MERLIN Low Detection Efficiency Study Results: First Two Years

1st Jonathan D. Hill
Scientific Lightning Solutions, LLC
Titusville, FL, USA
d.hill@sls-us.com

2nd Carlos T. Mata
Scientific Lightning Solutions, LLC
Titusville, FL, USA
c.mata@sls-us.com

***Abstract*—The Mesoscale Eastern Range Lightning Information Network (MERLIN) provides continuous lightning detection and location information for the Kennedy Space Center and Cape Canaveral Space Force Station. Weather officers at the 45th Weather Squadron utilize MERLIN data to advise space launch providers of potential lightning-related hazards preceding and during launch operations. Prior study results performed in 2015/2016 found that MERLIN's detection efficiency for lightning strokes that terminated on tall structures was lower than for strokes that attached directly to ground. A secondary study was commissioned to provide additional ground-truth data for lightning strokes to tall structures (launch pad catenary wire systems, vertical spacecraft integration buildings, communications towers, etc.) to determine if the detection efficiency results were statistically significant, and if so, utilize the acquired data to potentially modify MERLIN's algorithms to better detect strokes to tall structures. Ground-truth data (high-speed optical and electromagnetic field measurements) were acquired in 2020 and 2021 totaling 129 strokes to tall structures and 3431 strokes to nearby ground.**

***Index Terms*—lightning, lightning protection, MERLIN**

I. Introduction

In 2019, the 45th Weather Squadron at Cape Canaveral Space Force Station (CCSFS) funded a study for Scientific Lightning Solutions, LLC (SLS) or Titusville, FL to evaluate the detection efficiency (DE) of the Mesoscale Eastern Range Lightning Information Network (MERLIN) [1][2] for lightning strokes to tall structures and/or large catenary wire lightning protection systems. The MERLIN network consists of 10 Vaisala TLS-200 sensors installed at Kennedy Space Center (KSC), CCSFS, and Patrick Space Force Base (PSFB). A prior study conducted by the authors in 2015/2016 [3] found that the MERLIN DE for a dataset of 45 strokes to tall structures (84.4%) was lower than the DE for a dataset of 276 strokes attaching to ground (93.5%). Anecdotal evidence suggests that the MERLIN DE for strokes to tall structures may, in fact, be as low as 75%. The primary goal of the current study is to determine if the apparent MERLIN DE difference for strokes attaching to tall structures versus strikes to nearby ground is statistically significant, and if so, provide the resultant data to Vaisala (the MERLIN vendor) so that MERLIN can be tuned to improve DE for strokes to tall structures without degrading the overall performance of the system. Note that the MERLIN DE for strokes to tall structures is of critical importance at KSC/CCSFS, where many tall structures and large catenary wire lightning protection systems provide direct strike lightning protection for critical space launch vehicles, payloads, and fabrication/assembly facilities.

II. Instrumentation

To capture a statistically significant dataset of ground truth lightning events in a reasonable amount of time, SLS provided continuous, zero-deadtime high-speed video monitoring for tall structures using seven proprietary Jupiter OLS optical monitoring systems. The network covered all large active launch complexes at KSC/CCSFS including LC-37, LC-40, LC-41, LC-39A, and LC-39B. In addition, monitoring was provided for the Vehicle Assembly Buiilding (VAB), several other large vertical vehicle/spacecraft integration facilities, and LC-36 (after the catenary wire lightning protection system was completed during 2021). Jupiter OLS provides 100% detection efficiency for lightning events occurring in close proximity to the monitored target, including both direct strikes to the target and nearby strikes to open ground. In addition, a single Jupiter OLS station provides precision lightning location accuracy for direct strikes to tall structures/catenary wire systems. Jupiter OLS is equipped with an integrated GPS timing engine that provides sub-microsecond timing accuracy for each captured video frame to facilitate data correlation with MERLIN lightning strike reports. An image of a typical Jupiter OLS station is provided in Fig. 1.

Fig. 1. Image of a typical Jupiter OLS station (monitoring SLC-36).

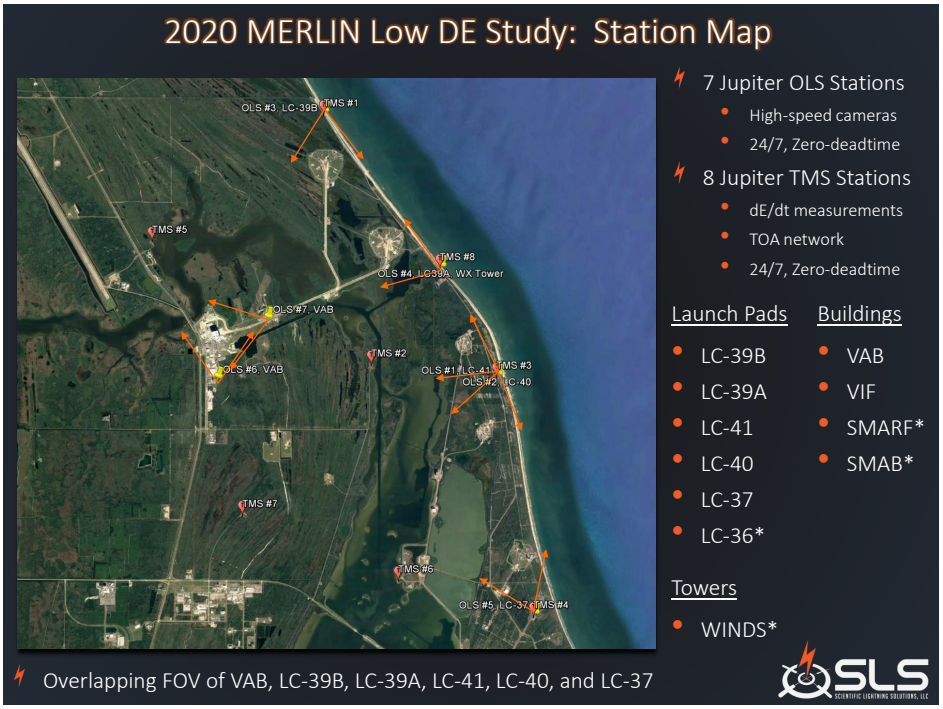

Fig. 2. Locations of Jupiter OLS and Jupiter TMS instrumentation stations. Note that LC-36 is located to the south of the view shown and is monitored by a single Jupiter OLS station beginning in July, 2021.

In addition, SLS installed an 8-station time-of-arrival (TOA) network to provide ground-truth strike point data in the vicinity of all large active launch pads and assembly buildings. The stations utilized proprietary Jupiter TMS transient monitoring systems to continuously sample the outputs of flat plate electric field derivative sensors ($\frac{dE}{dt}$). The network timing accuracy is of the order of 15 ns RMS, which provides excellent strike location accuracy and the ability to precisely correlate detected events with both Jupiter OLS high-speed video recordings and MERLIN lightning strike reports. A annotated aerial map of the sensor network is provided in Fig. 2. Instrumentation locations, monitored structures, and camera fields-of-view are provided. Note that the Jupiter OLS systems were located to provide mutli-angle views of the same structures of interest.

III. Discrimination Metrics

The following discrimination metrics were utilized to correlate lightning strike reports generated by MERLIN versus data recorded by SLS' Jupiter OLS and Jupiter TMS systems.

1) A stroke to a tall structure reported by MERLIN is considered to be a successful detection if and only if the ground-truth strike location (determined by SLS' Jupiter systems) is within the 95% error ellipse reported by MERLIN and the event times reported by both MERLIN and SLS' Jupiter OLS systems agree within 1.5 ms. Note the time correlation metric was chosen primarily based on the camera framing interval of 1.11 ms.
2) Every attachment point recorded by SLS' Jupiter systems is considered a unique event independent of the time duration or spatial separation between attachments. From the operator's perspective, each attachment (whether to a tall structure or to ground) presents a unique hazard because of the potential variation in peak current and radiated electromagnetic fields.

IV. 2020 Data Analyses

Lightning data were acquired from April 20, 2020 through October 29, 2020. There were a total of 71 return strokes imaged that directly impacted tall structures. A breakdown of the strokes is provided in Tab. 1. There were 46 strikes to catenary wire systems, 18 strokes to tall buildings, and 7 strokes to towers. MERLIN reported a total of 47 strokes, providing an overall stroke DE for strikes to tall structures of 66.2%. The DE's for strokes to launch pad catenary wire systems, buildings, and towers were 67.3%, 55.6%, and 85.7%, respectively.

Two of the 71 strokes were positive polarity while the remaining 69 strokes were negative polarity. MERLIN did not report either of the positive polarity return strokes. A total of six of the strokes to tall structures not reported by MERLIN (25% of the total number of strokes not reported) were associated with multiple-attachment events. The 71 strokes were associated with a total of 28 flashes. MERLIN reported 21 flashes, providing a flash DE of 75%.

There were a total of 1760 unique strokes to ground captured by Jupiter OLS that passed the criteria for being

TABLE I
SUMMARY OF 2020 LIGHTNING STROKES THAT TERMINATED ON TALL STRUCTURES (LAUNCH COMPLEX LPS AND BUILDINGS).

Structure	# Strokes	Detected by MERLIN	MERLIN DE
LC-39B LPS	6	5	83.3%
LC-39A LPS	18	12	66.7%
LC-39A Water Tower	1	1	100%
LC-41 LPS	6	6	100%
LC-40 LPS	5	2	40%
LC-37 LPS	11	6	54.5%
LC-40 Tower	3	3	100%
Tower 0110	1	1	100%
SMARF	5	0	0%
VAB	4	3	75%
VIF	9	7	77.8%
LC-36 Crane	2	1	50%
Totals	**71**	**47**	**66.2%**

included in the dataset (well-resolved, unambiguous ground termination, not a strike to a tall structure). Note that more than half of the strokes were imaged by at least two cameras, with many strokes imaged by multiple cameras. MERLIN reported 1356 of these strokes, for a DE of 77.04%. There were 70 strokes within the dataset that could be classified as nearly simultaneous ground attachments. If these cases are removed, the MERLIN DE is 80.23%. dE/dt data from the Jupiter TMS systems were utilized to verify the times and return stroke waveforms of the optical events imaged by Jupiter OLS.

Is the MERLIN DE for strikes to tall structures/catenary wire systems statistically significantly different than the MERLIN DE for strikes to ground? In this case, we are comparing two population proportions. A z-score test can be used to determine if two population proportions differ significantly. The null hypothesis, H_0 is that the DE for strikes to tall structures is equal to the DE for strikes to ground. The alternative hypothesis H_1 is that DE for strikes to ground is greater than the DE for strikes to tall structures (right-tailed z-score test). We first calculate the z-score, based on the standard normal distribution and a significance level α = 0.05, using (1)

$$Z = \frac{(P_1 - P_2)}{\sqrt{(P \cdot (1-P) \cdot (\frac{1}{N_1} + \frac{1}{N_2}))}} \quad (1)$$

where:
P_1 = Proportion for strikes to ground ($\frac{1356}{1760}$)
P_2 = Proportion for strikes to tall structures ($\frac{47}{71}$)
P = Overall sample proportion ($\frac{(47+1356)}{(71+1760)}$)
N_1 = Sample 1 size (1760)
N_2 = Sample 2 size (71)
Z = 2.117

After the z-score test statistic is determined, we can determine the corresponding p-value from a standard z-table.
p = 1 – 0.983 = .0171

The calculated p-value (.0171), which is less than the the signficance level (α = 0.05) suggests that the MERLIN DE difference for strikes to flat ground vs. strikes to tall structures is, in fact, statistically significant for the 2020 dataset.

V. 2021 DATA ANALYSES

In 2021, lightning data were acquired from March 6 through October 28. Note that OLS #6 (Fig .1), which had been located south of the VAB during 2020 and most of 2021, was re-located to view Blue Origin's SLC-36 during late July of 2021. The SLC-36 lightning protection system is the tallest structure at KSC/CCSFS, with two towers and a catenary wire system reaching about 620 ft above ground level. During 2021, there were a total of 58 return strokes imaged that directly impacted tall structures. A breakdown of the strokes is provided in Tab. 2. There were 50 strokes to catenary wire systems, 8 strokes to tall buildings, and 0 strokes to towers. MERLIN reported a total of 52 strokes, providing an overall stroke DE for strikes to tall structures of 89.7%. The DE's for strokes to launch pad catenary wire systems and buildings were 90% and 87.5%, respectively.

One of the 58 strokes was positive polarity while the remaining strokes were negative polarity. MERLIN did not report the single positive polarity return stroke. Only one of the strokes to tall structures not reported by MERLIN (16.6% of the total number of strokes not reported) was associated with a multiple-attachment event. The 58 strokes were associated with a total of 24 flashes. MERLIN reported 22 flashes, providing a flash DE of 91.7%.

TABLE II
SUMMARY OF 2021 LIGHTNING STROKES THAT TERMINATED ON TALL STRUCTURES (LAUNCH COMPLEX LPS AND BUILDINGS).

Structure	# Strokes	Detected by MERLIN	MERLIN DE
LC-39B LPS	28	26	92.9%
LC-39A LPS	8	7	87.5%
LC-41 LPS	3	3	100%
LC-40 LPS	2	2	100%
LC-37 LPS	5	3	60%
SMARF	5	5	100%
VAB	2	1	50%
VIF	1	1	100%
LC-36	4	4	100%
Totals	**58**	**52**	**89.7%**

There were a total of 1671 unique strokes to ground captured by Jupiter OLS that passed the criteria for being included in the dataset (same criteria as 2020). Note that more than half of the strokes were imaged by at least two cameras, with many strokes imaged by multiple cameras. MERLIN reported 1303 of these strokes, for a DE of 78%. There were 149 strokes within the dataset that could be classified as nearly simultaneous ground attachments (within a single high-speed video frame). If these cases are removed, the MERLIN DE is 82.3%.

The same hypothesis testing procedure (see (1)) was performed for the 2021 dataset with Z = -2.12 and p = .0168.

Similarly, this suggests that the MERLIN DE difference for strikes to flat ground vs. strikes to tall structures is statistically significant for the 2021 dataset.

VI. Comparison of 2021 & 2020 Datasets

The results of the 2021 and 2020 study periods for strokes to tall structures were notably different. During 2020, the MERLIN stroke DE for strikes to tall structures was 66.2% (47 strokes reported out of 71 strokes imaged) while in 2021, the MERLIN DE was significantly better at 89.7% (52 strokes reported out of 58 strokes imaged). With a relatively small dataset (129 total strokes), it is difficult to ascertain what factors may have influenced the increase in performance during 2021. Two points to consider when interpreting these preliminary results are the following.

1) During 2021, nearly half of the imaged strokes to tall structures impacted the LC-39B LPS (28 strokes out of 58 total). This is a disproportionate ratio compared to any single structure impacted during the 2020 campaign. If MERLIN's performance is influenced by geographical dependencies (the location of LC-39B within the network) or by the electromagnetic interaction of lightning with the LC-39B structure, the high percentage of strokes to one single structure may be affecting the overall DE (MERLIN reported 26 of the 28 strokes to LC-39B during 2021).

2) During 2021, there were only 8 strokes to tall buildings (DE = 87.5%) versus 18 strokes during 2020. During 2020, MERLIN exhibited the poorest DE (55.6%) for strokes to buildings versus strokes to catenary wire systems or towers.

While the MERLIN DE for strokes to tall structures was notably different during 2020 and 2021, the corresponding MERLIN DE for strokes to ground was remarkably similar. The 2020 dataset included 1760 unique strokes to ground with MERLIN reporting 1356 strokes (DE of 77.04%). During 2021, there were 1671 unique strokes to ground with MERLIN reporting 1303 strokes (DE = 78%). The corresponding statistical significance test results for both 2020 and 2021 (considered individually) yielded the same result- the MERLIN DE difference for strikes to flat ground vs. strikes to tall structures is statistically significant. During 2020, the MERLIN DE for ground strokes was higher than for strokes to tall structures, while during 2021, the DE for strokes to ground was lower than for strokes to tall structures.

If we consider the cumulative MERLIN DE for strokes to tall structures versus strokes to ground (combining the 2020 and 2021 datasets), the results are the following (performing the statistical significance test on the cumulative dataset).

MERLIN DE (Strokes to Tall Structures) = 76.7%
MERLIN DE (Strokes to Ground) = 77.5%
Z = 0.201
p = 0.420

Based on the cumulative 2020/2021 dataset, the statistical significance tests suggests that the MERLIN DE difference for strikes to flat ground versus strikes to tall structures is not statistically significant, in contrast to the results when the datasets are analyzed individually.

VII. Conclusion & Additional Comments

The MERLIN DE for strokes to ground was nearly identical for the 2020 (N = 1760, DE = 77%) and 2021 (N = 1671, DE = 78%) datasets. The consistency of the results (for a large set of ground-truth strokes, N = 3431) provides strong evidence that the MERLIN DE is, in fact, about 77-78% for the current station configuration and operational algorithms. It is unknown if this performance is considered acceptable. Note that the MERLIN DE for strokes to ground during the initial performance evaluation in 2015/2016 [3] for 276 strokes was 93.5%. The method of data capture for the initial and present studies were identical (high-speed video and dE/dt sensors). The present study incorporates additional cameras and covers a larger percentage of the operational area at KSC/CCSFS.

Unlike the consistency of the MERLIN DE for strokes to ground, the MERLIN DE for strokes to tall structures differed notably between 2020 (N = 71, DE = 66.2%) and 2021 (N = 58, DE = 89.7%). In this case, the cumulative dataset (N = 129 strokes) is not sufficiently large to determine if the 2020/2021 variation is statistically significant. The 129 stroke dataset contained 126 negative polarity strokes and three positive polarity strokes. Notably, none of three positive polarity direct strokes to tall structures were reported by MERLIN. A third year of data collection for the present study is ongoing during Summer 2022.

Acknowledgment

The authors would like to thank William Roeder and Brian Cizek of the 45th Weather Squadron at Cape Canaveral Space Force Station for their support during this ongoing study and for providing the MERLIN data for the analyses presented in this paper.

References

[1] Roeder, W.P. and J.M. Saul, "Four Dimensional Lightning Surveillance System: Status and Plans", International Lightning Detection Conference, Broomfield, Colorado, April 2012.

[2] Roeder,William P. and Jon M. Saull,"The New Mesoscale Eastern Range Lightning Information System", Sensors, 10:9, 2016.

[3] Hill, J. D., C. T. Mata, A. Nag, and W. P. Roeder, "Evaluation of the performance characteristics of MERLIN and NLDN based on two years of ground-truth data from Kennedy Space Center/Cape Canaveral Air Force Station, Florida", 24th International Lightning Detection Conference & 6th International Lightning Meteorology Conference, 18-21 Apr 16, 11 pp.