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Triggering Lightning Experiments: an Effective Approach to the Research of Lightning Physics

Artificial triggering lightning experiments by launching a small rocket trailing a thin wire toward a charged cloud overhead have been conducted since the 1960s. After decades of development, this has become an important means for investigating lightning physics and validating lightning protection and location techniques. Observations of the triggered lightning have provided considerable new insights into different aspects of lightning discharges. This paper presents an overview of worldwide artificial triggering lightning experiments by means of the rocket-and-wire technique. Some valuable results, including properties of upward positive leader (UPL), observational evidence for the leader stepping mechanism, return stroke currents, M component properties, and energetic radiation associated with the lightning discharges, are briefly reviewed.

Introduction

Lightning is a transient discharge event that occurs in the atmosphere during a thunderstorm. The high discharge current and intensive electromagnetic (EM) radiation of the lightning can cause severe damages to objects both on the ground and in the air. Knowledge of lightning physics and its EM fields in fine time resolution is very important not only from the view of scientific research objectives, but also from the view of lightning protection engineering, in particular with the wide utilization of the current micro-electronics and communications technologies.

Although most natural downward cloud-to-ground (CG) lightning flashes exhibit an overall direction from the thunderstorm to the ground, the corresponding strike points are always randomly determined. The randomness in time and space of lightning occurrences makes direct measurement of lightning difficult. Instruments installed at the top of high towers or buildings which have a greater chance of being struck have helped to overcome the difficulties in measuring the discharge current of lightning [1]. However, limitations still exist, owing to the temporal uncertainty and lower possibility of the downward lightning striking a high structure.

Since the 1960s, various techniques have been designed and tested to artificially trigger lightning discharge during thunderstorm events, such as rapidly extending a thin wire underneath a charged cloud, emitting laser beams from ground to cloud, water jets or firing transient flame, and so on. One of these is the rocket-and-wire technique, launching a small rocket that extends a thin wire (either grounded or ungrounded) into the gap between the ground and a charged cloud overhead, successfully triggering lightning [2]; [3]. After decades of development and improvement, the rocket-and-wire technique for triggering lightning has been used as an important means for investigating lighting physics and effects. In this paper, artificial triggering lightning experiments and some exciting results over recent decades are briefly reviewed.

The techniques and experiments of rocket-triggering lightning

The first successful triggering lightning discharge by artificial means was conducted on a research vessel at sea in the vicinity of St. Petersburg, Florida [2]. Then the triggering technique was improved and performed at Saint-Privat d'Allier, France, which was the first successful triggered lightning over land [3]. After that, artificial triggering lighting experiments over land have been continuously performed in different countries, e.g. in the United States of America [4]; [5]; [6];[7], in France [8], in China [9]; [10]; [11]; [12], in Japan [13]; [14];[15], and in Brazil [16]; [17].

In the rocket-triggering lightning experiment, the rockets are usually installed at a launching site, with a capability of launching several rockets during a thunderstorm event. Figure 1 shows a photo of the rocket launcher for the Shandong Artificial Triggering Experiment (SHATLE), China. The ascending speed of the rocket is usually about 200 m/s after ignition [18]; [19]. This speed guarantees a relatively rapid extending of the triggering wire that is trailed by the rocket, while

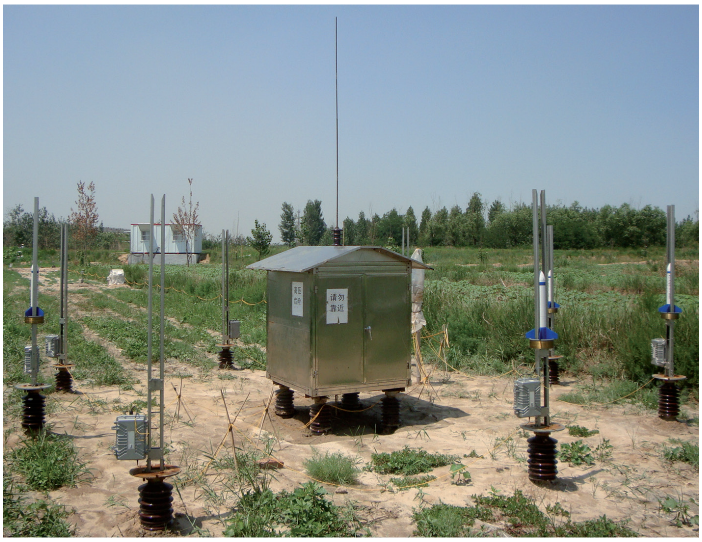


Figure 1 - Rocket launching site in Shandong Artificially Triggered Lightning Experiment (SHATLE), China.

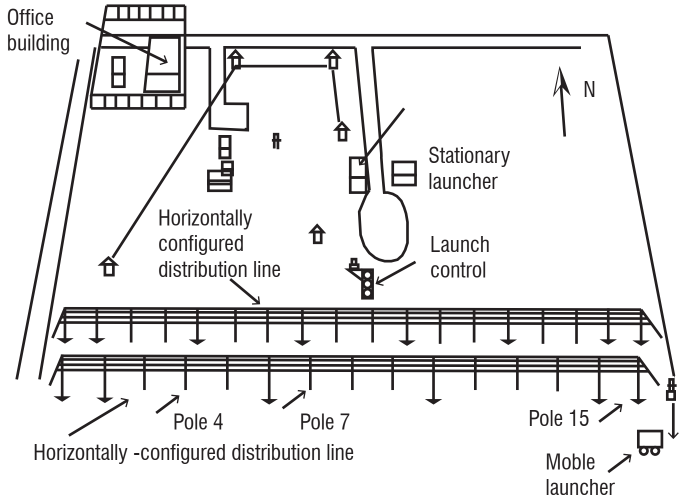


Figure 2 - Overview of the International Center for Lightning Research and Testing (ICLRT) in Florida, America. [21]

the associated pull force would not be too large to break the wire. Triggering wires (made of steel in China or copper in USA) with a diameter of approximately 0.2 mm are wound on a spool which is either fixed in the rocket or just installed on the ground. No matter where the spool is installed, one end of the triggering wire will ascend with the rocket. Due to the different grounding modes of the triggering wires, the techniques for triggering lightning are divided into conventional triggering and altitude triggering. For conventional triggering, the wire is well grounded, while for altitude triggering the rocket usually spools out 50-100 m of insulating Nylon followed by several hundred meters of conducting wire, so the triggering wire is not directly attached to the ground.

Various approaches to the observation of triggered lightning can be pre-designed and conducted close to the rocket launcher. Figure 2 shows an overview of the International Center for Lightning Research and Testing (ICLRT) in Florida, USA. In order to measure the discharge current of the triggered lightning, current sensors are installed at the rocket launching site which has been known to be struck by conventional triggered lightning. Generally, the current signals are transmitted through a fiber-optic link system to a control room (tens or hundreds of meters away) for data recording. Instruments for detecting the EM fields of the triggered lightning can be installed at different determined distances from the rocket launcher. The optical observations, by streak camera in the early years or by high speed video camera in recent years, are used to observe the evolution of the lightning luminous channel. Additionally, some particular observations can also be made using specially designed instruments, such as the so-called Pockels sensor for detecting the electric field very close to the lightning channel [20]. Overall, benefiting from the certainty of the occurrence of triggered lightning both in time and space, synthesized observation by different means can be designed and conducted, while it is not feasible for natural lightning.

Processes of the triggered lightning

The polarity of the triggered lightning is dependent on the charged cloud overhead at the time the rocket is ignited, both negative and positive lightning could be successfully triggered under suitable conditions. Generally, it is much easier to trigger negative lightning than positive, with the triggering success ratio being much higher when the cloud overhead is negatively charged [22]; [7]. Exceptions have occurred in Japan (during a winter thunderstorm) and in northeastern China, where the triggered events were always reported to be positive and contained just the initial continuing current stage when the cloud overhead was positively charged [14]; [23];[10].

The electric field at ground level is usually used as a reference to launch a rocket for triggering lightning, although the electric field at altitude is more indicative [24] but difficult to measure. The surface electric field is usually 5-10 kV/m when lightning is triggered successfully. Figure 3 shows two photographs of the triggered lightning using the conventional technique (with the wire grounded) and the altitude technique (with the wire ungrounded), respectively. The luminosity of the channels is due to the discharge process and the vertical straight portion corresponded to the wire-vaporized channel. Figure 4 shows the sketch processes of the triggered lightning from the ascent of the rockets under negative charged clouds, for the conventional triggering technique and the altitude triggering technique, respectively.

For conventional triggering, the wire tip reaches an altitude of 200-400 m 1-2 seconds after ignition of the rocket. A positive leader forms under the enhanced ambient electric field. This positive leader breaks down the virgin air and propagates toward the cloud, yielding an initial continuous current (ICC) which vaporizes the triggering wire. The natural channel established by the upward positive leader and the wire trace channel together build up the whole discharge channel between the cloud and the ground, and the discharge current can be measured at the channel bottom. The ICC lasts around several hundreds of milliseconds, on which some current pulses (referred as ICC pulses) may be superimposed. There is a no-current stage after the initial continuous current. Then one or more dart leader-return strokes will occur, generally traversing the original channel. The leader-return stroke sequences in triggered lightning is considered to be very similar to the dart leader-subsequent return stroke sequences in natural downward lightning [25]; [21]. Interstroke processes, such as continuous current and M component, can also be observed after the return stroke, or between adjacent return strokes. Triggered lightning using the conventional technique has contributed to most of the findings of the triggering lightning experiment, and more detailed information about it will be given in the following section.

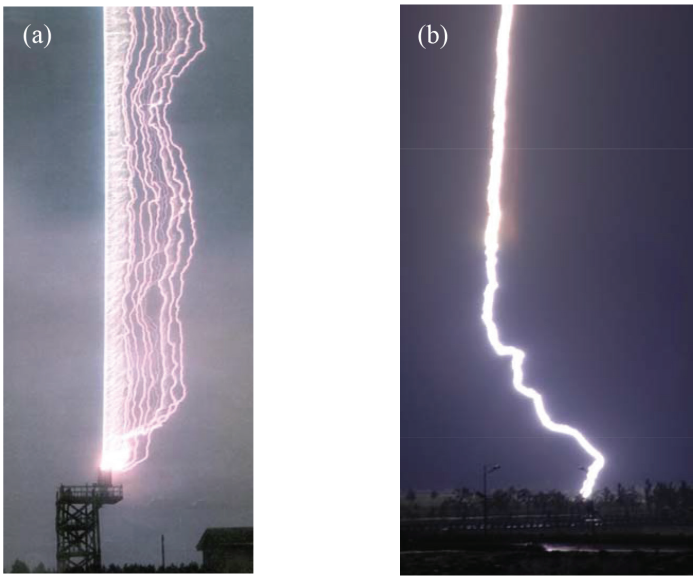


Figure 3 - Photographs of rocket-triggered lightning flashes. (a) with conventional technique, in ICLRT, Florida America, [7], (b) with altitude technique, in SHATLE, Shandong China, [11].

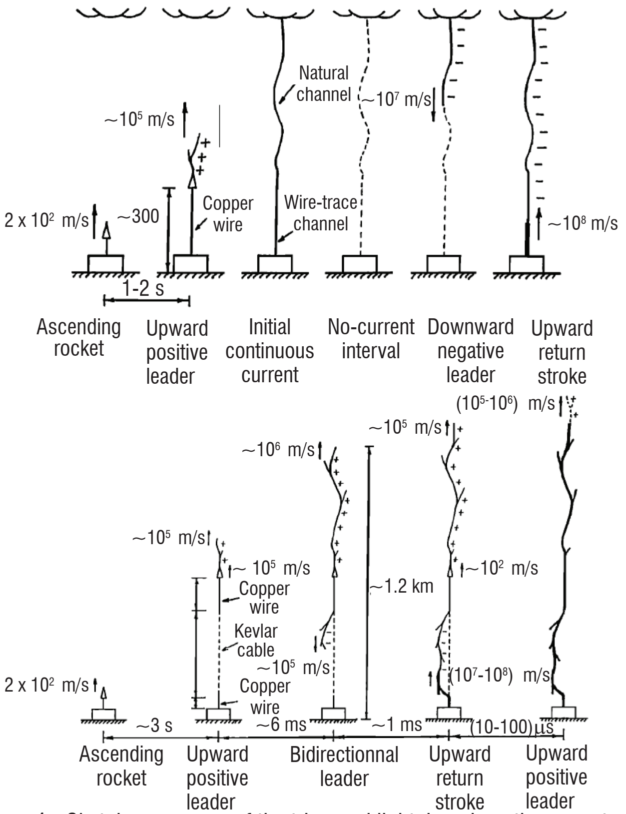


Figure 4 - Sketch processes of the triggered lightning since the ascent of the rockets, under negative charged clouds. (a) conventional triggering technique, (b) altitude triggering technique. [18]

For altitude triggering, the initial processes are different. A bi-directional leader process, which involves a primary upward positive leader at the wire tip and a following downward negative leader at the wire bottom with a lag time of a few milliseconds, occurs as the wire ascends to several hundred meters high. When the downward negative leader approaches the ground, a positive connecting leader initiates from the ground (sometimes from the triggering facilities or a short grounded wire connected to the bottom of the Kevlar cable), and the attachment of these two leaders results in a mini-return stroke or first return stroke. Because of its short discharge distance and different charge source, this return stroke is usually weaker than the normal strokes. The mini-return stroke or first return stroke quickly catches up and leads to an intensification of the upward positive leader. Then, the following processes are considered analogous to those in conventional triggered lightning. Triggered lightning by means of the altitude technique have provided clear optical evidence of the bi-directional leader development [26]; [27]; [28]. The developments of the upward leader and the downward leader (after emerging from the upper and lower extremities of the elevated wire, respectively) are coordinated in phase with each other. Generally, it is hard to measure the current of the altitude triggered lightning due to the indeterminacy of its grounding point. In this case, magnetic field measurement at close range would provide a good approach to current retrieval [29].

Initial stage and upward positive leader

Initial continuous current and ICC pulses

The upward positive leader and the initial continuous current (including the relevant ICC pulses) as a whole, are defined as the initial stage (IS) of a conventional triggered lightning. The initial stage is also present in structure-initiated lightning while absent in natural downward lightning. Wang et al., [30] have analyzed the current recordings of 37 negative triggered lightning flashes in Alabama and Florida. They found that the duration of the initial stage involved a geometric mean (GM) value of 279 ms and, correspondingly, the charge transferred by the ICC was 27 C. Based on charge transfer and duration of the initial stage, the average current was estimated to be 96 A with a minimum of 27 A and a maximum of 316 A. Miki et al [31], by using the data of 45 triggered lightning occurrences in Florida, found the GM values of the duration, charge transfer and average current to be 305 ms, 30 C, and 100 A, respectively. Yang et al. [32] have analyzed the IS in two SHATLE triggered flashes and found quite short durations of about 20 ms.

As for those pulses superimposed on the ICC, referred to as ICC pulses, Wang et al., [30] firstly pointed out that their current waveforms were similar to that of M components superimposed on the continuous current following the return strokes in triggered lightning and, reasonably, both the ICC pulses and the M component (which will be illustrated in detail in the following section) were associated with the same physical process or the same mode of charge transfer from cloud to ground. Qie et al., [33] have analyzed the simultaneous current and electric field of the so-called large ICC pulse (with the current peak up to several kilo amperes, as shown in figure 5) and confirmed this similarity. The dashed line in figure 5 indicated the times of the current starting, the peak of the electric field, and the peak of current. It is clear that the electric field waveform was recorded earlier than the current waveform at the channel bottom.

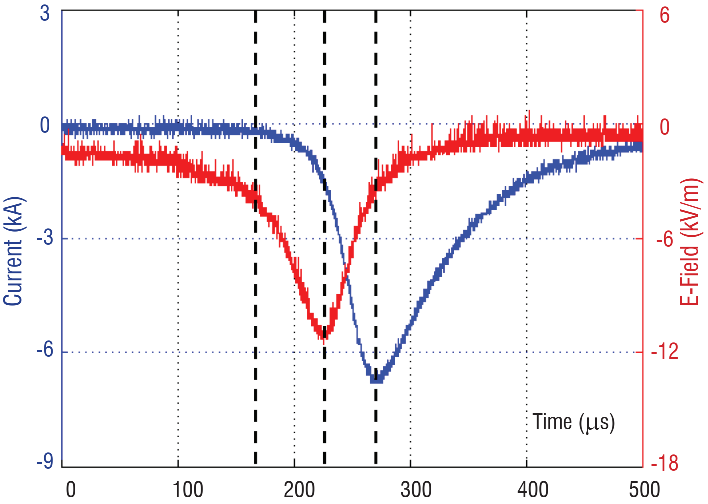


Figure 5 - Simultaneous current and electric field (at 30 m) waveforms of an ICC pulse with the current magnitude up to several kilo amperes. [33].

Upward positive leader

The formation and sustained development of an upward positive leader from the upper extremity of the ascending wire (when the cloud overhead is negatively charged) is the prerequisite to successfully triggering a negative lightning. Since the distance between the sensor and the launcher is exactly known it is possible to obtain the 2-D speed (by optical measurement) or even the 3-D speed (by VHF source imaging) of the leader with reasonable accuracy. Generally, the extending speed of the upward positive leader is between $\sim 10^4$ m/s - $\sim 10^5$ m/s at the initial stage after it emerges from the wire-tip, exhibiting an obvious acceleration tendency afterwards [22]; [8]; [34]; [35]. The speed value can increase to $\sim 10^6$ m/s as the leader reaches up to several kilometers high [36]. Table 1 shows the propagating speed results of UPLs observed during different lightning-triggering experiments.

The wire bottom current associated with UPLs generally starts as a cluster of pulses, which is followed by a steady current that increases gradually in magnitude, as shown in figure 6. The waveform of these current pulses are similar to those so called precursors [37] which are related to the inception attempt of the leader (non-sustained) during the ascent of the triggering wire. The starting of the stable upward positive leader was confirmed to take place at time t=0, in figure 6, making it easy to infer that the damped oscillating current pulses were attributed to the stepped development of the leader [38]; [39]. The electric field measurements associated with UPLs in other triggered lightning further supported such an inference [86]. Recently, similar impulsive currents of an UPL were observed to be coordinated with discrete steps in the initial development, distinguished by high speed video images [40]; [35]. It is reasonable that a leader step process would cause an injection of the positive charge to the leader tip, yielding an abrupt discharge which may physically be unipolar. Since the current signals were detected in the wire bottom, the oscillating behavior of the current pulses were probably caused by the current reflections occurring both at the wire tip and the ground. However, some observations of the UPLs did show the unipolar current pulses that are associated with leader steps [41]. Nevertheless, it is worth noting that the distinct confirmation of the stepped propagation associated with upward positive leaders is only possible with certainty during the very initial stage of their developments, after which they could propagate either continuously or intermittently.

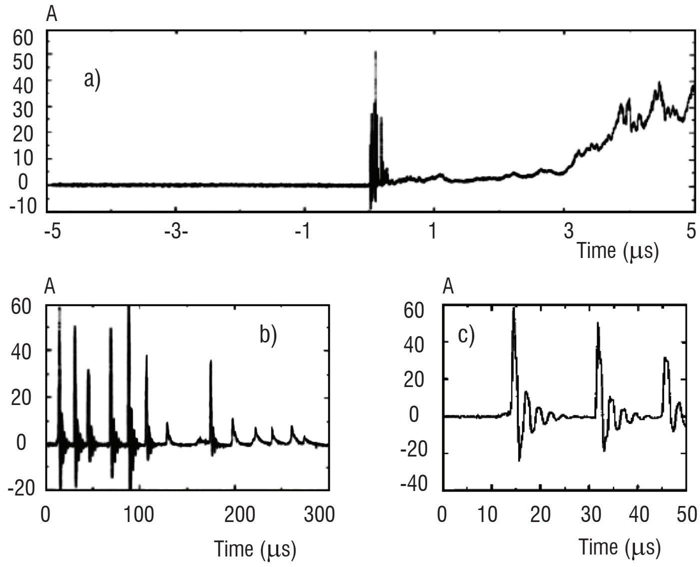


Figure 6 - Wire bottom current for an upward positive leader. [38]

Selected references	Measurement	2-D/3D	Brief notes on leader speed
[Fieux et al., 1978] [22]	Streak camera	2-D	2×10^4 to 1×10^5 m/s in the view range of the camera
[Laroche et al., 1985] [8]	Streak camera	2-D	$\sim 10^4$ m/s at the initial stage
[Y. Kito et al., 1985] [82]	Streak camera	2-D	Started at around 0.1×10^5 m/s with some branches, the final speed accelerated to 5 to 10 times faster.
[Idone, 1992] [83]	Streak camera	2-D	Flash 8827: 1.2×10^5 m/s to 6.5×10^5 m/s, Flash 8911: 2.7×10^5 m/s to 9.4×105 m/s
[Baigi et al., 2009] [34]	High speed camera	2-D	Stepped, a constant speed of 5.6×10^4 m/s over its initial 100 m.
[Yoshida et al., 2010] [36]	VHF	3-D	2 UPLs with average speeds of the order of 10^6 m/s at altitudes of 2.4 km and 3.7 km respectively
[Jiang et al., 2012] [41]	High speed camera	2-D	130-730 m above ground, average speed: 1.0×10^5 m/s, partial speeds: 2.0×10^4 m/s to 1.8×10^5 m/s.

Table 1 - Propagating speeds of upward positive leaders in triggered lightning.

Stepping evidence of negative leaders and the lightning attachment process

Evidence of the stepping mechanism in negative leaders

It is well known that the developments of negative leaders breaking down virgin air are step-wise, and those leaders propagating through the former channel are always continuous, referred to as dart leader. In some instances, the dart-stepped negative leader (also through former channel) may occur as an intermediate pattern, whether in natural lightning or in triggered lightning [42]. On the basis of the laboratory gap spark experiments, the stepped propagation of the negative leader has been attributed to the "space stem" development ahead of the leader tip. The connection of such space stem to the primary streamer channel was considered to result in a step [43]; [18]. This mechanism was presumed to be suitable for interpreting the step-wise development of negative leader occurring in the atmosphere. However, such an analogy is not very solid because the scales of discharge current, length, and duration of the leaders in the laboratory and in the atmosphere are really quite different. To clarify the above presumption, lightning-related observation facts are needed.

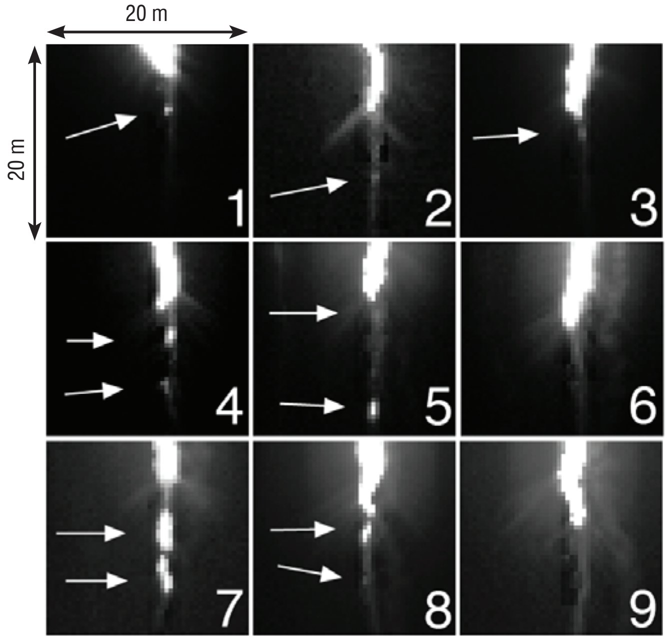


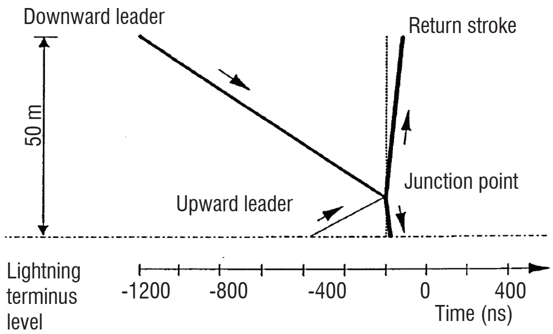
Figure 7 - Expanded images for channel tips (at different heights) of a downward dart-stepped negative leader in a triggered lightning in ICLRT, Florida. The images were taken by a high speed video camera operated at 240 kfps. [44]

Triggered lightning has, for the first time, provided evidence of "space stem" development in atmospheric negative leader [34], [44]. Figure 7 shows the expanded images for channel tips (at different heights) of a downward dart-stepped negative leader in a triggered lightning flash. The arrows indicate the separated luminous segments ahead of the channel, which were quite possibly associated with the "space stem" development. The lengths of these channel segments were found to be 1-4 m, and that of the dark gaps between the segments and the primary channel were 1-10 m. The occurrence of the space stems was reinforced by the leader-related dE/dt pulses, which exhibited 1-3 secondary peaks prior to or following the main peak [44].

Lightning attachment process

The attachment process of the downward leader and the upward connecting leader with different polarities (the upward one occurs in response to the approaching downward one) is an important issue in the study of lightning physics. Understanding of this process helps to reveal the transition between the leader stage and the return stroke stage of lightning, which is fundamental to the design of lightning protection. Based on triggered lightning, data has been obtained for investigating the attachment process [45]; [46];[47]; [34]. [46] observed two dart leader-return stroke sequences in conventional negative triggered lightning by using a digital optical system of ALPS. Figure 8a shows the diagrammatic sketch of the attachment process according to the observation results of one event. The upward connecting leader exhibited lower luminous intensity than the downward dart leader, with a propagating speed of about 2×10^{7} m/s. The junction point was 7-11 m above ground (4-7 m for another event), and the duration of the upward connecting leader was several hundred nanoseconds. It was confirmed that the return stroke process starts with a bidirectional development that originates at the junction point. Figure 8b shows the image of a downward negative leader and the responsive connecting positive leader before the occurrence of a subsequent return stroke in triggered lightning, which also illustrates the weaker intensity of the upward connecting discharge [34]. The so-called streamer zones, composed of filamentary corona streamers with even lower luminous intensity, were found to appear in front of the downward negative leader while not evident ahead of the upward connecting leader. Nevertheless, we need to recognize the limitation of the above results for revealing the attachment process in virgin air, since the dart leader-return stroke sequences occur in the remnant of the former channel. So further observations on the attachment process of altitude triggered lightning are needed, though an analysis had been briefly conducted by P. Lalande et al. [38] based on the data of channel base current and electric field.

a)



b)

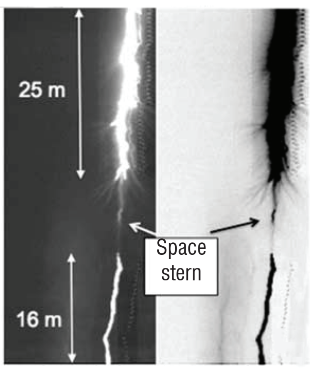


Figure 8 - Observation facts of the attachment process in triggered lightning. a) Diagrammatic sketch of the attachment process according to ALPS observation [46]. b) Image of a downward negative leader and the responsive connecting positive leader, just before the return stroke [34].

Channel base current and close EM field of return stroke

Current waveform parameters

The return stroke is always considered as the key issue in lightning physics since it is the strongest discharge process and results in the severest effects of lightning on ground objectives. An accurate understanding of the return stroke properties, especially the discharge current, is essential for the design of effective protection against lightning. It has been confirmed from different aspects that the return strokes in triggered lightning are similar to the subsequent return strokes in natural downward lightning. Hence, accumulation of the current records for the triggered lightning provides a good opportunity to obtain statistical characterization of return stroke current.

There are several statistical researches on the current waveform parameters based on triggered lightning [25]; [48]; [49]; [21]; [50]; [51]. Figure 9 shows the current waveform (the blue curve) of a return stroke in triggered lightning 0901 in SHATLE. The peak current of this return stroke was 11.7 kA, with the risetime from 10% to 90% peak (in the leading edge of the waveform) being 1.0 μs and the half peak width (the time interval between 50% values of the peak in the leading edge and the trailing edge of the waveform) being 20.9 μs. By calculating the time integral of the current waveform, the charge transferred (or neutralized) by this return stroke was 0.5 C. Since the duration of individual return stroke can not be easily differentiated when it is followed by continuous currents, the parameter of charge transfer is usually defined as a numerical integral of current to within 1 ms [11], although sometimes a duration of several hundred microseconds or even less than 100 μs have also been used [52]; [53].

Table 2 gives the statistical results of the current waveform parameters of return stroke, obtained by different experiments. As shown in the table, the statistics of the return stoke currents from different areas are generally consistent with each other. The GM values of the peak current are around 12 kA, though the result in Guangdong, China (GCOELD) is a bit larger, with the value of 16.1 kA. Shœne et al. [21] used the largest sample size and the GM value of the peak current was 12.2 kA, with a logarithmic standard deviation of 0.22. Some return stokes may involve the peak current up to more than 40 kA and, as in the table, Depasse et al. [48] have reported a peak value of 49.9 kA. At Camp Blanding, a peak current of 56 kA was measured during summer 2000 [54]. The largest peak current in triggered lightning was reported by Leteinturier et al. [55], with the maximum value exceeding the saturation current of 60 kA (estimated as 76 kA by $\int dI/dt$). Saba et al. [16] once reported an altitude triggered lightning of which the currents were obtained. Among the 7 return strokes, the most intense exhibited a peak current of 44 kA. The risetime from 10% to 90% peak by different authors are within the order of magnitude of a microsecond, with the usual GM values of no more than 1 μs, though the corresponding result from the SHATLE experiment was reported to be 1.9 μs, probably owing to the relatively low upper-frequency-limit of the current measuring system used in the first few years of the experiment [56]. Besides the above results, other parameters such as steepness from 10% to 90% peak, and the action integral ($\int i^2 dt$) have also been used by different authors when analyzing the current waveforms of return strokes. Fisher et al. [25] reported the GM values of 28 kA/μs and 3.5×10^3 $A^2 \cdot s$, for the parameters of steepness and action integral, respectively.

Close electric field changes for leader-return stroke sequences

The certainty of the strike point of the triggered lightning using the conventional technique facilitates the measurements of EM field at close ranges. Figure 9 shows the electric field waveform coordinated in time with the current measurement. The E-field sensor was located 30 m away from the lightning channel. The leading edge of electric field waveform was due to the approaching of the dart leader, which propagated from cloud to ground. The bottom of the asymmetric V-shaped electric field waveform corresponded to the instant when the leader reached to the ground and, consequently, the transition from leader to return stroke [57];[58]; [59].

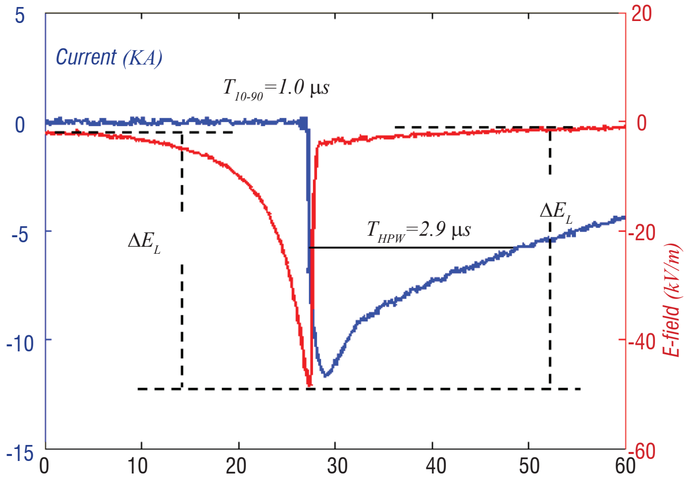


Figure 9 - Simultaneous current and electric field (at 30 m) waveforms of a return stroke in triggered lightning 0901, SHATLE.

It has been possible to obtain statistics on distance dependence of electric fields due to the leader-return strokes from multiple-station measurements in triggered lightning. By analyzing the fields measured at different distances from the lightning channel, Crawford et al. [57]. and Zhang et al. [59] have concluded that the distance dependence of leader electric field change (ΔE_L) was inversely proportional, or somewhat slower than that. Generally, the electric field change of return stroke (ΔE_{RS}) differed not very much from leader field change (ΔE_L), although some records involved a so-called residual electric field, with the ΔE_{RS} being appreciably smaller than the ΔE_L [58]. On the basis of the measurements for 86 return strokes during ICRLT 1999-2000, Shœne et al. [60] studied the statistical characteristics of ΔE_{RS} at 15 m and 30 m, of which the GM values were 96 kV/m and 55.3 kV/m, respectively.

M components superimposed on the continuous current after return strokes

The concept of "*M* component" was first proposed by Malan and Colleus [61], based on the temporary luminescence enhancement of lightning channel during the stage of continuing current flowing through the channel. The *M* component often associates a hook-shaped electric field change at the ground. Early researches into M components were mainly based on the optical and *EM* field observation of natural lightning [62]; [63]; [64]; [65], then VHF radiation source imaging of lightning also provided valuable results [87,66]. However, the absence of discharge current information and the uncertainty of the distance between the sensor and the channel hampered further investigation of the nature of *M* components using

Experiment	Sample	Min	Max	Arithmetic Mean	Standard Deviation	Geometric Mean	SD* $\log_{10}(x)$
Peak current (KA)							
KSC, Florida 1990 and Alabama 1991 [Fisher et al., 1993] [25]	45	--	--	--	--	12.0	0.28
Saint-Privat d' Allier 1986, 1990-1991 [Depasse, 1994] [48]	54	4.5	49.9	11.0	5.6	--	--
ICLRT, Florida 1997 [Crawford, 1998][49]	11	5.3	22.6	12.8	5.6	11.7	0.20
ICLRT, Florida 1999-2004 [Schoene et al., 2009] [21]	165	2.8	42.3	13.9	6.9	12.2	0.22
SHATLE 2005-2010 [Qie et al., 2012] [84]	36	4.4	41.6	14.3	9.2	12.1	0.23
GCOELD 2008-2011 [Zheng et al., 2011] [85]	29	6.7	31.9	17.43	6.95	16.1	0.18
Risetime from 10% to 90% of peak current (µs)							
KSC, Florida 1990 and Alabama 1991 [Fisher et al., 1993] [25]	43	--	2.9	--	--	0.37	0.29
Saint-Privat d' Allier 1986, 1990-1991 [Depasse, 1994] [48]	37	0.25	4.9	1.14	1.1	--	--
ICLRT, Florida 1997 [Crawford, 1998][49]	11	0.3	4.0	0.9	1.2	0.6	0.39
ICLRT, Florida 1999-2004 [Schoene et al., 2009] [21]	81	0.2	5.7	1.2	0.8	0.9	0.32
Half peak width (µs)							
KSC, Florida 1990 and Alabama 1991 [Fisher et al., 1993] [25]	41	--	--	--	--	18	0.30
Saint-Privat d' Allier 1986, 1990-1991 [Depasse, 1994] [48]	24	14.7	103.2	49.8	22.4	--	--
ICLRT, Florida 1997 [Crawford, 1998][49]	11	6.5	100	35.7	24.6	29.4	0.29
ICLRT, Florida 1999-2004 [Schoene et al., 2009] [21]	142	4	93	23	17	19	0.30
Charge et transfer within 1ms (C)							
ICLRT, Florida 1999-2004 [Schoene et al., 2009] [21]	151	0.3	8.3	1.4	1.4	1.0	0.35
SHATLE 2005-2010 [Qie et al., 2012] [84]	36	0.18	4.2	1.1	0.76	0.86	0.31
GCOELD 2008-2011 [Zheng et al., 2011] [85]	29	0.44	4.2	1.8	1.24	1.4	0.32

Table 2 - Statistical characteristics of current waveform parameters of return stroke in triggered lightning, obtained from various experimental campaigns.

natural lightning observation. Triggered lightning experiments now open new insight into such an interstroke process.

Based on the directly measured current data, M components register as current pulses superimposed on the continuous current after the return stroke, and the pulse waveforms on expanded timescale are typically more or less symmetrically V-shaped, as illustrated in figure 10 a. For most of the M components the preceding continuous current at the channel bottom was observed to be of the order of 30 A or higher [67]. Fisher et al.[24] firstly pointed out that M components generally involved longer rise time than return stroke current pulses, by 2 or 3 orders of magnitude. The waveform parameters of M component were statistically summarized by Thottappillil et al. [66], according to whom the peak current, 10%-90% rise time, and charge transfer of an M component were 100-200 A, 300-500 μs, and 0.1-0.2 C, respectively. The detailed statistics for each parameter are shown in table 3 and, based on triggered lightning data, the occurrence of M components were found to outnumber that of return strokes by 4:1. Though the majority of M components were observed to have peak current no more than several hundred amperes, there were a few samples with the current magnitude exhibited up to the kilo amperes range [6]; [20]. [68] Qie et al. [33]once found 5 larger-than-usual M components in a triggered lightning, with GM peak current, 10% to 90% rise time and half peak width being 5.1 kA, 34.6 μs, and 73.6 μs, respectively. It appeared that those M components with larger current magnitude may involve shorter time parameters.

Parameter	Sample Size	GM	Case exceeding tabulated value			
			SD $\log_{10}(x)$	95%	50%	5%
Magnitude, A	124	117	0.50	20	121	757
Rise time, μs	124	422	0.42	102	425	1785
Duration, μs	114	2.1	0.37	0.6	2.0	7.6
Half-peak width, μs	113	816	0.41	192	800	3580
Charge, mC	104	129	0.32	33	131	377
CC level, A	140	177	0.45	34	183	991
M interval, ms	107	4.9	0.47	0.8	4.9	23
Elapsed time, ms	158	158	0.73	0.7	7.7	156

Table 3 - Statistics of current parameters of M components in triggered lightning conducted in Florida (1990) and Alabama (1991). [67]

It is widely acknowledged that the M component involves a different mechanism to that of the leader-return stroke sequence; the former propagates in an already existing channel while the latter is usually in a channel with current cutoff. The measurements of discharge current and EM field at known distances for triggered lightning make it possible to verify the physical mechanism of the M component and establish an engineering model for mathematical representation and simulation. Rakov et al. [69] concluded that at a near distance, the magnetic field and current of the M component shared similar waveforms, while the electric field appears to be proportional to their time derivative. As in figure 10, the electric field began its negative directed change ahead of current. The red line in the figure indicates when the electric field reaches its peak, and at the same moment, the channel base current had already emerged from the background level with the value being about 3 kA. The multi-station observation showed that the electric field peak basically follows a logarithmic distance dependence [70]; [71]. On the basis of these concluded features, a "two wave" mechanism has been proposed to explain the developing process of the M component through the channel [69]. According to this mechanism the M component involves two guided waves which propagate in opposite directions and have equal amplitudes. The downward incident wave forms primarily and develops to the ground, and as it reaches the ground, a mirroring (reflected) wave starts to generate and propagate upward. The ground is sensed as a short circuit, with the reflectance for current at the ground being approximately $+1$ while the counterpart for charge density is -1. The two waves have similar contributions to the total outflow of the charge from the lightning channel base at any moment in time. And at any section of the discharge channel, their currents are additive while their charge densities are subtractive. The simulation of EM fields on the basis of a "two wave" theory has shown that such a mechanism is a reasonable explanation of the M component [70]; [71].

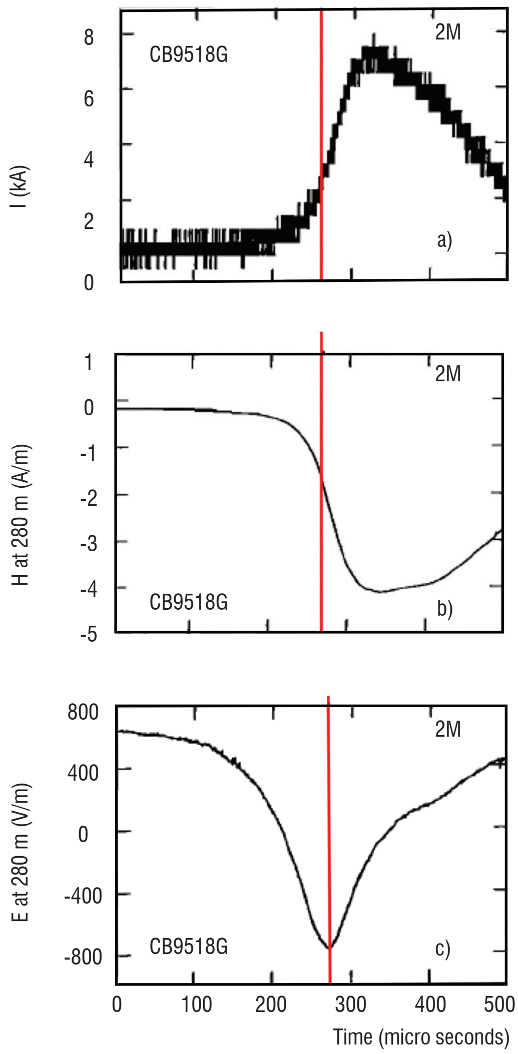


Figure 10 - Synchronous (a) current, (b) magnetic field, and (c) electric field for an M component in triggered lightning flash 9518 (Camp Blanding, Florida). The field sensors were located 280 m away from the launcher. [6]

Energetic radiations from triggered lightning

Early in the 1920s, Wilson [72] suggested that electrons could be accelerated to relativistic energies in electrified thunderstorms with very strong electric fields. Since then, numerous attempts have been made to observe the high-energy electrons or the associated energetic rays under thunderstorm conditions. Credible evidence of energetic radiation from thunderstorms or lightning flashes have been obtained by aircraft-, balloon- and satellite-based observations since the 1980s [73]; [74]; [75]. These findings have pioneered a leading edge field in lightning physics and, consequently, appropriate observations were designed and set up on the basis of the triggering lightning experiment. [76], [77] using NaI(TL) scintillation detectors, discovered marked bursts of energetic radiation which were confirmed to be definitely attributable to the occurrence of the triggered lightning. These energetic radiation events were observed to primarily consist of X-ray emission with the signals being recorded in the form of a pulse cluster, during the leader phases prior to or just at the beginning of the return strokes. The pulse trains of the X-ray emission generally start at $\sim$20 μs (occasionally up to $\sim$100 μs) before the return strokes, with a single burst lasting no more than 1 μs and involving an energy spectrum of 30-250 keV. Figure 11 shows the simultaneous waveforms of current, electric field (at 80 m) and X-ray energy at 3 different distances for a leader-return stroke in triggered lightning. This event exhibited long duration of the X-ray emission during the leader phase. The attenuation of the X-ray intensities with distance is shown in the figure (the peaks of the X-ray pulses indicate the deposited energies of a radiation burst). Also seen in the figure is the gradual increase of the X-ray intensities when the leader approaches the ground, with the largest pulses occurring immediately before the return stroke (see the UPMT curve). It seems that X-ray emission could be detected in most of the leader-return stroke sequences in triggered lightning. Based on the data from 2002 to 2003, [77] concluded that 81% of the leader-return strokes impulsively emitted energetic radiation and have suggested that X-ray emission is a common phenomenon in natural lightning.

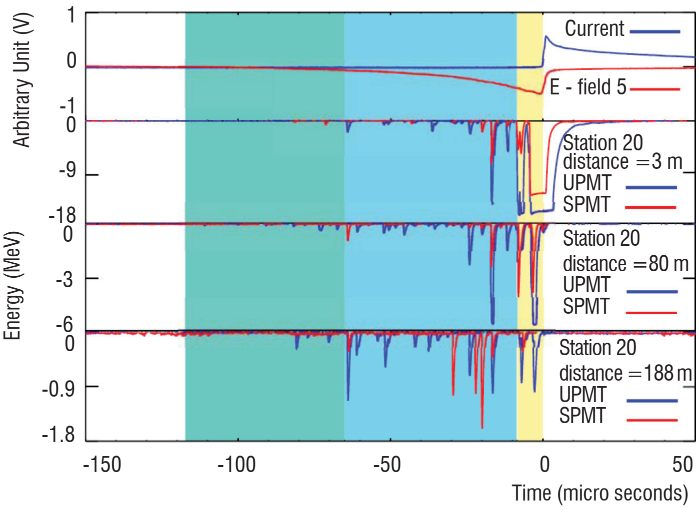


Figure 11 - Simultaneous waveforms of current at the channel bottom, electric field at 80 m, and X-ray energy at different distances (3 m, 80 m, and 188 m, respectively), for a leade r-return stroke in triggered lightning, with the return stroke started at time 0. [86]

It has been well demonstrated that in natural lightning X-ray emission is consistent over time with the leader steps [78]. The synchronous measurements of the current, electric field, and energetic radiation for the dart-stepped leaders in triggered lightning further confirmed such a close relation between the X-ray emission and the step formation [79]; [44]. It is confirmed by the multiple station signals that the X-ray emission and the leader step E-field changes may be derived from the same location, with a temporal deviation of 0.1-1.3 μs and spatial error of less than 50 m [79]. Although most of the observed energetic radiation associated with triggered lightning was in the form of X-rays, [79] once reported an intense gamma-ray burst detected on the ground 650 m away from the triggered-lightning channel, with the energies rising up to more than 10 MeV during a relatively long period of 300 μs. The gamma-ray burst was produced in coincidence with an extremely large current pulse with a peak of 11 kA occurring during the triggered lightning initial stage, that is, before the first dart-leader/return-stroke sequence.

Concluding remarks

The rocket-and-wire technique for artificially triggering lightning has been significantly improved and has become an effective approach to the study of lightning physics. Abundant valuable results have been obtained by the experiments conducted in different countries. These results have provided considerable new insights into lightning properties, many of which are not easily revealed by observation of natural lightning. Due to the length limitation on the manuscript, the review of the results of triggered lightning is very brief in this paper. For more detailed information, the reader may wish to consult the referred articles.

In addition to the investigation of the lightning process, triggered lightning also has wide application. Simultaneous measurements of the discharge current at channel bottom and the *EM* fields at different distances make it feasible to test the validity or applicability of various lightning models. Since the strike point of the triggered lightning is predetermined, observation programs could be designed for investigating the interaction between the lightning and the objects that are struck (or are located very close to the discharge channel), which may help toward better understanding of the mechanism of damage-causing lightning. And also, experiments to evaluate the effectiveness of lightning protection devices could be conducted under real lightning discharge conditions. In addition, the occurrences of triggered lightning, with exact location and time information, provides ground-truth data for the calibration of various lightning location systems [81].

The rocket triggering lightning experiment will be continued in various countries in the coming years. With state-of-the-art experimental and detection technologies it is hoped that new results will be obtained both in researches on lightning physics and applications in the validation of lightning protection and location devices

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Acronyms

IS (Initial Stage)
ICC (Initial Continuous Current)
VHF (Very High Frequency)
UPLs (Upward Positive Leaders)
ALPS (Automatic Lightning Processing Feature Observation System)
UPMT (Unshielded/Unattenuated Photomultiplier Tube)
RS (Return Stroke)
SHATLE (Shandong Artificially Triggered Lightning Experiment)
ICLRT (International Center for Lightning Research and Testing)

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