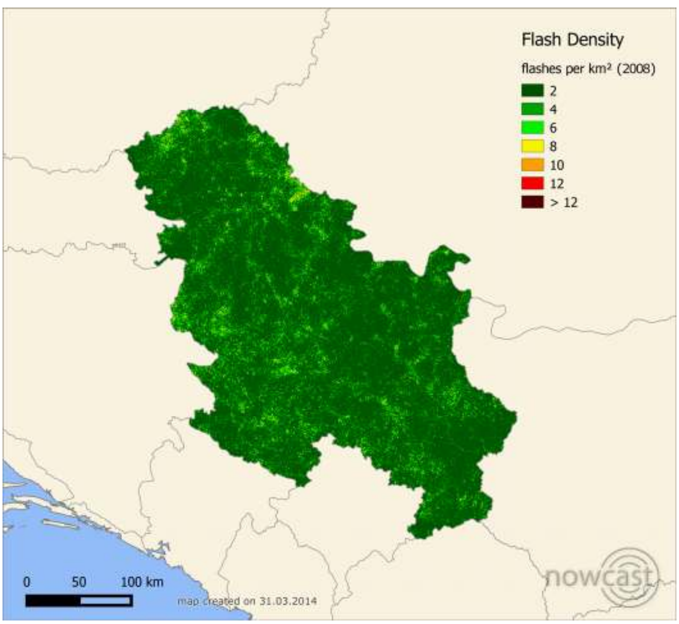


Fig. 23 – *Flash density map for 2008.*

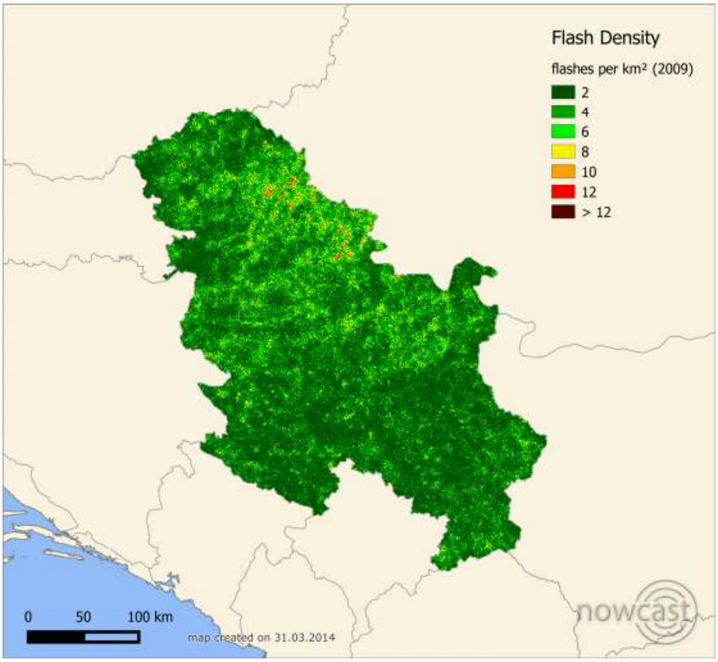


Fig. 24 – *Flash density map for 2009.*

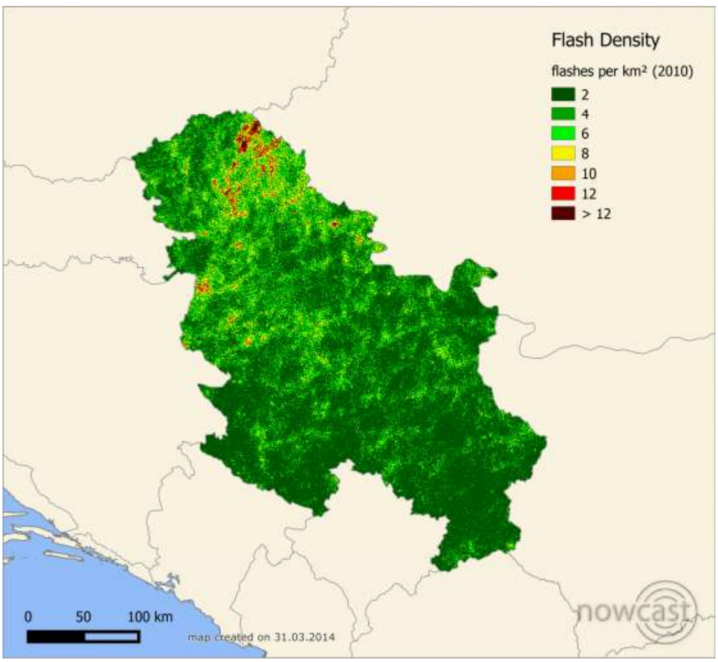


Fig. 25 – *Flash density map for 2010.*

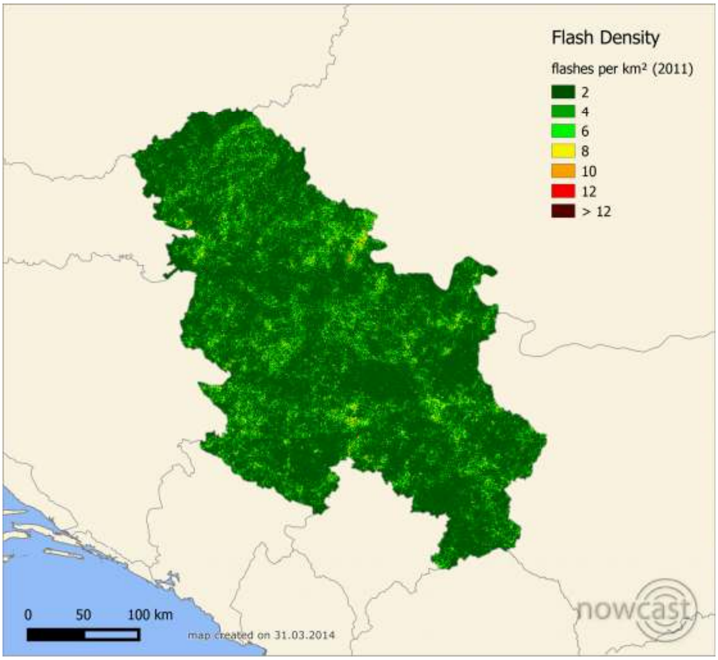


Fig. 26 – *Flash density map for 2011.*

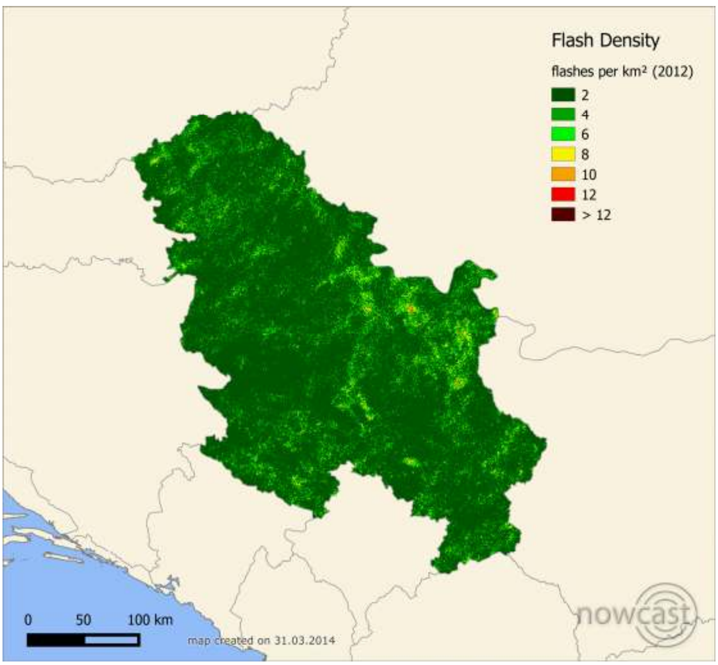


Fig. 27 – *Flash density map for 2012.*

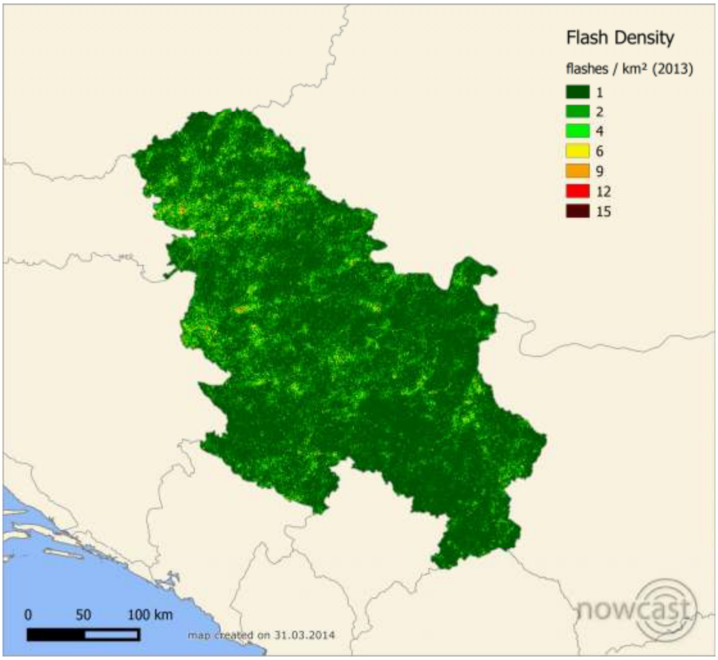


Fig. 28 – *Flash density map for 2013.*

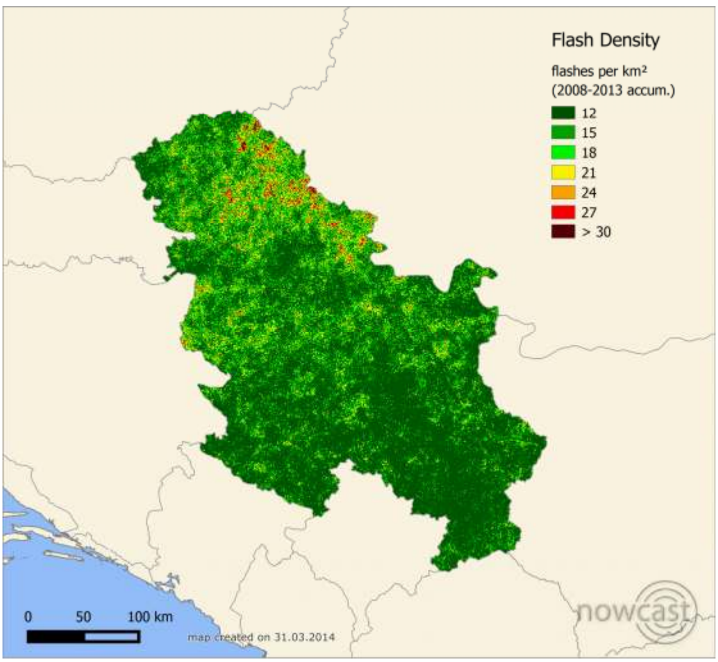


Fig. 29 – *Flash density map for 2008-2013 (accumulated for six years).*

5 Conclusion

Lightning detection systems such as LINET can be used to provide storm warning, possibly allowing precautions that reduce damages from lightning. They may help in preventing some direct and indirect effects on the environment and different structures, power systems, installation and equipment, devices and objects, but also on living beings. Statistics of lightning discharges in some region are needed for the design of lightning protection systems. Different lightning characteristics detected and located by LINET may be used for such purposes such as: the number of lightning events in some area in a certain time interval, movements of lightning discharge events along some territory, distribution of lightning amplitudes, stroke rate as a function of time, emission altitudes of IC strokes, striking points of CG strokes, etc. LINET 3D-technique provides excellent discrimination between CG and IC strokes. Scatter plots of storm activity show reliable stroke positions and, due to improved location accuracy, very little scatter due to erroneous locations. After having installed two sensors in Serbia six year ago, statistically significant flash density maps have become available.

6 Acknowledgement

Among ideas that Prof. dr Dragutin Veličković shared with his successors during work in different areas of research, his lightning protection rod with a horizontal circular loop is part of the Serbian standard on lightning protection SRPS N.B4.811 [10]. For this reason, this paper is written in the memory of his work in the named field.

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