The New Mesoscale Eastern Range Lightning Information System

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1. Introduction

The 45th Weather Squadron (45 WS) is the U.S. Air Force unit that provides weather support to America's space program at Cape Canaveral Air Force Station (CCAFS) and National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC). The weather requirements of the space program are very stringent (Harms et al., 1999). In addition, the weather in east central Florida is very complex. This is especially true of summer thunderstorms and associated hazards. Central Florida is 'Lightning Alley', the area of highest lightning activity in the U.S. (Holle et al., 2016). The 45 WS uses a dense network of various weather sensors to meet the space program requirements in this environment (Roeder et al., 2003).

The 45 WS is especially well instrumented with lightning detection sensors. The daily lightning reports issued by 45 WS (Roeder et al., 2005) requires high performance cloud-to-ground lightning locating. These reports are used to help assess the risk of induced current damage to electronics in satellite payloads, space launch vehicles, ground test equipment, and facilities (Flinn et al., 2010) (Flinn at al., 2010a). The reports include the location for each return stroke, location error ellipse, peak current, and other data. Other applications of the cloud-to-ground lightning locating (Roeder et al., 2005) include forecasting for lightning warnings (Weems et al., 2001) via continuity, incident investigation, development of forecast techniques, and climatology. In addition to the cloud-to-ground lightning system, the lightning aloft system is used to evaluate the Lightning Launch Commit Criteria (McNamara et al., 2010) to avoid triggered and natural lightning to the in-flight space launch vehicle, and to issue lightning warnings to gain lead-time over just cloud-to-ground lightning detection.

Other lightning systems used by 45 WS include the Launch Pad Lightning Warning System (LPLWS) (Eastern Range Instrumentation Handbook, 2016), a network of 31 surface electric field mills that has a limited total lightning detection capability. The 45 WS also has a direct connection to the National Lightning Detection Network (NLDN) that provides cloud-to-ground lightning locating across and surrounding the CONUS (Nag et al., 2016). Finally, the 45 WS has access to total lightning data, both lightning aloft and cloud-to-ground lightning, across the CONUS from the Earth Networks WeatherBug system (Heckman, 2013) (Heckman, 2011) via AFWEBS, the Air Force Weather website (weather.us.af.mil).

This paper presents an overview of the new Mesoscale Eastern Range Lightning Information Network (MERLIN) installed for use by 45 WS. MERLIN replaces the Four Dimensional Lightning Surveillance System (4DLSS) (Roeder, 2010) that has become unsustainable since the vendor no longer manufactures the sensors for maintenance (Roeder and Saul, 2012).

2. Overview of the Mesoscale Eastern Range Lightning Information Network (MERLIN)

2.1 MERLIN Overview and Local Sensors

The MERLIN system consists of ten total lightning sensors in and around CCAFS/KSC. The sensor type is the Total Lightning Sensor Model-200 (TLS-200) manufactured by Vaisala, Inc. (Vaisala, 2012), which is essentially a Vaisala cloud-to-ground LS-7001 sensor (Vaisala, 2009) and a Vaisala lightning aloft LS-8000 sensor (Vaisala, 2009) combined into one unit. A picture of a TLS-200 sensor is in Figure-1 and a map of the MERLIN sensor locations is in Figure-2. MERLIN system details and comparison with the 4DLSS are in Table-1.

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Figure 1. Picture of a TLS-200 sensor. This is the MERLIN North Patrick site on Patrick Air Force Base.

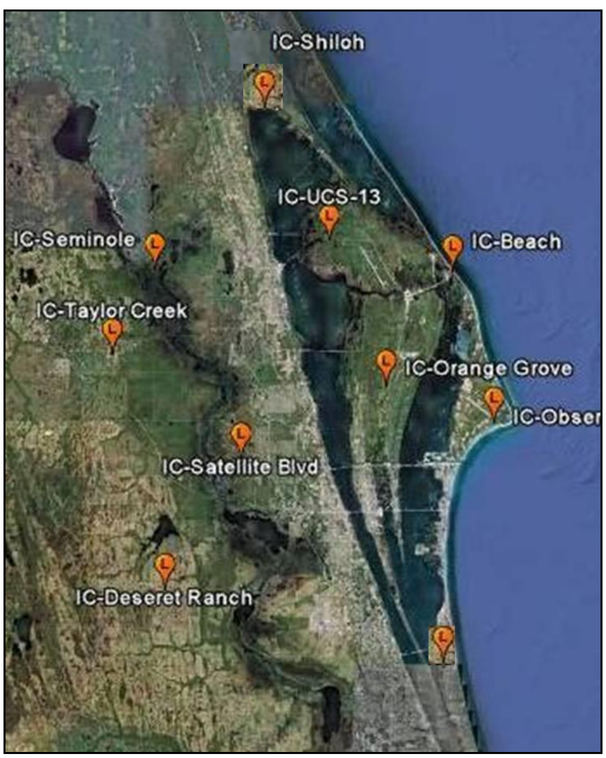

Figure 2. Location of the MERLIN sensors in and around CCAFS/KSC.

Table-1
MERLIN system details and comparison with 4DLSS, the system it is replacing. Items shaded in green indicate an advantage of that system over the other.

	MERLIN	4DLSS
Cloud-to-Ground		
Number of Local Sensors	10	6
Local Sensor Type	TLS-200	IMPACT
Number of NLDN Sensors	10	0
Typical Phenomena Detected	return stroke	return stroke
Detection Method	MDF/TOA	MDF/TOA
Frequency Band	LF/HF	LF
Reports	• location (x, y) • date/time • peak current • polarity • location error ellipse	• location (x, y) • date/time • peak current • polarity • location error ellipse
Processor Model	TLP	CP-8000
Processor Type	digital	analog
Lightning Aloft		
Number of Sensors	10	9
Sensor Type	TLS-200	LDAR-II
Typical Phenomena Detected	recoil leader	stepped leader
Detection Method	interferometry	TOA
Frequency Band	VHF	VHF
Reports	• 2D location projected on ground (x, y) • date/time	• 3D location (x, y, z) • date/time
Processor	TLP	CP-8000
Processor Type	digital	analog

2.2 Integration of In-Range NLDN Sensors

In addition to the ten local TLS-200 sensors, MERLIN also integrates ten LS-7002 (Vaisala, 2013) NLDN sensors that are close enough to provide cloud-to-ground lightning solutions in and around east central Florida including CCAFS/KSC. This makes MERLIN a hybrid local/regional lightning detection system. The NLDN sensor data are relayed to the MERLIN processor on CCAFS in real-time via a dedicated satellite link.

Using the more distant NLDN sensors does not significantly degrade the MERLIN cloud-to-ground lightning solutions. For example, in the Hill (2016) study, the location accuracy of MERLIN increased only 1 m with the NLDN data, well within the margins of statistical noise. The key is that the raw sensor data from those NLDN sensors (not the lightning solutions) are integrated with the local MERLIN sensors so that the MERLIN processor creates an individual best solution for each individual return stroke solution, i.e. to MERLIN, the integrated NLDN sensors look like part of the MERLIN network, just located farther away. As a result, if most of the local MERLIN sensors are participating with high quality in the stroke solution, the NLDN sensors will have less influence on the final solution. Conversely, if the local MERLIN sensors are not participating well in the solution, the NLDN sensors will have more influence. A map of the NLDN sensors integrated into MERLIN is in Figure-3. Unfortunately, the lightning aloft data from the NLDN sensors are not consistent with the MERLIN TLS-200 sensors and cannot be integrated into MERLIN.

Integrating the in-range NLDN sensors into MERLIN provides several benefits. First, it extends the range of MERLIN for cloud-to-ground lightning. Without integrating NLDN sensors, the detection efficiency of MERLIN begins to decrease significantly beyond 50 nautical miles (nmi), becoming near 0% beyond 100 nmi. However, with the integration of NLDN sensor data, MERLIN's detection efficiency decays with distance to the performance of NLDN, i.e. a detection efficiency of 95% vs. 0% (Hill et al., 2016). This increased range helps improve the evaluation of Lightning Launch Commit Criteria by 45 WS, especially for anvil clouds from persistent thunderstorms in the Gulf of Mexico and for missions in the near Atlantic Ocean. The Lightning Launch Commit Criteria are the weather rules to avoid a rocket-triggered and natural lightning strike to in-flight rockets. A second advantage of the NLDN integration is more robust performance inside the network if the local MERLIN sensors are not participating in the lightning solutions such as from maintenance issues or communication outages. As local sensors are lost, the cloud-to-ground performance of MERLIN decays to that of NLDN rather than zero.

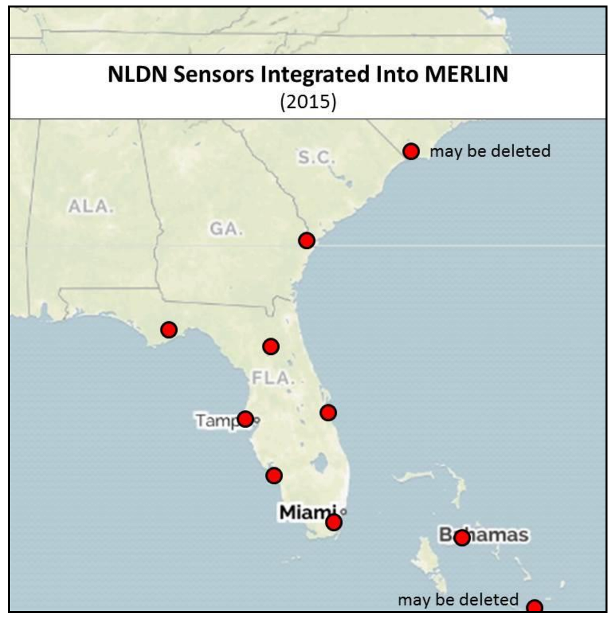

Figure 3. Location of the in-range NLDN sensors integrated into MERLIN for cloud-to-ground return stroke solutions.

3. Performance of MERLIN

MERLIN provides many benefits over 4DLSS. Those benefits are from more sensors, newer model of sensors, and a new central processor with digital signal processing and better algorithms. The integration of the ten NLDN sensors also provides more robust cloud-to-ground performance in and near the MERLIN local network, i.e. less degradation or performance if the same number of local sensors are not participating in the lightning solutions. The NLDN integration also improves MERLIN performance at long distances.

3.1 Cloud-to-Ground Lightning Performance of MERLIN

The performance of MERLIN's cloud-to-ground lightning was measured with the Accurate Lightning Location System (Mata et al., 2010), a high-performance short-range lightning detection system at KSC, with a return stroke detection efficiency of 100% and location accuracy of 10 m. Ground truth consisted of 321 return strokes measured from May-October 2015. The performance of 4DLSS using the same data was also done for comparison purposes. The performance of NLDN was also measured on the same data, but those results are not shown here (Hill et al., 2016). During this time, only nine of the ten local sensors in MERLIN were operational; the Satellite Boulevard sensor was not yet operating. The inclusion of the Satellite Blvd sensors is expected to provide a slight performance increase to MERLIN over CCAFS/KSC where the performance was evaluated. The Satellite Blvd sensor does provide better performance to the south of the MERLIN network including Patrick AFB and increases robust performance everywhere due to missing sensors because of communication outages, sensor outages, quality control filtering, etc. The performance of MERLIN and comparison with 4DLSS is in Table-2 (Hill and Mata, 2016) (Hill et al., 2016). Because one of the local MERLIN sensors was not installed at that time, and because the NLDN integration was excluded, these results are a lower limit on the real performance of MERLIN.

The sensors have excellent network geometry for lightning detection on CCAFS/KSC. The local MERLIN sensors can be considered two nested sub-networks. The four sensors on CCAFS/KSC can provide the best location accuracy on lightning strikes on CCAFS/KSC, especially in and around the launch pads and other key facilities. However, those same interior sensors are more likely to have missed detections from strong strokes to those locations and thus do not contribute to a high detection efficiency. The six sensors surrounding CCAFS/KSC are far enough away so that high current lightning strikes to those key facilities would not cause missed detections—thus those outlying sensors provide high detection efficiency and slightly lower location accuracy than the interior sensors.

Table-2

MERLIN performance for cloud-to-ground lightning and comparison with 4DLSS. All figures are for near the center of the network and should be representative across CCAFS/KSC. Items shaded in green indicate an advantage of that system over the other. One of the ten local MERLIN sensors was not installed for this analysis and the NLDN integration was excluded.

Cloud-to-Ground Lightning	MERLIN	4DLSS
Stroke Detection Efficiency	92%	82%
Flash Detection Efficiency	99.6%	96%
Location Accuracy	58 m	350 m
Peak Current	±10%	±20%
Polarity Identification	100% correct	100% correct
CG/CC Identification	95%	95%
Median Location Error Ellipses Contain X% of strokes (50% = perfect) * misleading due to 100m reporting increment in TLP	92%*	26%
False Detections	0%	0%

The TLP processor (Vaisala, 2015) has digital signal processing that allows several algorithmic improvements over the analog CP-8000 processor (Vaisala, 2004) in 4DLSS. The first improvement is tracking the time-of-arrival using the fastest rise-time in the waveform of the return stroke. This is more accurate than tracking the time of the maximum of the waveform, as done in 4DLSS. In the past, time-of-arrival did not contribute much to return stroke solutions over CCAFS/KSC from 4DLSS due to relatively large timing errors as compared to the direction-finding solutions over such short distances. The direction-finding errors increase much faster than the timing errors with range and so time-of-arrival is important for long range lightning solutions. However, that is less important to the primary application of lightning detection of 45 WS that emphasizes high performance detection over the short ranges to CCAFS/KSC. Even though the time-of-arrival solutions did not contribute much to location accuracy in 4DLSS, they did help with detection efficiency. However, the timing errors of the TLP processor are now so small so that time-of-arrival contributes as much to lightning solutions on CCAFS/KSC as direction-finding. This contributes to more robust location accuracy for MERLIN as compared to 4DLSS since there are up to 20 high quality inputs for lightning location (time-of-arrival and direction-finding from each of 10 sensors), as compared to up to just 6 high quality inputs from 4DLSS (mostly just direction finding from 6 sensors).

Another algorithmic gain from the TLP processor is additional return stroke waveforms that can be recognized as lightning. This should help reduce missed detections from strong local strokes. 4DLSS misses about 5% of return strokes from this problem (Sun and Roeder, 2015). While this is often referred to as a saturation from strong local strokes, the real cause is a more complex waveform from approaching stepped leaders being strong enough to generate signals that appear to be return strokes. The multiple timings from these signals leads to the quality control algorithms rejecting the event as a return stroke. The improved processing of the TLP helps identify more of these complex waveforms as real lightning.

Another problem 4DLSS had was lower detection efficiency for return strokes from tall structures. The faster rise times of those waveforms would sometimes be disqualified as lightning by the 4DLSS processor QC algorithms. This can be especially bothersome for 45 WS since launch pads and other key facilities at CCAFS/KSC are tall structures; 4DLSS had lower detection efficiency for some of the most important lightning strikes to space launch customers. The MERLIN processor is anticipated to mostly overcome this shortfall. However, preliminary evidence suggests this remains a problem (Hill and Mata, 2016) (Hill et al., 2016). This issue requires further investigation to either verify if the problem continues or pursue a solution.

3.2 Lightning Aloft Performance of MERLIN

The performance of MERLIN for lightning aloft was measured using 4DLSS for comparison (Cummins, 2015). The performance was measured from 20 Aug-15 Sep 2015. At that time, only 9 of the 10 MERLIN sensors were installed. The additional tenth MERLIN sensor will likely only provide slight gain in detection efficiency and location accuracy compared to these results, except to the southeast of the network, including Patrick AFB. The biggest gain will be more robust performance; the performance will degrade less to a sensor not participating in the lightning solutions. The lightning aloft data from both MERLIN and 4DLSS were also compared with weather radar as a crosscheck for reasonable lightning solutions. The lightning aloft performance of MERLIN is listed in Table-3.

Table-3

MERLIN performance for lightning aloft and comparison with 4DLSS. The figures are for inside the MERLIN network and should be representative across CCAFS/KSC. Items shaded in green indicate an advantage of that system over the other.

Lightning Aloft	MERLIN	4DLSS
Events Detected - MERLIN: recoil streamers, dart leaders - 4DLSS: stepped leaders	80% estimated	70%
Flash Detection Efficiency	100%	100%
Location Accuracy * not comparable since detecting different phenomena of very different sizes	500 m*	100 m*
False Detections	0%	Rare (and easily identified)

It is difficult to directly compare the performance of lightning aloft solutions from MERLIN and 4DLSS since they detect very different parts of the lightning flash, primarily recoil streamers and dart leaders, and stepped leaders, respectively. The recoil streamer and dart leader are much larger than stepped leaders. Therefore, an operationally based approach was chosen. Two metrics were used: 1) performance of lightning warnings that would have been issued and 2) relative storm area and flash extent.

3.2.1 Simulated Lightning Warnings

The same method was used to simulate lightning warnings for 139 warnings from the ten most active thunderstorms in the area from 20 Aug-15 Sep 2015. Five of the ten 5 nmi lightning warning circles on CCAFS/KSC and Patrick AFB were used to reduce overlap and measure the performance over as much of CCAFS/KSC as possible.

There was little difference in the warnings that would have resulted from the lightning aloft data from MERLIN and from 4DLSS. Only 1.4% of the warnings “issued” by 4DLSS were missed by MERLIN. However, 3.6% of warnings “issued” by MERLIN were missed by 4DLSS. This suggests that MERLIN is safer than 4DLSS for lightning warnings.

The start times of the simulated warnings were also considered—38.1% of the warnings started within 2 min of each other. Many of the disagreements were due to suspect 4DLSS data, e.g. apparent noisy solutions with just a few 4DLSS lightning aloft solutions displaced far from the other lightning data. In addition, the improved tuning of the grid filter in MERLIN was applied partway through the study. This helps eliminates noisy MERLIN solutions while improving the horizontal extent of the lightning aloft. Considering the change in performance after the grid filter was applied, 52.5% of the warnings would have occurred within 2 min of each other.

Allowing for suspect 4DLSS solutions and misses that were close in space and/or time, especially just outside the edge of the lightning circle, the overall conclusion is that MERLIN lightning aloft solutions are at least as good if not better than 4DLSS for lightning warnings.

3.2.1 Relative Storm Area and Flash Extent

The second approach to verifying MERLIN’s lightning aloft was to place both the MERLIN and 4DLSS lightning aloft into 1 km boxes for 2 sec periods and analyze the areas of overlap and disagreement. The overall conclusion was the same as for the simulated lightning warnings: allowing for suspect 4DLSS solutions and differences that were close in space and/or time, and the retuned grid filter applied to MERLIN partway through the analysis, the MERLIN lightning aloft solutions are at least as good if not better than 4DLSS. One exception may be that 4DLSS seems to detect slightly more horizontal extent of long horizontal flashes than MERLIN.

3.2.3 Other Comments on MERLIN Lightning Aloft

Inside the MERLIN network, MERLIN provided 30% more solutions than 4DLSS for the same lightning aloft flash. At about 30 nmi from the network, MERLIN and 4DLSS provided a similar number of lighting aloft solutions for the same flash. Beyond about 30 nmi, 4DLSS provided ever increasing number of lightning aloft solutions. Since previous analysis showed that 4DLSS (then the Lightning Detection And Ranging system) detected 70% of stepped leaders using radio generators on aircraft (Maier et al., 1995), the 30% gain of MERLIN for event detections suggests that MERLIN has a detection rate of 80% for recoil streamers and dart leaders, its detected events.

The Cummins (2015) analysis was done after the grid filter in MERLIN was retuned. After the initial installation of MERLIN, 45 WS noticed that the horizontal extent of lightning aloft was not being fully depicted, especially for long horizontal branches of lightning aloft, such as anvil lightning. This is important to 45 WS operations since long horizontal branches of lightning can suddenly bring lightning inside the 10 nmi threshold for the Lightning Launch Commit Criteria and also inside the 5 nmi lightning warning circles. If the full horizontal extent of lightning aloft is not depicted, rocket launches, personnel safety, and resources could be endangered unknowingly. Fortunately, 45 WS detected the problem and worked with Dr. Cummins and Vaisala to tune the grid filter to improve the detection of valid long horizontal branches of lightning aloft without misidentifying too many real events as outliers and inadvertently filtering out those valid solutions.

One of the shortfalls of 4DLSS lightning aloft is that radio noise can sometimes lead to false solutions. The main source of these false solutions is strong nocturnal inversions, when ducting brings in more radio noise. Fortunately. The false solutions are easily recognized since real lightning does not occur under those conditions in central Florida and the pattern of the false solutions look very different from real lightning. Another source of false solutions under very high flash rates where so many signals from so many lightning flashes are crisscrossing the network and producing false solutions by sheer coincidence. This type of false solution is more difficult to detect since they appear as extra flashes among the real lightning though with more radial error, i.e. it appears as slight radial smearing of the real lightning.

After 3 years of anecdotal observation, these sources of false solutions have not been seen even though 4DLSS showed false solutions several times. Apparently the radio noise that gives false solutions by 4DLSS is not strong enough to meet the signal strength thresholds of the MERLIN sensors since 4DLSS detects stepped leaders, which have much weaker radio pulses than the recoil streamers detected by MERLIN. Likewise, because a recoil streamer is made up of many stepped leaders, there should be fewer signals from recoil streamers than stepped leaders from the same flash, thus reducing the chance of coincidental false solutions.

4. Possible Future Improvements to MERLIN

4.1 Within 1-Year of MERLIN Acceptance

The following improvements should be achievable within the first year accepting MERLIN.

4.1.1 Add LS-7001 at Melbourne Airport

The 45th Space Wing has three cloud-to-ground LS-7001 sensors manufactured by Vaisala. These were purchased as replacements/enhancements for the original IMPACT sensors when 4DLSS was having maintenance problems and running out of these older sensors. One LS-7001 sensors was installed at Melbourne Airport as part of 4DLSS. The other two are spares for maintenance.

These LS-7001 sensors were no longer needed for MERLIN. However, the Melbourne Airport site could not be used by MERLIN since the TLS-200 sensor is much taller than the LS-7001 sensor and violated flight safety at that location. Therefore, the 45 WS wants to integrate the LS-7001 sensor already at Melbourne Airport into MERLIN. This will improve cloud-to-ground lightning detection especially on the south side of MERLIN including Patrick AFB and avoid losing the investment in the three LS-7001 sensors already purchased. Since the MERLIN TLP processor can easily handle the additional sensor and the communication path to the TLP already exists, the integration of the LS-7001 sensor at Melbourne airport should be achievable within 1-year of the installation of MERLIN.

4.1.2 Annual NPEPs

Vaisala offers the Network Performance Evaluation Program (NPEP) (Vaisala, 2010). This program optimizes the performance of lightning detection networks by changing configurable settings to minimize errors on many lightning strikes across the range of the network. Vaisala recommends an NPEP be conducted every 18 months on mature networks. However, 45 WS plans on annual NPEPs for MERLIN. This is due to three main reasons: 1) the very high frequency of lightning at CCAFS/KSC, 2) the large impact lightning has on preparation for space launch, and 3) the profound annual periodicity of lightning activity at CCAFS/KSC. The annual NPEP for MERLIN would best be done just before the start of the lightning season that usually begins in late May or as early in the lighting season as possible.

4.1.3 Update the LS-7001 sensors to LS-7002

As discussed in 4.1.1, 4DLSS has three LS-7001 sensors, one installed at Melbourne Airport and two as maintenance spares. These sensors can be upgraded to LS-7002 sensors with a relatively simple software update. This would improve the cloud-to-ground detection performance of this sensor through by accessing the advantages of the digital signal processing discussed previously. This upgrade should be done on all three of the 4DLSS LS-7001 sensors so there is no change in performance as the sensors are replaced during maintenance.

4.1.4 Maintenance Status Guide

The 45th Space Wing uses three tiers of system statuses to help set maintenance priorities. The three tiers are: 1) Fully Mission Capable (FMC), 2) Partially Mission Capable (PMC), and 3) Not Mission Capable (NMC). FMC means the system is at or near its full capability and fully satisfies mission requirements. PMC means the system is moderately degraded but can still be used to partly meet mission requirements. NMC means the system is significantly degraded and the performance is significantly below that needed for mission requirements.

For MERLIN, the system status should be set by the detection efficiency at the launch pads as a function of which sensors are operating. The mission requirement is a detection efficiency of 96% for cloud-to-ground flashes, which leads to criteria in Table-3. The 45 WS needs a guideline that gives detection efficiency vs. operating MERLIN sensors using the Vaisala performance model. A guideline based on some Vaisala modeling and professional judgement was developed. However, a guideline based on complete modeling will be more accurate and reduce overly cautious maintenance statuses and associated higher costs. The maintenance status process for lightning aloft is not discussed here.

Table-3

System status criteria for MERLIN.

Cloud-to-Ground Lightning Flash Detection Efficiency	System Status
Fully Mission Capable (FMC)	≥ 98%
Partially Mission Capable (PMC)	≥ 96% to < 98%
Not Mission Capable (NMC)	< 96%

4.1.5 Evaluate MERLIN Performance with Distance

The performance of MERLIN with distance is not well documented. The performance vs. distance for CG lightning could be created from the Vaisala performance model. The performance vs. distance for lightning aloft was partly analyzed by Cummins (2015) and showed that MERLIN detects more lightning aloft events than 4DLSS within about 30 nmi of the network but less than 4DLSS beyond that distance. However, the details of how that performance decays with distance is not known. This is important since 45 WS needs to detect lightning in attached anvil clouds through which the rockets will launch to evaluate the Lightning Launch Commit Criteria (McNamara et al., 2010), regardless of the distance to the parent thunderstorms. This mostly applies when there are long distance attached anvil clouds over CCAFS/KSC from parent thunderstorms in the eastern Gulf of Mexico.

The 45 WS would like a study of MERLIN performance vs. distance, especially for anvil lightning. This could be done using past satellite detectors of lightning such as Lightning Imaging Sensor on the TRMM and the upcoming Geostationary Lightning Mapper (GLM) sensor on GOES-R.

The 45 WS also to confirm how well GLM detects anvil lightning since that could serve as a good alternate to MERLIN for long distance attached anvil lightning. This could be done as part of the above study by using MERLIN reports of anvil lightning inside the MERLIN network to verify GLM. The performance of GLM would be assumed to be the same within a few hundred miles of CCAFS/KSC, which meets the distance for anvil clouds to occur over CCAFS/KSC.

4.1.6 Evaluate Benefit of NLDN Integration

As discussed in section-2.2, MERLIN integrates the raw sensor observations (not the lightning solutions) for cloud-to-ground lightning from the ten in-range NLDN sensors. However, there is a financial cost in leasing that NLDN data. An analysis should be done to assess the benefit of the NLDN integration to determine if it is cost-effective. We suspect the NLDN integration will be worthwhile just by providing more consistent cloud-to-ground lightning detection with long distances, let alone increased robust solutions inside and near the MERLIN network if local MERLIN sensors or communications fail, let alone possible increased detection of strokes to tall structures.

4.2 Within 1-5 Years of MERLIN Acceptance

The 45 WS will take steps to toward the following improvements within 1-5 years of accepting MERLIN.

4.2.1 Upgrade TLP software to 10 m location reporting increment

The current TLP software has an internal location reporting increment of 100 m for cloud-to-ground lightning. This degrades the ultimate location accuracy of MERLIN and makes its location error ellipses contain a higher percentage of return strokes than expected, e.g. the MERLIN 50% location error ellipse contains 92% of the return strokes (Hill and Mata, 2016) (Hill et al., 2016). The 100 m location reporting increment is likely a holdover from many years ago in the Vaisala lightning detection process when a 100 m location increment was much smaller than the capability of the system and was a reasonable choice at that time. Vaisala is upgrading the TLP software to a 10 m location reporting increment (Cook, 2016). Once that TLP upgrade is available, 45 WS wants to implement that upgrade and retest the location accuracy and location error ellipses of MERLIN.

4.2.2 Extend Verification of MERLIN

The cloud-to-ground performance of MERLIN has been well verified (Hill et al., 2016), but should be extended, especially after the new TLP software with 10 m location increment is implemented, as discussed in section 4.2.1. In particular, the 45 WS wants to verify that the problem with the overly conservative error ellipses is corrected by the new software.

In addition, the Hill et al. (2016) study suggested that MERLIN did not improve the problem of lower detection efficiency of strokes from tall structures as much as expected. MERLIN had a detection efficiency of 84.4% based on 45 strokes from tall structures compared to 97.8% for NLDN on the same strokes. The difference could have been an artifact of the small sample size. Therefore, efforts should also be made to increase the sample size with additional study.

The study showed that MERLIN has relatively large location errors for strokes very near the Vehicle Assembly Building (VAB) on KSC. In addition, the strokes near the VAB contributed disproportionately to non-Gaussian distribution of the location error ellipses. In addition, the strokes near the VAB were disproportionately among the outliers rejected from the analysis. Interestingly, the strokes near the Mobile Launch Platform did not have the problems. The Mobile Launch Platform is nearly as tall as the VAB but is much narrower. This suggests the problem is not the geographical location, but the VAB itself. There is speculation that the problem with the VAB may be its relative broad profile. Perhaps the waveforms from return strokes from such a tall broad structure are different from tall narrow structures and are being rejected by the QC algorithms in MERLIN. Another possibility is that perhaps the VAB construction makes it act as a secondary radiator during return strokes. If so, a modification of the allowable waveforms in the

TLP would alleviate this problem. The poor quality stroke solutions from strokes from the VAB deserve further research.

Finally, Hill et al. (2016) did not consider the Chi^2 correction factor developed by Cummins (2011) where the size of the location error ellipse is sometimes increased based on the value of the CHI^2 quality metric for the stroke solution. Documenting the value added of this approach should be done to justify using it in the 45 WS daily lightning reports.

4.2.3 Upgrade NLDN Palm Bay, FL to TLS-200

The MERLIN network is heavily dependent on the Satellite Boulevard sensor for detection of lightning aloft to the south of the network, which includes Patrick AFB (Cummins, 2015). Therefore, at least one more sensor located to improve detection efficiency over Patrick AFB is desired. One way to achieve that goal is to upgrade the NLDN sensor at Palm Bay, FL to a TLS-200. Unfortunately, Vaisala did not embrace this idea, understandably preferring to have consistent sensors throughout NLDN.

4.2.4 Add 1-4 Additional Sensors to MERLIN

Although MERLIN already has excellent performance, another 1-4 local sensors could improve performance even further. At present the only local sensor providing a look angle from the north is the Shilo sensor. The first sensor might be sited on the barrier island about 7-13 nmi north-northeast of Launch Pad 39A/B and would provide another look angle from the north for improved robustness. The second sensor might be placed near the south end of the Shuttle Landing Facility and near the bank of the Indian River to provide the opportunity for improved location accuracy near the launch pads by filling in the largest gap in look angles among the four MERLIN sensors on CCAFS/KSC. Likewise, a third sensor near the Port (or east end of Kennedy Causeway if the Port has too much radio noise) would help improve location accuracy near the launch pads. However, given the excellent location already provided by MERLIN, adding these two sensors may not be cost effective. Finally, a fourth sensor near Viera, FL would improve detection efficiency and provide another look angle from the southwest to CCAFS/KSC and improve MERLIN's performance over Patrick AFB. This last sensor may not be needed if the NLDN sensor at Palm Bay, FL is upgraded to a TLS-200 as discussed in section 4.2.2.

4.3 Long-range (beyond 5 years) possible improvements to MERLIN

The 45 WS hopes research will continue to work towards achieving the following improvements beyond 5 years of accepting MERLIN.

4.3.1 Recover Height Capability

One of the few shortfalls of MERLIN as compared to 4DLSS was the loss of height for lightning aloft. The 45 WS would like to recover that capability. Vaisala and 45 WS have both proposed software changes to MERLIN to add height for lightning aloft. Presumably adding another set of VHF antenna to MERLIN except with horizontal rather than vertical orientation could also add this capability, albeit at high cost. Finally, using other sensors have been discussed, such as a Lightning Mapper Array for lightning aloft and using MERLIN for cloud-to-ground lightning. Unfortunately, there appears to be little interest in detecting the height of lightning aloft by other customers of Vaisala and so they understandably have little incentive in pursuing this capability.

4.3.2 Improved Peak Current Error

The following improvements may be possible in MERLIN in the far future (beyond 5 years). Some of these improvements will require significant research to achieve.

Improved measurements of peak current are needed. Peak current is important to the 45 WS since the primary application of MERLIN is helping the launch customers assess the likelihood of induced current damage from nearby CG lightning. The key lightning parameters are location (distance to facility), peak current, and size of the location error ellipse (Flinn et al., 2010) (Flinn et al., 2010a).

Considerable effort has been made over the years to improve detection efficiency, location accuracy, and discriminating between CG lightning and lightning aloft. Two recent examples are the 2013 upgrades to NLDN (Nag et al., 2016) and GLD360 (Said and Murphy, 2016). However, not nearly as much effort has been dedicated to improving the measurement of peak current. The same regression equation has been used for many years. This regression equation takes the mean peak magnetic field observed at all the sensors after correction for ground propagation effects and normalized to 100 km and converts it to peak current (Cummins et al., 1998). This regression equation was based primarily on data from rocket-triggered lightning. As a result, first stroke data is excluded since these first strokes behave differently than in natural lightning due to the preexisting conducting path. This is important to operations since the first stroke in a flash tends to have the highest peak current. Thus, the first stroke can generally cause more induced current damage at the same distance or the same induced current damage at farther distances than subsequent return strokes.

Perhaps the best way to improve peak current estimates is to create a new regression equation based on observations of natural lightning. Unfortunately, there have been few direct peak current measurements of natural lightning. There may be ways to improve the attenuation-corrected range-normalized regression equation used at present. For example, using an average peak magnetic field weighted by distance to the stroke for each sensor, rather than a simple mean, may yield some performance improvement. Sensors farther from the stroke would receive less weight in the distance weighted average. Correction for attenuation from ground affects would still be applied.

Another possible improvement could be separate regression equations based on stroke polarity. Likewise, different regression equations for varying peak current should also be considered, e.g. perhaps an iterative process where the regression coefficients are modified based on the peak current from the previous iteration, or a simpler approach of stratified regression equations for weak, moderate, and strong peak current.

Finally, entirely new approaches should be explored to avoid the additional uncertainties introduced by the range-normalization and the regression equation.

4.3.3 Improved Peak Current Error

Just as measurements of peak current, the peak current error need improvement. Some of the 45 WS customers increase the reported peak current error by the expected error to provide a conservative assessment of the risk of induced current damage. The 45 WS would like to have peak current error tailored to each return stroke, as is done of location accuracy. One approach might be use the distribution of peak currents estimated for each sensor in 4.3.1, e.g. the standard deviation of the individual sensor peak currents might be used, such as $\pm 1.96\sigma_{mean}$ as a 95% confidence interval about the mean. Or if the distribution of peak currents tend not to be Gaussian, a percentile approach might be used, such as an interquartile range for a 50% confidence interval about the median.

4.3.4 *Use of Electric Current Rise Times*

One of the main purposes of MERLIN is to help the space launch customers assess the risk from nearby return strokes of induced current damage in the electronics of satellite payloads, space launch vehicle, ground test equipment, and other key facilities. The primary factors are the distance and peak current to the return stroke. However, since electrical induction is the main mechanism, the rise time of the peak current of the return stroke should be used, rather than the peak current itself. The TLS-200 sensors used in MERLIN can detect the rise time over a short range. However, the performance of this capability has not been well documented. Research needs to be done to document the performance of the TLS-200 and improving that capability if needed, especially its range. Once the rise time capability becomes sufficient for operational use, the space launch customers would need to set new thresholds for using those rise times to decide when to conduct inspections to test electronic systems for induced current damage. Or other rise time sensors separate from MERLIN and collocated with the key systems may more cost effective.

4.3.5 Recoil Streamer Signal Generator

Verifying MERLIN lightning aloft is difficult given the lack of appropriate ground truth. Other lightning aloft detectors tend to detect stepped leaders, which are much smaller than the recoil streamers detected by MERLIN. What is needed is a recoil streamer generator that matches the strength and waveform of a recoil streamer than can be flown on an aircraft with no lightning in the area to unambiguously determine the precise location and time at which a recoil streamer solution is expected. This sort of ground truth would allow precise testing of the lightning aloft including location, accuracy, detection efficiency, and false alarm rate.

5. Summary

The Mesoscale Eastern Range Lightning Information Network (MERLIN) is replacing the Four Dimensional Lightning Surveillance System (4DLSS) as the primary lightning detection system at CCAFS/KSC. The main reason for the replacement is that 4DLSS has become unsustainable since those sensors are no longer being manufactured.

MERLIN uses 10 new total lightning sensors, as compared to 6 legacy CG lightning and 9 legacy lightning aloft sensors in 4DLSS. In addition to the 10 local total lightning sensors, MERLIN integrates the 10 in-range NLDN sensors. The raw sensor observations (not the NLDN lightning solutions) are combined with the local MERLIN sensors by the MERLIN central processor to create the best overall CG lightning solution. Therefore, MERLIN is actually a hybrid local/regional lightning detection network. The NLDN lightning aloft data is not compatible with the MERLIN lighting aloft data and so is not integrated into MERLIN.

MERLIN also provides several performance improvements over 4DLSS. For cloud-to-ground lightning, MERLIN provides better detection efficiency and much better location accuracy than 4DLSS, i.e. a median location accuracy of 58 m vs. 350 m. In addition to more and higher quality sensors as compared to 4DLSS, the digital signal processing of MERLIN's central processor also provides several performance gains for cloud-to-ground lightning. The timing errors are now comparable to the magnetic direction finding errors and so contribute as much to the CG stroke solutions. This makes the performance of MERLIN more robust to lost sensors, such as from communication outages. The digital signal processing also allows more waveforms to represent more diverse types of lightning. As a result, MERLIN should have fewer missed detections of lightning to tall structures and from strong local strokes. However, preliminary results indicate the missed detections of CG strokes from tall structures still persists, though the sample size is small and more study is needed.

The lightning aloft part of MERLIN provides about 30% more detections within about 30 nmi of the center of the network as compared to 4DLSS. The area extent of the MERLIN lightning aloft solutions are similar to 4DLSS within that same distance. However, the detection efficiency of MERLIN rapidly drops below that of MERLIN beyond 30 nmi. The 45 WS is working with Vaisala to see if MERLIN's decay of detection efficiency for lightning efficiency can be improved. Another shortfall of MERLIN versus 4DLSS is the loss of the height of the lightning aloft.

MERLIN is an excellent improvement over 4DLSS, but there is still room for improvement. The most important short-term improvements are upgrading the central processing software to change the location reporting increment to 10 m, which should improve the location error ellipses being excessively large. At present, the median location error ellipses contain 92% of the return strokes while the expected value is 50% (Hill and Mata, 2016) (Hill et al, 2016).

6. Acknowledgements

This paper was reviewed by the following 45 WS personnel: Col Shannon, Commander; and Maj Josephson, Chief of Systems. This paper was also reviewed by Dr. Huddleston of the NASA Kennedy Space Center Weather Office and Dr. Cummins of the University of Arizona.

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