

Recent CIGRE Work on Lightning Parameters for Engineering Applications

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Abstract—Lightning parameters needed in different engineering applications and presented in CIGRE Technical Brochure (TB) #549 (2013) are reviewed. New experimental data, as well as the old data, are evaluated. An overview of remote measurements of lightning peak currents by lightning locating systems is given. Positive and bipolar lightning discharges, previously not considered by CIGRE, are discussed. Possible geographical and seasonal variations in lightning parameters are examined. The areas in need of further research are indicated.

Keywords—Lightning parameters, number of strokes per flash, multiple ground terminations, return-stroke current, lightning locating systems, positive and bipolar lightning, geographical and seasonal variations

I. INTRODUCTION

In 2013, CIGRE Working Group C4.407 has completed its five-year work on the Technical Brochure on Lightning Parameters for Engineering Applications. This Brochure (CIGRE TB 549, 2013) contains a number of important updates relative to the previous CIGRE documents on the subject published in Electra more than three decades ago: Berger et al. (1975) and Anderson and Eriksson (1980). Selected topics covered by CIGRE TB 549 (2013), with a number of updates, and issues in need of further research are discussed in the following sections.

II. GENERAL CHARACTERIZATION OF LIGHTNING

Typically 80% or more of negative cloud-to-ground lightning flashes are composed of two or more strokes. This percentage is appreciably higher than 55% previously estimated by Anderson and Eriksson (1980), based on a variety of less accurate records. The average number of strokes per flash is typically 3 to 5, with the geometric mean interstroke interval being about 60 ms. Roughly one-third to one-half of lightning flashes create two or more terminations on ground separated by up to several kilometers (see Fig. 1). When only one location per flash is recorded, the correction factor for measured values of ground flash density to account for multiple channel terminations on ground is about 1.5-1.7, which is considerably larger than 1.1 previously estimated by Anderson and Eriksson (1980). First-stroke current peaks are typically a factor of 2 to 3 larger than subsequent-stroke current peaks. However, about one third of cloud-to-ground flashes contain at least one subsequent stroke with electric field peak, and, by theory, current peak, greater than the first-stroke peak.

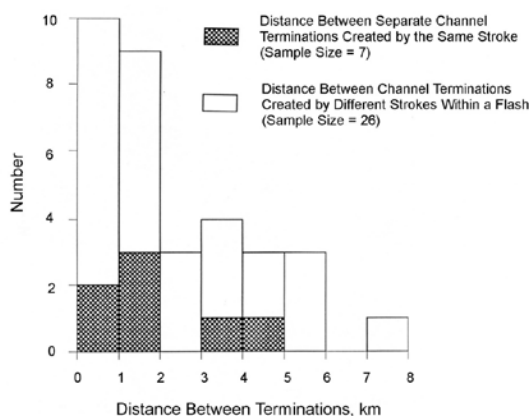


Fig. 1. Histogram of the distance between the multiple terminations of 22 individual ground flashes in Florida. The distances were determined using optical triangulation and thunder ranging. Adapted from Thottappillil et al. (1992).

III. RETURN-STROKE PARAMETERS DERIVED FROM CURRENT MEASUREMENTS

From direct current measurements, the median return-stroke peak current is about 30 kA for negative first strokes in Switzerland, Italy, South Africa, and Japan, and typically 10-15 kA for subsequent strokes in Switzerland and for triggered and upward (object-initiated) lightning. Corresponding values from measurements up to 2017 in Brazil are 43 kA (n=50) and 17 kA (n=78) (S. Visacro, personal communication, 2018). Additional measurements are still needed to determine more reliably the tails of the distributions.

The “global” distributions of lightning peak currents for negative first strokes currently recommended by CIGRE and IEEE are each based on a mix of direct current measurements and less accurate indirect measurements, some of which are of questionable quality. However, since the “global” distributions have been widely used in lightning protection studies and are not much different from that based on direct measurements only, continued use of these “global” distributions for representing negative first strokes is recommended. Direct lightning current measurements on instrumented towers should be continued. Presently, direct current measurements are performed on instrumented towers in Austria, Brazil, Canada, Germany, Japan, and Switzerland, although the overwhelming majority of observed flashes (except for Brazil and Japan) are of upward type.

Recommended lightning current waveshape parameters are still based on Berger et al.'s (1975) data, although the current rate-of-rise parameters estimated by Anderson and Eriksson (1980) from Berger et al.'s oscillograms are likely to be significantly underestimated, due to limitations of the instrumentation used by Berger et al. Triggered-lightning data for current rates of rise can be applied to subsequent strokes in natural lightning.

IV. REMOTE MEASUREMENTS OF PEAK CURRENTS

Besides direct measurements, lightning peak currents are also estimated from measured electric or magnetic fields (the so-called remote current measurements) by multiple-station lightning locating systems. The field-to-current conversion procedure employed by the U.S. National Lightning Detection Network (NLDN) and other similar lightning locating systems has been calibrated, using rocket-triggered (see Fig. 2) or tower-initiated lightning data as ground truth, only for negative subsequent strokes. The median absolute error was determined to be 10 to 20%, which is better than expected for remote current measurements. To date, peak current estimation errors for negative first strokes and for positive lightning are generally unknown.

Besides systems of NLDN type (such as the European systems participating in EUCLID or nationwide and regional systems in Japan), there are other lightning locating systems that are also reporting lightning peak currents inferred from measured fields, including LINET (mostly in Europe), USPLN (in the U.S., but similar systems operate in other countries), ENTLN (in the U.S. and other countries), WWLLN (global), and GLD360 (global). For the latter three systems, there are estimates of errors in peak currents reported by them, obtained using triggered-lightning data as ground truth (Mallick et al., 2014b, c, 2015; Zhu et al., 2017).

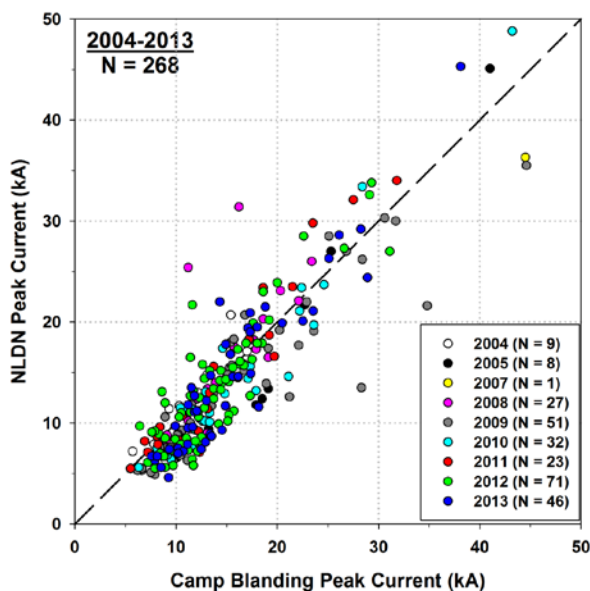


Fig. 2. NLDN-reported peak current versus peak current directly measured for 268 return strokes in lightning flashes triggered at Camp Blanding, Florida, in 2004–2013. The slanted broken line (slope = 1) is the locus of the points for which the NLDN-reported peak currents and the directly-measured peak currents are equal. Adapted from Mallick et al. (2014a).

V. POSITIVE AND BIPOLAR LIGHTNING DISCHARGES

Although positive lightning discharges account for 10% or less of global cloud-to-ground lightning activity, there are several situations, including, for example, winter storms, that appear to be conducive to the more frequent occurrence of positive lightning. The highest directly measured lightning currents (near 300 kA vs. a maximum of about 200 kA or less for negative lightning) and the largest charge transfers (hundreds of coulombs or more) are associated with positive lightning. Positive flashes are usually composed of a single stroke, although up to four strokes per flash have been observed. Subsequent strokes in positive flashes can occur either in a new (a more common situation) or in the previously-formed channel. In spite of recent progress, our knowledge of the physics of positive lightning remains considerably poorer than that of negative lightning.

Because of the absence of other direct current measurements for positive lightning return strokes, it is still recommended to use the peak current distribution based on the 26 events recorded by K. Berger, even though some of those 26 events are likely to be not of return-stroke type (see Fig. 3b). Clearly, additional measurements for positive lightning return strokes are needed to establish reliable distributions of peak current and other parameters for this type of lightning.

Bipolar lightning discharges are usually initiated by upward leaders from tall objects. However, natural downward flashes also can be bipolar. In the latter case, a negative subsequent stroke typically follows the channel of preceding positive stroke, but subsequent positive strokes developing in the channel of preceding negative stroke have been also observed (e.g., Zhu et al., 2016).

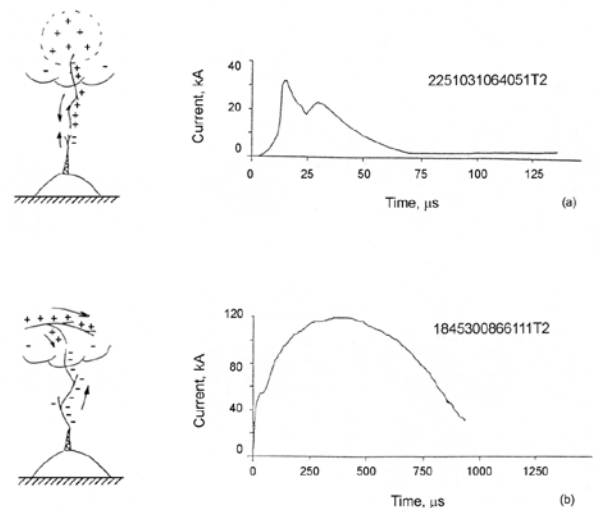


Fig. 3. Examples of two types of positive lightning current vs. time waveforms observed by K. Berger: (a) microsecond-scale waveform, similar to those produced by downward negative return strokes, and a sketch illustrating the lightning processes that might have led to the production of this waveform; (b) millisecond-scale waveform and a sketch illustrating the lightning processes that might have led to the production of this current waveform. Arrows indicate directions of the extension of lightning channels. Adapted from Rakov (2003).

VI. GEOGRAPHICAL AND SEASONAL VARIATIONS IN LIGHTNING PARAMETERS

From the information available in the literature at the present time, there is no evidence of a systematic dependence of negative cloud-to-ground lightning parameters on geographical location (see, as examples, Table I and Fig. 4), except maybe for first and subsequent return-stroke median peak currents, for which relatively insignificant (less than 50% or so) from the engineering point of view, variations may exist. It is important to note, however, that it cannot be ruled out that the observed differences in current measurements are due to reasons other than "geographical location", with the limited sample size for some observations being of particular concern. Similarly, no reliable information on seasonal dependence is available. Thus, at the present time, the available information is not sufficient to confirm or refute a hypothesis on dependence of negative cloud-to-ground lightning parameters on geographical location or season. On the other hand, some local conditions may exist (for example, winter storms in Japan) that give rise to more frequent occurrence of unusual types of lightning, primarily upward flashes initiated from tall objects, whose parameters may differ significantly from those of "ordinary" lightning. Another example is non-occurrence of upward flashes with the typical charge transfer of the order of a few tens of coulombs at the Brazilian tower: no upward flashes were observed in 2008-2009 and only relatively weak ones in 2010-2017. The latter (a total of 19 with 4 of them containing return strokes) exhibited charge transfers as low as 0.9 to 5.9 C, with a GM of 3.3 C (S. Visacro, personal communication, 2018). Further studies are necessary to clarify the local conditions that can lead to the observed peculiarities of lightning parameters at different instrumented towers.

TABLE I. Number of strokes per negative flash and percentage of single-stroke flashes. Adapted from CIGRE TB 549 (2013) with updates.

| Location (Reference) | Average Number of Strokes per | Percentage of Single-Stroke Flashes | Sample Size |
|--|-------------------------------|-------------------------------------|-------------|
| New Mexico (Kitagawa et al., 1962) | 6.4 | 13% | 83 |
| Florida (Rakov and Uman, 1990) | 4.6 | 17% | 76 |
| Sweden (Cooray and Perez, 1994) | 3.4 | 18% | 137 |
| Sri Lanka (Cooray and Jayaratne, 1994) | 4.5 | 21% | 81 |
| China (Qie et al., 2002) | 3.8 | 40% | 83 |
| Arizona (Saraiva et al., 2010) | 3.9 | 19% | 209 |
| Brazil (Ballarotti et al., 2012) | 4.6 | 17% | 883 |
| Malaysia (Baharudin et al., 2014) | 4.0 | 16% | 100 |
| Florida (Zhu et al., 2015) | 4.6 | 12% | 478 |

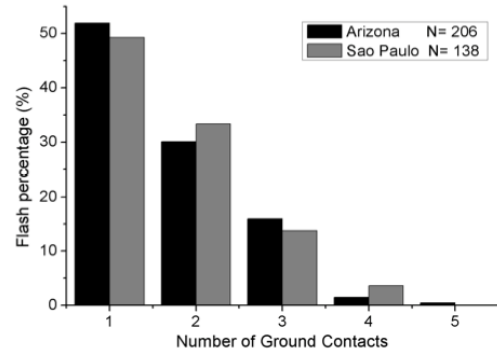


Fig. 4. Percentage of flashes that produced a given number of ground contacts in Arizona, USA and São Paulo, Brazil. Adapted from Saraiva et al. (2010).

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