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Extreme Values of Lightning Parameters

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***Abstract*— In this paper we present an online database where we have collected a number of reports on extreme lightning parameters: peak current, fastest and slowest rise time, fastest and slowest time to half value, rate of change of current, flash duration, charge and action integral.**

Keywords—lightning, upward lightning, downward lightning, lightning current, lightning parameters

I. INTRODUCTION

Obtaining data on lightning parameters is a challenging task, on one hand due to the fact that it is, at present, impossible to predict when and where it will strike and, on the other hand, to the inherent harsh electromagnetic environment with which it is associated. Our understanding of lightning is based on numerous direct and indirect observations. Direct measurements are performed at lightning research stations located around the world and actively working on collecting the data of lightning discharges. Different methods are used to register lightning currents directly at the strike location, for example: magnetic links, shunts and Rogowski coils. Indirect methods rely on empirical relation between the lightning channel current and electromagnetic field measured at some distance from the lightning discharge. The International Standard on lightning protection IEC, [2006] defines the key parameters necessary to characterize a lightning flash and proposes standardized waveform for testing in high-voltage laboratories.

Lightning current waveforms were recorded for the first time by Stekolnikov, I. and Valeev, C., [1937] and later by Davis and Standring, [1947], followed by the measurements on the Empire State Building in New York City performed by McEachron, [1939], [1941] those by Hagenguth and Anderson, [1952]. A significant amount of data has been collected since that time until now in the works of Berger, [1967], Garbagnati and Lo Piparo, [1982], Miyake et al., [1992], Depasse, [1994], Rakov et al., [2005], Diendorfer et al., [2009], Schoene et al., [2009], Visacro et al., [2012], Romero et al., [2013]a and others. A thorough comparison of the obtained data is given in the report by CIGRE, [2013]. The goal of this paper is to establish an interactive and openly accessible database to store, update and compare extreme values of lightning parameters measured everywhere in the world.

The remaining of the paper is organized as follows. In Section II, the definitions of the selected parameters are given. In Section III, the extreme values of the parameters defined in the previous section are given. Section IV defines the way the collected data will be shared and updated. Finally, Section V presents some conclusions and suggestions for the future work.

II. PARAMETERS DEFINITIONS

Lightning discharges can be categorized as a function of their origin and direction of propagation as shown in Figure 1.

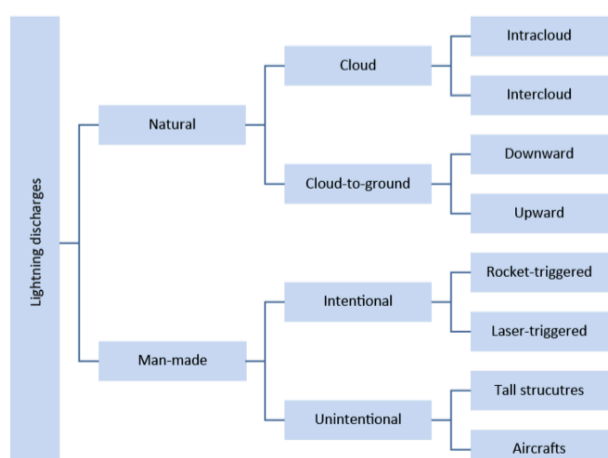

Fig. 1. Classification of lightning discharges

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Within natural lightning discharges, the first group is the so-called cloud flashes that constitute the majority of all lightning discharges, the ratio of cloud flashes to cloud-to-ground flashes varying from about 2 to 10 or more as noted in Rakov and Uman, [2007]. Cloud flashes can be of either intracloud or intercloud type.

Cloud-to-ground lightning flashes can be subsequently divided into downward and upward flashes, depending on the direction of the propagation of the initial leader.

Lightning discharges can be artificially initiated by launching a rocket with a trailing wire towards a charged thundercloud (Rakov et al., [2005]). Other means of artificial initiation of lightning have also been suggested using, to name a few, laser beams, microwave beams water jets. In addition to these purposeful artificial initiation techniques, lightning can be triggered unintentionally by tall man-made structures or aircraft. This is the case of upward flashes that occur from very tall structures or from structures of moderate height located on a hill or a mountain summit.

According to the polarity of the charge lowered to the ground, all lightning discharges involving the ground can also be subdivided into positive, negative or bipolar. Downward negative discharges constitute about 90% of all cloud-to-ground lightning (Uman, [1987]). About 10% or less are downward positive discharges. Rarely, bipolar flashes are observed which transfer both positive and negative charges to ground.

Depending on the observation station, specific types of lightning discharges can be recorded. Lightning research towers located on the mountains are more frequently struck by lightning and therefore are able to collect a larger dataset within a shorter time period. However, the majority of lightning strikes to these towers are of the upward type.

On the other hand, transmission towers or wind turbines situated in flat areas are less frequently struck by lightning, but they contribute to the characterization of downward discharges, which are more frequently observed on these structures.

Finally, the stations where lightning is triggered using artificial means can contribute not only to the study of this specific type of lightning discharges, but also to other processes in the lightning discharge. Indeed, the properties of natural downward lightning processes following the first stroke are similar to the characteristics of triggered lightning processes after the initial stage (Jerauld et al., [2007]).

Measurement reports published in the scientific literature usually contain information about the key lightning parameters: their statistical distribution, maximum and minimum values. These parameters were grouped in the categories using the following criteria: types of lighting (upward, downward and triggered) and lightning polarity (positive and negative).

The lightning discharge is a transient phenomenon and a typical return-stroke current waveform represented in Fig. 2 can be used to define the key parameters of the discharge according to the IEC, [2010] standard. The definitions used in this paper are given hereafter.

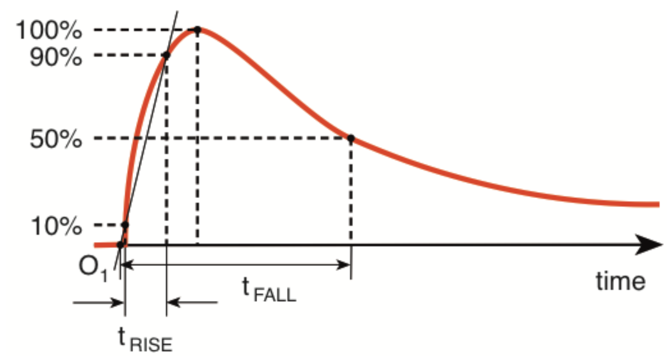

Fig. 2. Typical lightning current waveshape

A. Peak current

Maximum value of the lightning current.

B. Front time

Front time of short stroke current t_{rise} is a virtual parameter defined as 1,25 times the time interval between the instants when the 10 % and 90 % of the peak value are reached

C. Half-peak time

Time interval between the virtual origin O_1 and the instant at which the current has decreased to half the peak value

D. Current maximum steepness

The maximum rate of rise of the lightning current during front time

E. Flash duration

Total duration of the flash.

F. Flash charge

Time integral of the lightning current for the entire lightning flash duration

G. Action integral

Integral of the current squared over time

H. Multiplicity

Number of return strokes in the flash. Typical time intervals between them are in the order of tens of ms.

I. Location

Information includes the measurement station location: country and station.

J. Date

Observations on a specific measurement station may last for decades. During this time, the data acquisition system or data processing procedure may be updated and will influence the results.

III. Extreme Values (As of January 2018)

A. Peak current

The largest peak currents inferred from measured fields ever reported are −957 kA for negative and + 580 kA for positive flashes (Lyons et al., [1998]) as can be seen in Table I. But the remote estimations are based on the assumption that the observed relationship between the peak electric/magnetic field and the peak return stroke current measured in triggered subsequent return strokes is valid also for first return strokes and that it can be extrapolated to larger currents (Cooray and Rakov, [2012]). In addition, the relations used for remote estimation depend on the speed of the return stroke, which is an unknown parameter for specific strokes.

The largest peak current of 340 kA was measured directly in Japan as reported by Goto and Narita, [1995] and it corresponds to a positive flash. The record value for a negative flash measured directly and reported by Anderson and Eriksson, [1980] is 200 kA. Other extreme values of peak current are listed in Table I.

In order to verify the possibility for lightning currents to reach such values, a theoretical estimate of the upper limit of lightning currents has been given by Cooray and Rakov, [2012] and it suggests that the largest negative first return stroke peak current that can exist in nature is about 300 kA in temperate regions and about 450 kA–500 kA in the tropics.

Lightning superbolts were also detected from space as reported by Turman, [1977]. The largest registered peak optical power emitted by these superbolts was $8.1 \cdot 10^{12}$ W and were characterized by the maximum value of optical energy of $2.7 \cdot 10^{9}$ J.

Another extreme value of lightning current of a superbolt was reported by Andrews, [1952] and was registered atop the University of Pittsburgh's tower in 1947 with a peak current of 345 kA. However, there are no indications about the used instruments, polarity and type of this discharge.

TABLE I. Largest Peak Current Values, kA

Type	Negative	Positive
LLS*	957[a]	580[a]
Upward	100[b]	340[c]
Downward	200[d]	208[e]
Triggered	77[f]	132[f]

* Estimation based on remote observation with NLDN lightning location system (LLS)

[a] Lyons et al., [1998]
[b] Miyake et al., [1992]
[c] Goto and Narita, [1995]
[d] Anderson and Eriksson, [1980]
[e] Schulz et al., [2013]
[f] Nakano, [1996]

B. Front time

The fastest rise times have been reported in a study in Switzerland by Berger, [1978] and correspond to an upward negative stroke. The slowest rising times correspond to a winter positive upward lightning in Japan. Other extreme values are given in Table II.

TABLE II. Extreme Front Time Values, µs

Flash type	Negative		Positive	
	min	*max*	*min*	*max*
Upward	0.1[a]	2000[b]	0.2[b]	10000[b]
Downward	0.3[c]	28[d]	-	-
Triggered	0.2[e]	5.7[e]	-	-

[a] Berger, [1978]
[b] Miyake et al., [1992]
[c] Visacro et al., [2012]
[d] Garbagnati et al., [1981]
[e] Schoene et al., [2009]

C. Half-peak time

The shortest and longest half-peak intervals have been reported in a study from Japan by Miyake et al., [1992] and correspond to an upward negative and positive strokes, respectively. Other extreme values are given in Table III.

TABLE III. Extreme Half-Peak Time Intervals, µs

Flash type	Negative		Positive	
	min	*max*	*min*	*max*
Upward	3[a]	4000[a]	6[a]	10000[a]
Downward	6.5[b]	280[c]	-	-
Triggered	4[d]	103.2[e]	-	-

[a] Miyake et al., [1992]
[b] Takami and Okabe, [2007]
[c] Garbagnati et al., [1981]
[d] Schoene et al., [2009]
[e] Depasse, [1994]

D. Current steepness

The maximum current steepness of 411 kA/µs was measured during a rocket-triggered lightning campaign in Florida (USA) in 1987 as reported by Leteinturier et al., [1991]. Extreme values for other types of lightning flashes are given in Table IV.

TABLE IV. LARGEST CURRENT STEEPNESS, kA/µs

Flash type	Negative	Positive
Upward	150[a]	70[b]
Downward	76[c]	-
Triggered	411[d]	-

[a] Garbagnati et al., [1981]
[b] Miyake et al., [1992]
[c] Takami and Okabe, [2007]
[d] Leteinturier et al., [1991]

E. *Flash duration*

Negative lightning flashes of both upward and downward type can have very long duration, almost up to 2 s as can be seen from Table V. The maximum duration of positive flashes is significantly smaller and has reached 795 ms. These results are based on current measurements. However, at Toronto CN Tower, a video recording has registered a flash with a duration of 2135 ms. However, the length of the corresponding current record was only 908 ms, as reported by Hussein et al., [2017].

TABLE V. LONGEST FLASH DURATION, ms

Flash type	Negative	Positive
Upward	1937[a]	370[b]
Downward	1928[c]	795[d]
Triggered	0.3[e]	-

[a] Warner et al., [2012]
[b] Romero, et al., [2013]
[c] Kitagawa et al., [1962]
[d] Schumann et al., [2016]
[e] Depasse, [1994]

F. *Flash charge*

Winter lightning in Japan is known to be characterized by high-amplitude currents as can be seen from Section A, Table 1, but also by high values of the charge transferred to ground as can be seen from Table VI.

TABLE VI. LARGEST FLASH CHARGE, ms

Flash type	Negative	Positive
Upward	1000[a]	3000[a]
Downward	126[b]	1311[b]
Triggered	243[c]	640[c]

[a] Miyake et al., [1992]
[b] Schumann et al., [2016]
[c] Nakano, [1996]

G. *Action integral*

The extreme values of this parameter are given hereafter in Table VII. A positive flash registered in Japan has been characterized by an extreme value of action integral of $3.6{\cdot}10^7$ A^2s.

TABLE VII. LARGEST ACTION INTEGRAL, $\cdot 10^3$ A^2s

Flash type	Negative	Positive
Upward	500[a]	36000[b]
Downward	213[c]	-
Triggered	41.8[c]	-

[a] Garbagnati et al., [1981]
[b] Goto and Narita, [1995]
[c] Visacro et al., [2012]
[d] Depasse, [1994]

H. *Multiplicity*

A lightning flash may consist of several subsequent strokes. The highest multiplicity of 69 strokes/flash has been observed in Switzerland for an upward flash by Romero et al., [2013]. The highest multiplicity for a downward flash of 26 strokes/flash has been observed in the USA by Kitagawa et al., [1962]. Both flashes were of negative polarity.

IV. WEB PAGE OF LIGHTNING RECORDS

An interactive table has been created to store the collected data. The users have a possibility to correct, update and propose new parameters for comparison. The table can be accessed at the address: http://tiny.cc/extremelightning

In the table, we have added the parameters discussed in this paper. These can be updated as more data are published or if errors are detected. In addition, other parameters may be added.

In order to ensure an orderly update process, the changes will only be authorized if they are made by registered users. Changes will be checked periodically by the authors or any other designated keepers of the database.

V. CONCLUSIONS

A set of extreme records of lightning current registered around the world has been presented for the first time. This attempt to collect such data is not assumed to be complete. Contributions from the users are very welcome and will serve to keep the database updated.

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