

New Triggered Lightning Testing Capabilities at the International Center for Lightning Research and Testing (ICLRT)

C.T. Mata and J.D. Hill
 Scientific Lightning Solutions, SLS
 Titusville, FL, USA
 c.mata@sls-us.com

Abstract— Scientific Lightning Solutions (SLS) has partnered with the University of Florida with the purpose of conducting real lightning testing operations at the International Center for Lightning Research and Testing (ICLRT). The ICLRT is one of only two locations in the United States where lightning is artificially initiated or “triggered” using the rocket-and-wire technique. Triggered lightning can be used to effectively characterize the responses of various systems and articles to the direct and indirect effects of lightning currents, electromagnetic fields, and energetic radiation. The characterization can then be used to develop mitigation strategies or protection schemes to make the systems under test less vulnerable to lightning strikes, since unlike in high-voltage laboratory tests, systems are exposed to actual lightning currents and lightning-induced electromagnetic fields. The SLS/UF partnership opens the door for the commercial industry to test components, equipment, or complete systems to real lightning currents. These testing capabilities will be of great interest to many different industries, including aerospace, oil, military, green power generation, and emerging technology.

Keywords-component; lightning; triggered lightning; testing; lightning protection

I. INTRODUCTION

Recently, Scientific Lightning Solutions (SLS), a new company based in Titusville, FL partnered with the University of Florida with the purpose of conducting real lightning testing operations at the International Center for Lightning Research and Testing (ICLRT). The ICLRT is located on the Camp Blanding Army National Guard base east of Starke, FL. The facility occupies a land area of about 1 km². The ICLRT is one of only two locations in the United States where lightning is artificially initiated or “triggered” using the rocket-and-wire technique. *Rakov and Uman* [2003, Chp. 7] provide a thorough review of the triggered lightning process. A time-exposed still image of a triggered lightning discharges is shown in Fig. 1. Triggered lightning return strokes are very similar to natural lightning subsequent strokes in terms of their currents and radiated electromagnetic fields. While not a direct proxy for natural lightning, triggered lightning has the distinct advantages of repeatability, control over the location where the

lightning terminates, and control over the lightning current path after the termination has occurred. Unlike natural lightning discharges, the channel-base current of triggered lightning return strokes can be reliably and directly measured. These characteristics together allow triggered lightning to be used to effectively characterize the responses of various systems and articles to the direct and indirect effects of lightning currents, electromagnetic fields, and energetic radiation.

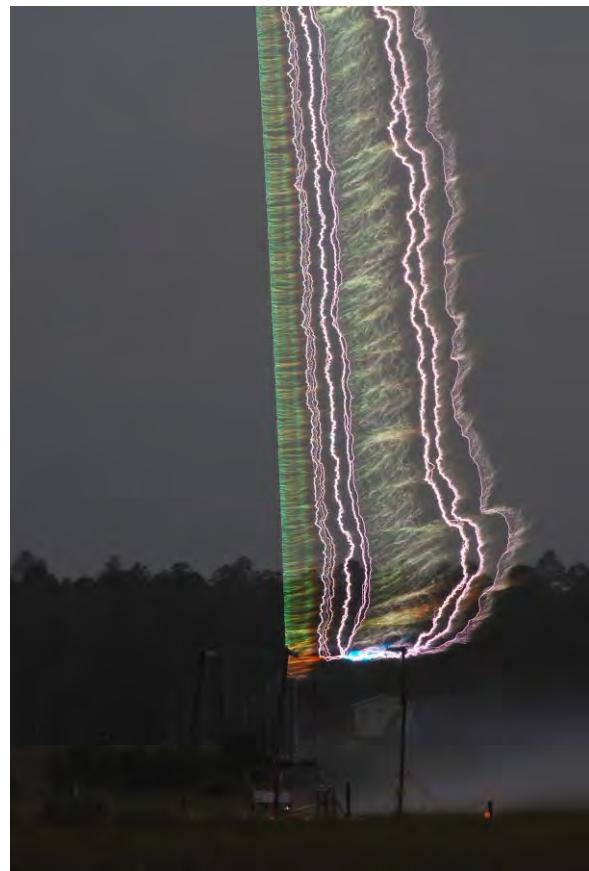


Figure 1. Triggered lightning discharge at the ICLRT.

Triggered lightning testing began at the ICLRT in 1993 and has continued to the present day. For much of the history of the ICLRT, the lightning testing conducted was practical in nature and was driven by real-world lightning protection, mitigation, and grounding problems. Experiments included, but were not limited to, 1) testing the lightning susceptibility of sections of natural gas pipeline, 2) determining the effects of directly injected lightning currents on runway lighting systems, 3) determining the effects of lightning currents injected into power distribution lines of various configurations, 4) testing the distribution of currents injected into residential and commercial lightning protection systems on simulated houses, 5) characterizing the effects of nearby lightning on tall vertical conductors, and 6) determining the current distribution of directly injected lightning currents to a scale model of the lightning protection system at Launch Complex 39B at the Kennedy Space Center.

More recently, triggered lightning testing at the ICLRT has focused more strongly on the detailed physics of the lightning initiation, propagation, and attachment processes under funding from the United States Defense Advanced Research Projects Agency (DARPA). During the past 10 years, the collaborative studies of many researchers at the ICLRT have greatly enhanced the cumulative understanding of these processes. Today, researchers at the ICLRT are attempting to better understand the upper atmospheric and ionospheric effects of lightning, again using triggered lightning as a controlled and quantified source of energy injection to the earth-ionospheric waveguide.

With the focus of research at the ICLRT having shifted from more practical lightning problems to detailed lightning and high-energy physics, there is a need for an advanced lightning testing capability for more industry-related problems. Currently, most components, assemblies, and systems that are at risk of being damaged by the direct and indirect effects of lightning are tested in high-voltage laboratories. High voltage laboratories typically utilize large Marx-type generators to produce small-scale discharge processes with the resultant current, voltage, and electromagnetic field waveforms. Test articles are either connected directly in the discharge current path, or are located in close proximity to an electrode where a short arc originates when the supplied voltage exceeds the dielectric breakdown threshold.

Laboratory surge generators are typically designed to supply outputs that mimic either the high voltage or high current present during a lightning discharge. A single surge generator does not exist that can simultaneously supply both realistic lightning high voltage and high current to a test article. Therefore, complex configurations of multiple generators must be used in consecutive tests to simulate, on a very small scale, the cumulative effects of lightning on a test article. High voltage generators can produce potentials up to about 10 MV, with resulting arc lengths typically less than 20 m. These generators can be used to initiate arcs to test articles of various impedances, but cannot drive realistic lightning

currents through the test article following the arc formation. High current generators can produce microsecond-scale current transients through low resistance test articles, but cannot simulate the damaging, long time duration continuing currents that occur following lightning return strokes. The interaction of the test article impedance with the generator circuit strongly affects the ability of the generator to accurately subject the test article to realistic lightning impulses, particularly for poorly conductive or insulating materials. Unless the test article has very low impedance, the laboratory generated excitation waveforms do not closely resemble the wave shapes of real lightning.

The electromagnetic fields produced by laboratory high voltage or high current generators do not adequately represent the real lightning electromagnetic fields incident upon a test article, primarily due to the many orders of magnitude difference in the length scale of the discharges processes. Test articles located either directly in the current path or close to triggered lightning are exposed to high-amplitude, high-frequency electromagnetic field changes during the decent of the lightning leader along the 6-8 km path between the negative cloud charge and ground over a time duration of up to several tens of milliseconds. When a triggered lightning leader nears ground, the test article is then exposed to the rapid, high-amplitude field changes associated with the attachment process and the subsequent return stroke. The radiated fields can have deleterious effects on a test article in the form of transient induced currents and voltages prior to any directs effects from the lightning current itself. High voltage laboratories cannot simulate these effects due to limited available space and physical constraints of the generators.

High voltage laboratory surge generators are suited for testing individual components or assemblies, but are not capable of exposing fully integrated systems, which are typically composed of materials of various impedances, to realistic lightning currents, voltages, and electromagnetic fields. In the high voltage laboratory environment, the effects of simulated lightning impulses on a full system must be extrapolated post-test from the response characteristics of the individual components or assemblies. In addition, laboratories must provide a return current path for the generator circuitry, and therefore cannot accurately simulate the response of the grounding configuration of an installed, fully integrated system exposed to the direct and indirect effects of a real lightning discharge.

Triggered lightning leader/return stroke sequences at the ICLRT can be used to subject a component, assembly, or fully integrated system to an arc discharge of many kilometers in length, that, in most cases, repeats 2-5 times during a triggered flash over the time span of a few hundred milliseconds. This scenario is representative of the real lightning environment where multiple subsequent return strokes traverse the path of the first stroke between the cloud and ground. In contrast to

laboratory surge generators, triggered lightning leader/return stroke sequences simultaneously expose the test article to both high voltage (> 10 MV) and high current while remaining insensitive to the impedance or scale of the test article. In addition, triggered lightning can be used to reliably subject a test article to long-duration continuing currents ranging from tens to hundreds of milliseconds. Test articles are exposed to real lightning electromagnetic fields that occur during the downward leader phase, the attachment process to ground, and the subsequent return stroke. Triggered lightning provides the capability of testing the responses of conductive, semi-conductive, or insulating components, assemblies, and fully integrated systems of any size to the direct effects (high-potential, arcing, current propagation, and burn through) and indirect effects (induced transient voltages and currents from radiated electromagnetic fields) to real, full-scale lightning channels.

II. EXPERIMENTAL PLAN

During 2017, SLS will begin providing a live lightning testing facility located at the ICLRT. While the University of Florida will provide the real-estate and some infrastructure to support this testing capability, the SLS triggered lightning facility will operate independently from that utilized by University of Florida researchers. SLS aims to provide the ability to trigger lightning with much greater frequency and efficiency than what has typically been possible with historical experiments at the ICLRT. During a typical summer, about 25 lightning discharges are successfully triggered by ICLRT personnel. The number of successful triggered lightning discharges has always been limited by a finite availability of the specialized copper wire spools used to trigger lightning. The frequency with which lightning can be triggered at the ICLRT has also been heavily influenced by long dead-times between triggering attempts as a result of slow data downloads. SLS plans to provide a simple, cost-effective method for triggering lightning that can potentially allow as many as 20 lightning discharges to be triggered in a single storm.

The ICLRT provides an ideal environment for conducting customer-driven triggered lightning testing and experimentation. The adaptable facility is capable of supporting test articles including individual electrical/mechanical components, assemblies, and fully constructed systems. In addition, the triggering facility can accommodate large-scale test articles including vehicles, aircraft (or portions thereof), and green energy related products (photovoltaic arrays, wind turbines, etc.). A custom testing configuration is designed for the specific requirements outlined by each customer. SLS is capable of supporting multiple, independent test-configurations concurrently through the use of separate launching and measurement systems. In addition, the location of the ICLRT on a United States military facility provides a secluded, secure location for testing many types of sensitive assets.

Triggered lightning provides the ability to subject test articles to a variety of different lightning phenomena. During a single triggered lightning discharge, a test article can be subjected to a large variability of currents, ranging from low-amplitude, long duration currents, moderate-amplitude and rise-time current pulses, to fast-rising, high-amplitude transients. Customers will have the ability to define exactly how a test-article is exposed to the direct and indirect effects of triggered lightning currents, voltages, and electromagnetic fields. Example testing configurations are provided below.

A. Long Duration Current Injection

The initial stage of a triggered lightning discharge consists of the rocket-ascent, the launching of an upward positive leader (UPL) from the ascending triggering wire, the subsequent vaporization of the triggering wire, and the resultant initial continuous current (ICC) flow that is established as the propagating UPL encounters negative charge aloft. The ICC often has duration of many hundreds of milliseconds (as long as one second) and transfers many tens of Coulombs of negative charge to ground (occasionally as much as 250 Coulombs). The average current amplitude during the ICC is about 100 A, with larger, super-imposed current pulses frequently exceeding 1 kA. The ICC reliably follows the path of the triggering wire to the metallic launching structure. A test article placed within the current path of the ICC can be subjected to long duration, high-charge transfer current flow. This current path to the test article can be either continuous (direct connection between ground, the test article, and the metallic launcher), or can include spark gaps to force arcing to occur to one or both sides of the test article in order to establish the ground connection. This type of testing is ideally suited for testing the burn-through susceptibility of conductive materials and the effects of specific energy heating on poorly-conductive or insulating materials. Much of the material and structural damage associated with the direct effects of lightning is due to heating resulting from the continuing current period following a return stroke. The triggered lightning ICC provides a method for subjecting test articles to realistic lightning continuing currents.

B. Direct Strike Capability

Test articles can be reliably subjected to direct attachment from negative polarity lightning leaders. With this configuration, the test article is arranged to directly intercept the downward leader, with typical length of several kilometers, that would normally terminate on the grounded launching structure. The long duration ICC currents discussed above can be optionally passed through the test article. The direct strike test configuration most closely mimics the fast-rising currents and voltages a test article will experience when exposed to direct attachment from natural lightning subsequent leader/return stroke sequences. A test article configured to receive direct attachment will be exposed to typically 2-5 leader/return strokes sequences during a single

triggered lightning flash, with some flashes exceeding 10 leader/return stroke sequences. Triggered lightning return strokes have current rise times of about 300 ns with peak current amplitudes averaging 10-15 kA. Triggered lightning strokes having peak currents between 30-40 kA occur regularly along with occasional higher peak-current events. Current derivatives exceeding 100 kA/ μ s are frequently recorded.

C. Transient Direct Current Injection

Downward leaders preceding triggered lightning return strokes can also be intercepted above the launching structure by an elevated conducting strike object. The current path, which carries the impulsive return stroke currents and any subsequent continuing currents, can then be routed directly from the strike object to a test article located some distance away from the launcher. The test article can be placed directly within the current path, providing a continuous path to ground, or be allowed to float between the elevated conductor and ground, forcing arcing to occur to either one or both sides of the test article. This type of configuration is well suited for controlled injection of current to a particular location on a test article (via either direct connection or customer-defined spark gap length), in contrast to the direct attachment method discussed above, where less control of the exact strike point on the test article is attainable.

D. Indirect Lightning Effects

The triggered lightning channel is a more-or-less vertical conductor that radiates a primarily vertical electric field and azimuthal magnetic field. Test articles may be placed in any proximity to the triggered lightning channel (distances ranging from meters to hundreds of meters) in order to test the susceptibility of the test article to the lightning radiated electromagnetic fields and resultant induced voltages and currents. Calibrated electric and magnetic field sensors are co-located with the test article to determine the field amplitudes and wave shapes incident upon the test article. Sensor outputs are recorded for all triggered lightning discharges, as well for any natural lightning discharges that terminate in the vicinity of the test article.

III. INSTRUMENTATION

SLS provides state-of-the-art digitization systems and sensors for monitoring the electromagnetic and optical emissions of triggered lightning. The digitization systems and sensors have been rigorously tested and qualified both at the ICLRT and at NASA's Kennedy Space Center (KSC) since 2008, and are presently being used to monitor the lightning environment at Launch Complex 39B, the next generation launch facility at KSC for NASA's new Space Launch System rocket. Data are digitized in the field at each sensor location and are then transmitted via fiber-optics to a shielded instrumentation building for storage. Triggered lightning currents ranging from milli-amperes to tens of kilo-amperes

are directly measured with a variety of high-bandwidth sensors that can be flexibly arranged to accommodate the measurement requirements of the customer. SLS can implement customized direct and induced current and voltage measurements for a test article, or alternately, the outputs of customer-supplied sensors or test points can be digitized. SLS also supplies custom, high-bandwidth electromagnetic field sensors for measuring lightning electric and magnetic fields and their derivatives. Finally, SLS can provide support for measurements of the mechanical properties of a test article exposed to the direct and indirect effects of triggered lightning (e.g., temperature, displacement, vibration, etc.). The triggering facilities are equipped with high-speed cameras that are used to closely monitor the test article per customer requirements.

IV. HIGH-SPEED PHOTOGRAPHY

SLS has designed a custom, high-speed camera image acquisition system (Optical Jupiter) to capture high-fidelity photographs of 100% of lightning events striking within the monitored area, including all triggered and natural lightning discharges. Optical Jupiter utilizes ruggedized, low-power digital high-speed cameras to provide high-resolution imagery of triggered and natural lightning. The small form-factor cameras are field-deployable in small, environmentally controlled housings. The Optical Jupiter system is powered exclusively via an integrated photovoltaic array, requiring no external power input or other supporting infrastructure. Lightning image data are automatically acquired, processed, time-tagged with microsecond accuracy, and transmitted to the user. Optical Jupiter is designed using the most advanced aerospace-grade components to provide years of maintenance-free operation with zero system down time. The robust performance of the Optical Jupiter system has been fully tested and qualified at Kennedy Space Center, including prolonged exposure to extreme heat, humidity, and harsh corrosive and electromagnetic environments. Optical Jupiter stations can be placed at any proximity to the triggered lightning channel to closely monitor the effects of lightning on the test article. An example Optical Jupiter station is shown in Fig. 2.

V. CONCLUSIONS

For the first time, triggered-lightning experiments are being made available to private industry at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL. This is the result of a partnership between the University of Florida (UF) and Scientific Lightning Solutions, LLC (SLS), a new company that seeks to bridge the gap



Figure 2. Optical Jupiter station.

between state-of-the-art lightning research and the lightning protection industry. This partnership brings many years of combined expertise in triggered-lightning experimentation and state-of-the-art lightning instrumentation to industries that may benefit from triggered lightning testing, including, but not limited to green energy, oil and natural gas, aerospace, communications, power generation and distribution, lightning protection and shielding, and military and defense.

Triggered lightning provides a reliable, repeatable, and adaptable method for testing and qualifying components, assemblies, and full systems beyond the capabilities of high voltage laboratories. The SLS triggered lightning facility at the ICLRT can be configured to thoroughly characterize the performance of a test article to:

- Long duration, hundred ampere level continuing currents with kilo-ampere level super-imposed pulses delivered via direct injection or controlled length arc
- Direct attachment from negative polarity lightning leaders with subsequent return strokes having tens of kilo-ampere peak currents and sub-microsecond rise times to peak
- Return strokes having tens of kilo-ampere peak currents and sub-microsecond rise times to peak delivered via direct injection or controlled length arc
- Leader phase, attachment phase, and return stroke electromagnetic fields at distances from meters to hundreds of meters from the triggered lightning channel.

When a test article's response and susceptibility to triggered lightning has been well characterized, the customer can be confident in the test article's performance in a real lightning environment.

REFERENCES

- [1] Rakov, V. A., and M. A. Uman (2003), *Lightning: Physics and Effects*, Cambridge Univ. Press, Cambridge, United Kingdom.