Electric Power Systems Research 118 (2015) 89–92

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

High-speed video and electric field observation of a negative upward leader connecting a downward positive leader in a positive cloud-to-ground flash

Marcelo M.F. Saba[a,*], Carina Schumann[a], Tom A. Warner[b], John H. Helsdon[b], Richard E. Orville[c]

[a] National Institute for Space Research, INPE, S. José dos Campos, Brazil
[b] South Dakota School of Mines and Technology, Rapid City, SD, USA
[c] Texas A&M University, College Station, TX, USA

ARTICLE INFO

Article history:
Received 19 February 2014
Received in revised form 26 May 2014
Accepted 2 June 2014
Available online 24 June 2014

Keywords:
Positive lightning
Positive leader
Stepped leader
High-speed video
Electric-field
Connecting leader

ABSTRACT

It has been discussed in past papers if a positive leader propagates in a stepped fashion or not. Some studies state that, in some positive cloud-to-ground flashes, the electric field pulses observed just before the connection of the positive leader to ground could be a manifestation of the stepping of the leader. Some authors say, however, that it may be due to the stepping of the negative upward connecting leader during its ascension toward the downward positive leader.

In this work we present a well-documented case of a positive cloud-to-ground flash that shows that the pulses observed in the electric field preceding the return stroke are due solely to the upward propagation of a negative connecting leader. This flash was recorded simultaneously by a fast electric field sensor and a high-speed camera in July 2012 in the Black Hills area of South Dakota.

1. Introduction

1.1. Past optical observations

It is a common agreement that negative leaders show very distinct steps. Streak-camera photography revealed that this is true for both downward and upward negative leaders [1].

It has been discussed in past papers if a positive leader also propagates in a stepped fashion or not. Berger [1] using streak cameras has observed that positive leaders in general have no distinct steps, but show rather a periodic variation in light intensity and move in an apparently continuous manner. Wang and Takagi [2] recently observed, using a high-speed optical imaging system, a downward positive leader that radiated optical pulses like a negative stepped leader. According to the authors, the downward positive leader radiated more than 20 optical pulses during its downward progression over the height from 299 m to 21 m above the ground.

1.2. Past electric-field observations

Some studies attribute the electric field pulses of a positive leader before connecting ground in a positive cloud-to-ground (+CG) flash as a manifestation of the stepping of the positive leader. Following this assumption, Brook [3] analyzed electric field changes from nine +CG leaders in New Mexico and concluded that two (22%) exhibited stepping; Proctor [4] observed positive leaders in South Africa and reported that two out of 175 stepped. Kong et al. [5] also suggested that pulses in fast E-field change about 0.5 ms before the return stroke was an indication of stepped-like development (Fig. 4b of their paper).

Electric field observations done by Cooray and Lundquist [6] indicate that in some cases the positive leader behaves in a stepped manner during the last few hundred of microseconds of its journey toward the earth. However, the authors state that the small amplitude pulses that preceded the return stroke may be caused by the stepping of the negative upward connecting leader during its ascension toward the downward positive leader.

According to Nag and Rakov [7] "the reason for the occurrence of field pulses indicative of stepping prior to the return stroke pulse in some +CG discharges is not known. It could be associated with a descending positive leader, an upward connecting negative leader,

* Corresponding author at: Av. Dos Astronautas 1758, São José dos Campos, SP 12227-010, Brazil. Tel.: +55 12 3208 6768; fax: +55 12 3208 6768.
E-mail address: marcelo.saba@inpe.br (M.M.F. Saba).

http://dx.doi.org/10.1016/j.epsr.2014.06.002
0378-7796/

which may be launched in response to the nonstepped positive downward leader, or both".

2. Instrumentation

In this work we present a well-documented case of a +CG flash that shows that the pulses observed in the electric field preceding the return stroke are due solely to the upward propagation of a negative connecting leader. This flash was recorded simultaneously by a fast electric field sensor and a high-speed camera in July 2012 in the Black Hills area of South Dakota.

Utilizing the physics sign convention, which is used in this paper, the electric field change due to a positive CG return stroke is positive. Some characteristics of this instrumentation are described here.

2.1. Lightning location systems

Information obtained from the NLDN lightning location system in US were used to obtain an estimate of the location and of the peak current of the positive stroke. More details about this lightning location system and its performance can be found in Cummins and Murphy [8]. Note that to date, there is not enough experimental data that can be used to evaluate errors in peak current estimates for positive return strokes.

2.2. Electric field sensor

The measuring system for the electric field sensor consisted of a flat plate antenna with an integrator and amplifier. Fiber-optic links were used to transmit the signal from the integrator/amplifier to the digitizer. In order to have time synchronization a GPS receiver is connected to a PC with two PCI-cards (a GPS card Meinberg GPS170PCI and a 12-bit data acquisition card NI PCI-6110). The sampling rate of the waveform recording system was 5 MS/s on each channel. The lower frequency and the upper frequency bandwidth of the system is 306 Hz and 1.5 MHz respectively.

2.3. High-speed cameras

A high-speed digital video camera (Phantom v12.1) with time-resolution and exposure times of 100 μs (10,000 frames per second) was used to record the images of the positive cloud-to-ground lightning. For more details about the measuring systems and about the use of high-speed camera for lightning observations, see the works by Saba et al. [9] and Warner et al. [10].

3. Data and results

On June 10th, 2012 (03:33:03 UT) when a training line of storms moved over Rapid City, SD a downward +CG attached a 163-m telecommunication tower (Tower 1 in Fig. 1). This +CG flash was followed by an upward positive leader from another telecommunication tower (height of 153.5 m) about 5 km away (Tower 8 in Fig. 1). The +CG was a single stroke flash followed by a continuing current lasting 298 ms. The National Lightning Detection Network (NLDN) indicated that the estimated peak current of this stroke was +124 kA. The calculated strike point given by the NLDN was 1.7 km from the tower connected. One must bear in mind that peak current estimation by lightning detection networks such as NLDN is based on remote measurement of the discharge electromagnetic radiation and calibrated using data from triggered negative lightning strokes. Also, the presence of the tower may affect the electromagnetic radiation used to estimate the peak current. Although the estimated value may be not accurate it is nonetheless very intense.

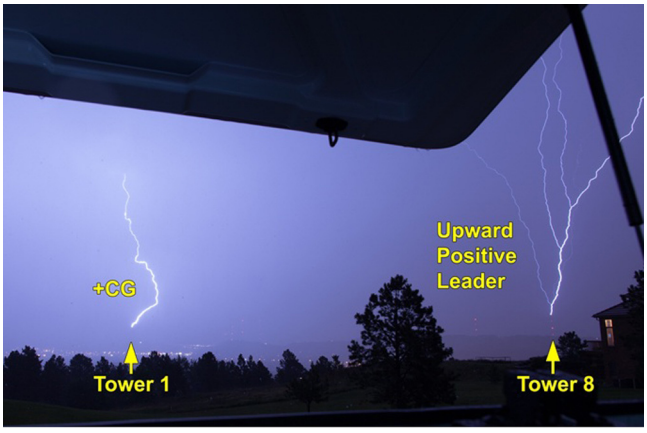

Fig. 1. Still photograph showing the +CG flash striking Tower 1 and the subsequent upward flash originated on Tower 8.

Images recorded by the high-speed camera at 10,000 images per second (ips) show a positive downward leader and a negative upward connecting leader from Tower 1 preceding the +CG return stroke (Fig. 2). The connection and return stroke occur in the last image ($T = 0$) of Fig. 2. The total distance covered by the negative upward connecting leader during 0.9 ms was estimated to be 270 m. The calculated average 2D speed of the connecting leader was $3.0 \times 10^5\ \mathrm{m\,s^{-1}}$ which is very similar to the average speed ($3.3 \times 10^5\ \mathrm{m\,s^{-1}}$) of 62 negative stepped leaders analyzed by Campos et al. [11].

The graph in Fig. 3 shows some milliseconds of the electric field change prior to the +CG return stroke. The electric field sensor was located only 1.2 km away from the location struck by the return stroke (Tower 1).

Arrows in Fig. 3 show the moment of the initiation of the upward negative connecting leader and the field change produced by the return stroke after 0.9 ms. Note that the initiation of the negative upward connecting leader coincides with the initiation of a sequence of pulses in the field signature. The sequence of pulses lasts till the moment of the connection with the downward leader, i.e., the return stroke (Fig. 3) and the average time between the pulses in the present case is approximately 23 μs.

4. Discussion

The physical mechanism of leader attachment to ground together with the characteristics of upward connecting leaders is one of the most important issues in lightning physics research according to Dwyer and Uman [12]. Recent studies on the subject have analyzed this mechanism for negative CG flashes (e.g. Lu et al. [13] and Wang et al. [14]). The case presented here is however, to the best of our knowledge, the first optical report of the attachment of a positive return stroke.

Due to the limited spatial and temporal resolution of our optical measurements, no leader stepping was observed on the video recordings. However, our close electric-field measurements show pulses that are evidences of leader stepping.

The initiations of the upward negative leader and of the pulses occur simultaneously at approximately 1 ms before the return stroke. The leader produce pulses in the electric field right at beginning of its propagation and, according to our observations, it does not need to be long in order to propagate in a stepped manner.

The upward negative connecting leader had characteristics similar to what is observed in past studies on negative stepped leaders. The 2D speed of the upward connecting leader is also very similar to the average speed of negative stepped leaders analyzed by Campos