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Four Dimensional Lightning Surveillance System: Status and Plans

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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), National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC), and Patrick Air Force Base (PAFB). 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 their associated hazards. Central Florida is ‘Lightning Alley’, the area of highest lightning activity in the U.S. (Huffines and Orville, 1999). The 45 WS uses a dense network of various weather sensors to meet the operational requirements in this environment (Roeder et al., 2003).

The 45 WS is especially well instrumented with lightning detection sensors. The Four Dimensional Lightning Surveillance System (4DLSS) is the main lightning detection used by 45 WS. The 4DLSS detects both cloud to ground return strokes and lightning aloft step leaders and other lightning aloft mechanisms. This paper will discuss the status and plans for 4DLSS, as of early 2012.

Other lightning systems used by 45 WS include the Launch Pad Lightning Warning System (LPLWS) (Eastern Range Instrumentation Handbook, 2012), 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) (Orville et al., 2002).

2. Applications Of 4DLSS

The 45 WS uses 4DLSS for several applications in support of space launch operations at CCAFS/KSC. The lightning aloft data is critical to evaluating the Lightning Launch Commit Criteria, the weather rules to avoid natural and rocket triggered lightning strikes to in-flight space launch vehicles (McNamara et al., 2010) (Willet et al., 2010) (Merceret et al., 2010) (Krider et al., 2006) (Roeder and McNamara, 2006).

The lightning aloft data is also used to issue lightning watches and warnings at CCAFS/KSC and Patrick AFB (Weems et al., 2001) via continuity for approaching thunderstorms. It also provides a few minutes of lead-time for “last chance” warnings for cloud-to-ground lightning from locally developing thunderstorms that were not predicted by the 45 WS radar lightning forecast techniques or the other lightning prediction techniques (Roeder and McNamara, 2011) (Roeder and Pinder, 1998).

The cloud-to-ground lightning data allows the 45 WS space launch customers to assess the potential for induced current damage in payloads, space launch vehicles, and test equipment (Flinn et al., 2010a) (Flinn et al., 2010b). The cloud-to-ground lightning data is also used to issue lightning watches and warnings at CCAFS/KSC and PAFB via continuity for approaching thunderstorms. The cloud-to-ground data does not help with lightning warnings for locally developing thunderstorms since those warnings would be too late for workers to get to safety, end operations, or protect resources.

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3. Benefits Of 4DLSS

The 4DLSS was a major upgrade to the previous Lightning Detection And Ranging (LDAR) system that detected lightning aloft (Boccippio et al., 2001) and the Cloud to Ground Lightning Surveillance System (CGLSS) (Boyd et al, 2005) (Roeder et al., 2005). The 4DLSS began support to CCAFS/KSC in April 2008. The detection principles of 4DLSS were discussed in Roeder (2010). The performance of 4DLSS was discussed in Murphy et al. (2008).

3.1 Lightning Aloft Benefits Of 4DLSS

The primary reason for the LDAR upgrade was to replace the legacy LDAR sensors and processor that had been in use since the early 1990s and were becoming too difficult and costly to maintain. The legacy LDAR sensors were non-commercial one-of-a-kind devices developed by KSC in the early 1990s. Commercial off the shelf products are preferred for Air Force systems for long-term sustainability. The seven legacy LDAR sensors were replaced with nine LDAR-II sensors and processed through a new CP-8000 processor (Vaisala, 2004). A picture of a LDAR-II sensor is at Figure-1. A map of the LDAR-II sensors is at Figure-2. The location where the legacy LDAR sensors were located is also shown. The new LDAR-II network had average sensor spacing about 2.5 times larger than the previous LDAR network. This new system increased the detection rate of step leader and related events by 40%, based on comparison of 4DLSS with the legacy LDAR on the same weather events during testing of 4DLSS. The increased detection rate improved the initial detection of some small thunderstorms by a few minutes when compared with than the legacy LDAR system. This 40% improvement was for step leaders and other lightning aloft sub-flash mechanisms, not for flash detection. Since there are usually many sub-flash mechanisms in each lightning flash, both the legacy LDAR and 4DLSS detect essentially 100% of flashes in and around those networks, though 4DLSS detects more of the sub-flash events.

Another benefit included reduced “radial smearing”, where detections from small areas of lightning outside the network, like individual thunderstorms, would be stretched along a radial line to the center of network. This radial smearing was caused by the radial error increasing faster than the azimuthal error with range. Reduced radial smearing allows 4DLSS to resolve finer lightning structures. It also appears to reduce the number of false lightning warnings from radial smearing of nearby thunderstorms into the warning areas. This is especially likely with thunderstorms just inland from CCAFS/KSC that form on the Atlantic Ocean sea breeze front, contributing to the rapid increase of climatological lightning activity in that location.

The new LDAR-II network eliminated the detection of electrostatic discharges from some aircraft flying through clouds, which used to be observed every one to two weeks on the legacy LDAR. This was observed during parallel testing where no aircraft detects were seen on 4DLSS while they were seen on the legacy LDAR. Furthermore, there have been no observations of aircraft detections in the nearly 4 years since 4DLSS was implemented. This was an unexpected benefit of the wider spacing of the new LDAR-II network. Part of the quality control algorithm requires the strength of a detected signal to exceed a certain threshold at five or more sensors. The signals from aircraft flying in clouds are much weaker than step leaders and fall below the threshold before they can reach the required number of sensors in the new wider network.

Finally, the solutions for lightning aloft solutions were improved by better algorithms in the new CP-8000 processor. The biggest improvement, especially for lightning aloft solutions outside the network, was the use of a spherical Earth model. The legacy LDAR system used a flat Earth model, since its original purpose was for high precision, short-range detection of lightning aloft within about ten miles of the network.

Figure 1. Picture of one of the LDAR-II sensors used in 4DLSS.

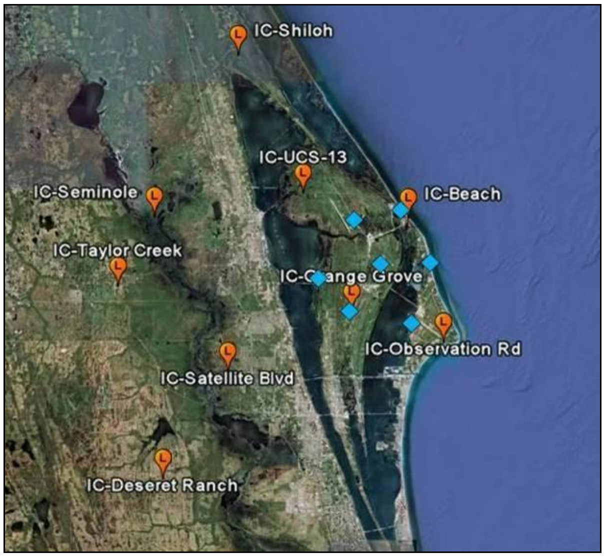


Figure 2. Map of the nine LDAR-II sensors used in 4DLSS. The orange pins are the LDAR-II sensor locations. The blue diamonds are where the legacy LDAR sensors were located. Note the wider spacing of the 4DLSS LDAR-II sensors compared to the LDAR sensors.

3.2 Cloud-to-Ground Lightning Benefits Of 4DLSS

The CGLSS sensors are the Improved Accuracy though Combined Technology (IMPACT) Model-141T-Enhanced sensors manufactured by Vaisala. Under the 4DLSS upgrade, the same six sensors used under CGLSS were still used, but processed in the new CP-8000 processor. The use of the new processor allowed the detection and display of cloud-to-ground return strokes in real-time (the previous CGLSS processor could only display flash data in real-time). This was a significant improvement since at least half of lightning flashes have multiple ground strike locations (Cummins et al., 1998) and the median distance between these multiple ground strike locations is about 3 km (Valine and Krider, 2002). Displaying strokes in real-time resulted in about 250% more data being displayed relative to the legacy CGLSS flash data. A picture of a CGLSS sensor is at Figure-3. A map of the CGLSS sensors is at Figure-4.

The cloud-to-ground lightning solutions were also improved by better algorithms in the new CP-8000 processor. These improvements included a better model of soil dielectric constant and better tuning of the peak current regression.

Figure 3. Picture of one of the IMPACT sensors used in 4DLSS.

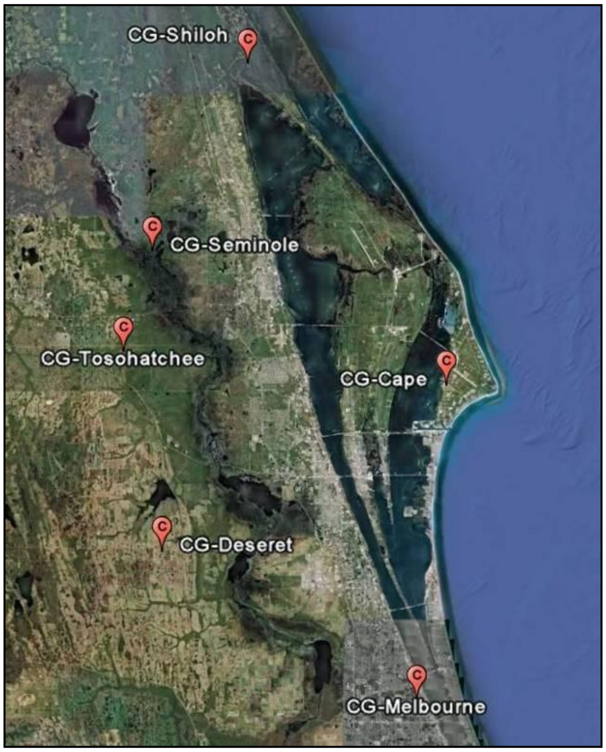


Figure 4. Map of the six CGLSS sensors used in 4DLSS.

4. Sustainment Problems Of 4DLSS

The 4DLSS is becoming unsustainable. Vaisala no longer manufactures either the LDAR-II or the CGLSS sensors. These sustainment issues are discussed in section-4.1 and section-4.2, respectively. In addition, recent major maintenance events, many of which affect these sustainability problems, are discussed in section-4.3.

4.1 LDAR-II Sustainment Problem

Vaisala no longer manufactures the LDAR-II sensor and the maintainers have enough spare parts to sustain the lightning aloft capability of the system through at least the end of 2012. At some point thereafter, the lightning aloft capability of 4DLSS will begin to degrade as sensors break, eventually leading to the loss of the lightning aloft capability of 4DLSS, seriously degrading weather support to America's space program in FL. The maintainers of 4DLSS are seeking additional LDAR-II sensors to help alleviate this sustainability problem. In addition, a complete replacement of the 4DLSS system is being actively pursued.

4.2 CGLSS Sustainment Problem

Vaisala no longer manufactures the IMPACT sensor and the maintainers of 4DLSS have used all the spare parts on-hand. The cloud-to-ground capability of 4DLSS is already degraded, having had only four to five sensors operational since June 2009, rather than the nominal six sensors. Several efforts have attempted to overcome this problem. The NASA Marshall Spaceflight Center had five IMPACT sensors from an old project. These sensors were obtained by the 4DLSS maintainers. Unfortunately, four of those sensors were models that were outdated the one suitable sensor did not pass testing for 4DLSS due to inconsistent performance with the other CGLSS sensors. Vaisala is retiring the IMPACT sensors from NLDN as they upgrade to their LS-7001 (Vaisala, 2009) and TLS-200 (Vaisala, 2011) sensors (Hembury and Holle, 2011). Although, the IMPACT sensors might have been used for 4DLSS spares, there were implementation problems with Air Force system security requirements. Three of the newer LS-7001 sensors have been purchased from Vaisala and are being employed to bring 4DLSS back to its full complement of six cloud-to-ground sensors and provide two spares that should sustain 4DLSS into 2013.

4.3 Recent 4DLSS Maintenance Events

Since 2009, several significant maintenance events affecting sustainability occurred to 4DLSS. These events are described here to help other lightning detection networks avoid similar problems and to document these events for future reference. These events are listed chronologically in the following sections.

4.3.1 July 2009

The CGLSS sensor at Melbourne was damaged by lightning in July 2009. Since no spare parts were available, the sensor at Tosohatchee was moved to the Melbourne site (Figure-5). According to the Vaisala performance model, this optimized performance in the CCAFS/KSC area for a 5-sensor CGLSS configuration. Even so, the flash detection rate near the launch pads fell to 95% and the location accuracy fell to 450 m (50% confidence), compared to 96% and 330 m for the full 6-sensor configuration, according to the Vaisala performance model.

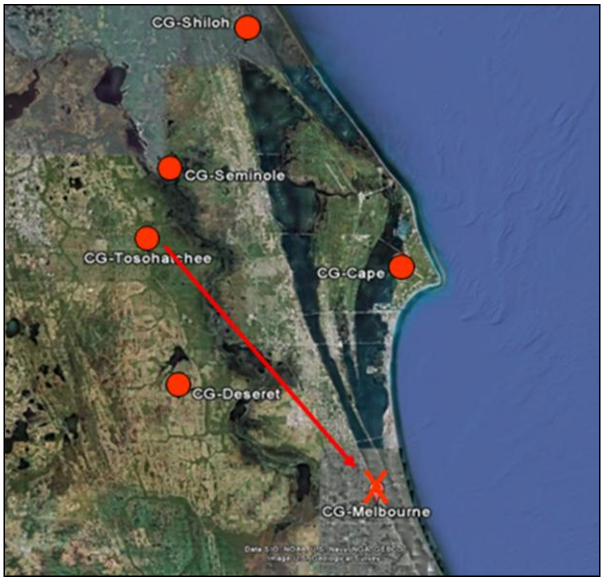


Figure 5. The CGLSS sensor at Tosohatchee was moved to Melbourne after the Melbourne sensor was damaged by lightning in July 09. This was done to provide the optimum performance in the CCAFS/KSC area for a 5-sensor configuration.

4.3.2 January 2010

The 45 WS checked the 4DLSS cloud-to-ground performance in January 2010. The performance had degraded much more than expected after use of the 5-sensor configuration began in Jul 09 (see section-4.3.1). The 95% confidence error ellipses doubled in size from 0.1 nmi^2 to 0.2 nmi^2. Investigation determined that the maintenance program to optimize configuration settings wasn't downloading the settings. As a result, when the Tosohatchee sensor was moved to Melbourne, the download of the Melbourne settings were downloaded, but was unknowingly unsuccessfully. This problem was discovered in January 2010. Vaisala fixed the maintenance program and the correct settings were implemented in February 2010.

4.3.3 November 2010

A Network Performance Evaluation Program (NPEP) (Vaisala, 2008) was run by Vaisala on the cloud-to-ground portion of 4DLSS in November 2010. Some performance shortfalls were discovered in the Melbourne sensor and new optimized configuration settings recommended. Further investigation revealed that a large metal building had been built 200 meters from the sensor. This building changed the magnetic propagation near the sensor. The new configuration settings corrected for this new building and implemented December 2010.

Figure 6. A large metal hanger had been built unknowingly within 200 meters of the cloud-to-ground sensor at the Melbourne airport. This required an update to the configuration settings.

4.3.4 April 2011

Three major maintenance events occurred to 4DLSS during April 2011: 1) the sensor at Shilo broke, 2) a major configuration error at the Cape sensor was discovered and fixed, and 3) a new IMPACT sensor became available.

4.3.4.1 Shilo Sensor Broke (April 2011)

The cloud-to-ground sensor at Shilo broke in April 2011. This reduced 4DLSS to a 4-sensor configuration and seriously degraded its capability. The flash detection rate fell to 92% and location accuracy fell to 650 m near the launch pads, as compared to 95% and 450 m for the already degraded 5-sensor configuration, according to the Vaisala detection model. The full 6-sensor configuration has a flash detection rate of 96% and location accuracy of 330 m. The Melbourne sensor, which was previously relocated from the Tosohatchee site, was moved to Shilo to provide the best performing 4-sensor configuration for the CCAFS/KSC launch pads and other facilities (Figure-7).

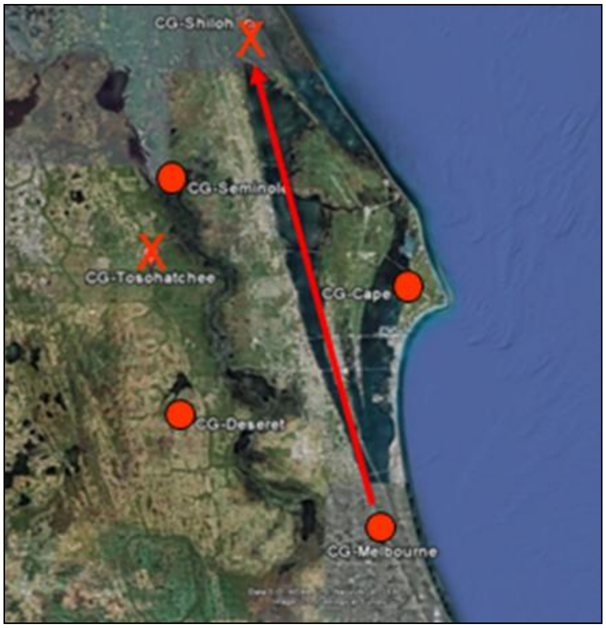


Figure 7. The Melbourne sensor was relocated to Shilo in Apr 11 when the Shilo sensor broke.

4.3.4.2 Major Configuration Error Discovered and Fixed at the Cape Sensor (April 2011)

A second significant maintenance event occurred in April 2011. The quality control configuration setting for rise time of negative polarity return strokes at the Cape sensor was in error. This error caused the Cape sensor to be ignored for negative polarity strokes. This has two important impacts since negative strokes account for about 97% of all lightning and, based on the Vaisala performance model, the Cape sensor is the most important to 4DLSS performance, due its central location and based on the Vaisala performance model. As a result, 4DLSS had effectively been operating as a 3-sensor configuration with the most important sensor not used, seriously degrading performance. This problem was detected in April 2011 and immediately corrected. Analysis showed that the problem began in January 2011, so the problem existed for 3 months. Fortunately, relatively little lightning occurs in the CCAFS/KSC area during the winter and the problem was fixed before the summer lightning season.

4.4.3.3 A New IMPACT Sensor Became Available (April 2011)

A third significant maintenance event also occurred in April 2011. Computer Sciences Raytheon (CSR), the maintenance contractor for the 45 WS systems, built a usable IMPACT sensor from two broken sensors. This sensor was installed at the Melbourne site, returning the 4DLSS cloud-to-ground lightning capability to a 5-sensor configuration, still one sensor short of the full 6-sensor configuration. This extra effort by CSR was deeply appreciated by 45 WS.

The Space Lift Range Systems Contractor (SLRSC), the contractor that manages system acquisitions for the 45th Space Wing, also built an IMPACT sensor from broken sensors. This was an extra effort by SLRSC, not required by the 45th Space Wing, as an initiative to return the 4DLSS cloud-to-ground lightning capability to its full 6-sensor configuration, though still with no spares. Unfortunately, although a laudatory effort by SLRSC, that sensor did not pass performance tests and was not implemented into 4DLSS.

4.3.5 August 2011

The 45 WS obtained a performance evaluation of the cloud-to-ground <u>stroke</u> capability of 4DLSS in August 2011 (Vaisala, 2011b). This evaluation provided different performance characteristics than the previous evaluation for CGLSS flashes. The new performance evaluation estimated the detection rate and local accuracy for first return strokes, subsequent return strokes, and all return strokes for all combinations of the six cloud-to-ground sensors in 4DLSS at 12 key locations in and around CCAFS/KSC and PAFB.

This performance evaluation was performed by Vaisala based on their flash performance evaluation model modified for return strokes. It will be used to advise customers of the expected performance of the system under various sensor configurations, set maintenance priorities when a sensor is not functioning, and optimize the network configuration when one or more sensors are not available for an extended time.

This new performance evaluation is important since 4DLSS reports individual return strokes, as compared to only flashes in the legacy CGLSS system. It is also important since a significant fraction of flashes with multiple return strokes have multiple ground strike locations and the median distance between those ground strike locations is about 3 km and can be as high as 12 km (Valine and Krider, 2002). As a result, the difference between stroke and flash detection is critical to space launch customers.

4.4 Recent Performance Assessment

Recent assessment of the cloud-to-ground capability of 4DLSS suggests that the location accuracy is very good (Mata et al. 2012). This assessment was done using lightning detected by new lightning detection new system at launch pad 39B on KSC as ground truth (Mata and Rokov, 2011). The results also suggest that the detection rate is not as good as expected. However, these results are very preliminary since the number of flashes and strokes detected by this new system is still low. In addition, the results are difficult to interpret since the number of cloud-to-ground sensors in 4DLSS was reduced due to the sustainment problem discussed above. Also, the lightning analyzed attached to the launch pad protection system and there is a known problem with detection of stokes to tall structures since those waveforms are sometimes rejected by the quality control algorithms of the 4DLSS sensors. Therefore, the detection rate of cloud-to-ground lightning by 4DLSS for a full 6-sensor configuration and for lightning strikes to the ground may be higher than in this study.

5. Plans For 4DLSS

5.1 Replacement for 4DLSS

An entirely new system to replace 4DLSS is being procured, primarily to overcome the sustainment problems described in Section 4. Other reasons to procure the new hardware include improving the 45 WS cloud-to-lightning detection capabilities via more sensors and to take advantage of new, improved technology such as better digital filtering of radio noise. The proposed name for this new system is the Mesoscale Eastern Range Lightning Network (MERLiN), which will be used hereafter to refer to the 4DLSS replacement. The completion date for MERLiN is tentatively scheduled for early 2013.

Another improvement expected under MERLiN is real-time integration of the sensors of a wider network that are close enough to be useful for lightning solutions in east central Florida. This would integrate the observations from the sensors into the local processor with the new local network of sensors. This is as opposed to using the lightning solutions from both networks and trying to resolve any disagreements. Integrating the observations from the wider network with the local network would provide lightning solutions that are consistent with both networks and synergistically combine the strengths and overcome the weaknesses of both networks.

The main reason for integrating the other sensors is that 4DLSS currently misses 28% of local cloud-to-ground flashes with peak currents 50 KA or greater which makes up 10% of all lightning, missing 2.8% of all lightning (Ward et al., 2008). Allowing for 4DLSS missing some flashes with peak current < 50 KA, though with decreasing miss rate, the 45 WS estimates that 4DLSS misses a total of ~4% of all local cloud-to-ground flashes due to this strong peak current problem. Since the modeled flash detection rate of 4DLSS is 96%, this suggests that the strong peak current problem accounts for almost all of the missed flashes. A recent performance assessment of 4DLSS (Mata et al., 2012), albeit with small sample size, implies that combing observations with NLDN would provide a detection rate of nearly 100%. It should be noted that NLDN misses 17.5% of flashes with peak currents less than 12 KA (Ward et al., 2008). These flashes are 12% of the total, so NLDN misses 2% of all flashes from this weak peak current problem.

Additionally, integrating in-range sensors from a wider network into MERLiN will not degrade MERLiN's performance. When many of the local MERLiN sensors are used in the lightning solutions, the MERLiN processor will produce the optimum solution based on available sensors; essentially giving less weight giving to the more distant lower quality sensors when sufficient higher quality local MERLiN sensors are available.

Until these in-range sensors from a wider network are integrated into MERLiN, 45 WS and KSC will continue using the StrikeNet reports from Vaisala (Vaisala, 2006) for lightning flashes near critical facilities. These StrikeNet reports include strokes, as opposed to the more common flash reports, detected by NLDN to help discern strokes 4DLSS missed for analysis by the space launch customers.

Yet another improvement under MERLiN will be the replacement of the LDAR display system. The current display still uses legacy LDAR software running on a workstation using a proprietary VAX operating system. This operating system is no longer produced and long-term sustainment is becoming problematic. In addition, the legacy hardware cannot process the full, real-time data throughput of lightning in central FL summer—some lightning aloft is detected, but not displayed, and thus not available for operational decisions by 45 WS.

5.2 Other Desired Improvements

The following subsections detail desired improvements in lightning detection for the 45 WS. These projects are only ideas and are not yet in-progress or funded.

5.2.1 Desired Improvements to Cloud-to-Ground Lightning Detection

The following six improvements to cloud-to-ground lightning detection capability are desired: 1) peak current, 2) peak current error, 3) periodic network performance evaluations, 4) improved sensor siting, 5) improved location error ellipses, and 6) establish a climatology of peak current rise times.

5.2.1.1 Improved Peak Current

At present, the peak current estimate is calculated from the peak magnetic field at each sensor. The peak magnetic field is corrected for attenuation from ground propagation effects and normalized to a range of 100 km. The mean of the attenuation-corrected, range-normalized peak magnetic field is converted to peak current via a regression equation (Cummins et al., 1998). That regression equation is based primarily on data from rocket-triggered lightning. As a result, it is not representative of, the nominally highest current, first strokes from natural lightning. This is important to operations since the first stroke in a flash tends to have the highest peak current and generally causes 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. An appropriately instrumented tall tower in a wide-open, flat area with frequent lightning and subsequent analysis of that data may provide better peak current estimates, especially for the operationally significant first strokes. The CCAFS/KSC has a network of existing weather towers that may be candidates for such an instrumented tower. An analysis of tower height versus climatological flash density, along with surrounding terrain and logistical accessibility, should be conducted to identify the best tower to be instrumented. For example, Tower-313 is the tallest tower in the network (500 ft) but is located only ~3 nmi from the coast. Shorter towers farther inland might be more likely to be struck by lightning since the climatological lightning flash density increases inland. Recently, a new suite of lightning sensors has been installed at Launch Pad-39B, which would be a good source of observations for this project (Mata and Wilson, 2012) (Mata and Rokov, 2010).

There may be ways to improve the range-normalized, attenuation-corrected regression equation approach 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.

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 could be explored to avoid the additional uncertainties introduced by the range-normalization and the regression equation.

5.2.1.2 Improved Peak Current Error

The estimated error associated with the peak current estimates for cloud to ground lightning strokes from CGLSS-II has not been as well studied as location accuracy and detection rate, especially for various combinations of sensors used in the solution for each stroke. At present, a single error estimate of ±20% is used for all strokes, regardless of number of sensors used in the solution and distance of those sensors to the lightning stroke. This is the vendor's recommendation and is based on the performance of the NLDN, which itself appears to be based on some old studies of relatively small sample size. It appears that most customers are more concerned with detection rate and location accuracy than peak current accuracy. Some lightning detection experts have suggested that the actual errors in peak current are larger than ±20% (Mata, 2009).

The 45 WS is interested in improved error estimates for peak current provided by CGLSS-II. One approach might use the variability of the peak current estimated from each sensor. This could also allow a statistical estimate of the confidence intervals and/or a high percentile, e.g. inter-quartile range, 95th or 99th percentile. A best-fit Gaussian distribution might also be applied. The standard deviation of the best-fit Gaussian distribution could be used to generate confidence intervals. The space launch customers could then factor the uncertainty of peak current more effectively into decisions to inspect mission essential electronics, just as done now with location accuracy, i.e. determine the probability of exceeding their combined thresholds of distance and peak current. Another approach could use the existing peak current regression equation to calculate the error bars based on the reported peak current. Calculating error bars associated with linear regression is a well-known easy-to-do process that is underutilized in meteorology.

5.2.1.3 Periodic NPEP Assessments

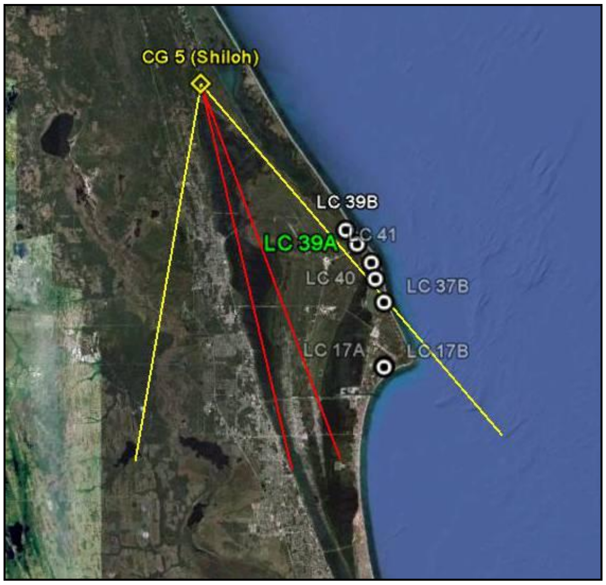
Periodic network performance evaluations would be useful to optimize network performance continually as the local environment changes. Periodic performance evaluations will also identify undetected problems, allowing the diagnosis and correction of those problems. Vaisala recommends their Network Performance Evaluation Program (NPEP) to be done every 18 months for mature unchanging cloud-to-ground lightning detection networks using their sensors (Vaisala, 2008). However, annual NPEPs may be more appropriate for MERLiN. This is based on the large amount of lightning in central FL, the sensitivity of the space program to lightning (Weems et al., 2001), and the strong annual seasonality to lightning in central, FL. A likely time for these annual performance evaluations would be early-Jun, since the lightning season in central FL usually begins in late-May. A June performance evaluation should ensure sufficient lightning for an effective evaluation while ensuring recent results to optimize configuration settings for the majority of the beginning lightning season. The actual date should vary, based on how much lightning had occurred and the distribution of the lightning around the network. For example, if several squall lines and/or strong cold front passages during the winter produced enough lightning at various ranges and various locations around the network, the performance evaluation could be conducted sooner than normal.

5.2.1.4 Improved Sensor Locations

The Shilo sensor in the 4DLSS network has been shown to participate in relatively fewer cloud-to-ground stroke solutions to the south-southeast of that location (Figure-10a). This is important since it affects the quality of stroke solutions near many of the launch pads at CCAFS/KSC and the Shilo sensor is the second most important sensor in 4DLSS. This problem might be due to higher than average radio noise in that area or signal blockage from a nearby radar facility in that direction (Figure 10b).

5.2.1.5 Verify Location Error Ellipses

The location error ellipses have become vital to 45 WS lightning reports, enabling the space launch customers to better evaluate the potential for induced current damage from nearby cloud-to-ground strokes (Flinn et al., 2010a) (Flinn et al., 2010b). The 50% confidence location error ellipses for strokes near the key facilities are scaled to 95% and 99% confidence error ellipses depending on the customer. However, this scaling assumes a Gaussian distribution. While this assumption seems reasonable, since many measurement errors have a Gaussian distribution, the authors do not know of any studies verifying that assumption. The error ellipses are also integrated over the key radius around key facilities for some



(a) Sectors in which the detection rate of the Shilo sensor is degraded.

(b) The problem may be due to signal blockage from a nearby radar facility located in that direction.

Figure 10. The Shilo sensor participates in relatively fewer cloud-to-ground stroke solutions to its south-southeast.

customers, again assuming a Gaussian distribution (Huddleston et al., 2011) (Huddleston et al., 2010). As a result, the Gaussian distribution of location error ellipses is important to the 45 WS lightning reports. However, a small, limited study, based on the new short-range lightning location system recently installed by KSC at Space Launch Complex 39B, indicated that more than 5% and 1% of actual stroke locations are occurring outside the 95% and 99% error ellipses, respectively (Mata, 2010). This suggests that the Gaussian distribution may not be appropriate and should be verified. For example, if the location error distribution was an extreme value distribution, the 50% confidence ellipses might be fairly accurate, but the larger confidence ellipses, such as the 95% and 99% ellipses provided by 45 WS, might under estimate the actual size of those ellipses, as seen in the Mata study (Mata, 2010).

5.2.1.6 Peak Current Climatology

The main purpose of 45 WS lightning reports is to allow the space launch customers to estimate the potential of induced current damage from nearby lightning strokes (Flinn et al., 2010a) (Flinn et al., 2010b). The lightning reports include the distance between key facilities and the stroke, the location error of the stroke, and the peak current of the stroke. Some customers also add the expected 20% error in peak current for conservatively safe estimates.

However, the induced current potential also depends strongly on the rise time of the peak current of the stroke. These rise times are not detected by the lightning detection system, nor would the customers know how to use the rise times if they were available. The customers are essentially assuming that all return strokes have the same rise times. This is known to be incorrect, but no other solutions are available at this time. A climatology of the distribution of return stroke rise times would document the variability of rise times and highlight the need to detect rise times and develop methods to incorporate rise times into the estimates of potential for induced current damage.

5.2.2 Desired Improvements to Lightning Aloft Detection

Given the expected acquisition of MERLiN to replace 4DLSS (see section-5.1), the 45 WS has identified three desired improvements for lightning aloft capability: 1) network performance evaluation capability, 2) add height detection, and 3) reduced noise.

5.2.2.1 Network Performance Evaluation Capability for Lightning Aloft

Vaisala provides network performance evaluations to optimize cloud-to-ground lightning networks using their sensors. A similar capability is not available for lightning aloft networks. If available, a lightning aloft performance evaluation capability would provide the same benefits as for cloud-to-ground networks: periodic optimization of performance, and detection of network problems so they can be fixed.

5.2.2.2 Height Detection

The commercially available systems to detect step leaders and other sub-mechanisms of lightning aloft do not provide the height of those events, only their horizontal locations, i.e. x-y but not z. The 45 WS has proposed a method to add height capability to one of those systems using data already detected by the sensors. Thus, the height capability can be added without a hardware change to the system by modifying the software and reusing preexisting algorithms. Unfortunately, the market is limited for this capability and the vendor is not planning this upgrade at this time. The 45 WS is interested in a commercially-available off-the-shelf system that can detect the height of the lightning aloft sub-mechanisms in addition to their full horizontal extent, i.e. x-y-z-t.

5.2.2.3 Reduced Noise in Lightning Aloft Detection

The lightning aloft data at 45 WS occasionally displays random noise, presumably from radio interference. Figure-11 shows a stronger than normal example of this noise with a few hundred false solutions per minute. A more typical noise rate is a few tens of false solutions per minute or less. This noise occurs under strong nocturnal inversions after strong cold front passages in winter.

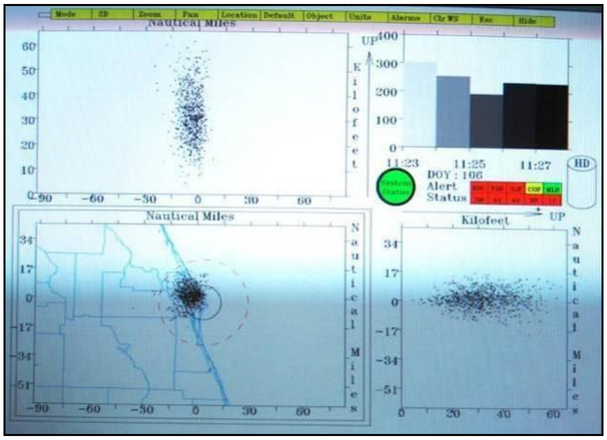


Figure 11. An example of noise occasionally displayed by the lightning aloft sensors of 4DLSS on mornings with strong nocturnal inversions. This example is a strong case with a well above average amount of noise (200-300 non-lightning detections per minute (see histogram in upper right). Typical rates are now less than 10 erroneous detections per minute. The noise problem seems to have decreased significantly in frequency and intensity, perhaps due to the national conversion of television from analog to digital broadcasts. No action is planned to mitigate this minor inconvenience.

The 45 WS considers this a minor irritation to operations since is easily identified by three conditions: 1) random 3-D distribution and persistence over time, which is very unlike lightning flashes, 2) the weather conditions and timing do not coincide with expected lightning timing, and 3) the lack of lightning signatures on the other lightning detectors and the lack of deep convection on radar. Indeed, except for perhaps some shallow stratus or stratocumulus clouds, there are usually no clouds in the area at these times, and certainly no deep convective clouds that would be producing lightning. This problem appears to be radio interference caused by low-level ducting by the nocturnal inversion. The obvious solution is to decrease the sensitivity of the LDAR-II sensors. Unfortunately, this might decrease the detection rate for real lightning, which is counterproductive. A radio interference survey under these weather conditions might allow identification of a specific wavelength causing the interference and allow a notch filter.

A decrease of the frequency and intensity of the noise was noticed in the winter of 2008-2009 as compared to the winter of 2007-2008, which may have been due to the national conversion of television from analog to digital broadcasts. However, an increase was noticed in winter 2009-2010, presumably due to more strong nocturnal inversions than average. A return to less noise was noted in winter 2010-2011 and that reduction of noise continued in winter 2011-2012.

6. Summary

The Four Dimensional Lightning Surveillance System (4DLSS) detects lightning aloft and cloud-to-ground lightning for the 45th Weather Squadron (45 WS) in support of America’s space program in FL. 4DLSS provided several major upgrades over the previous lightning detection systems used by 45 WS, but is becoming unsustainable since the sensors are no longer being produced and spare parts are running out. Several efforts are underway to overcome this sustainability problem, especially the acquisition of a new system to replace 4DLSS. A proposed name for this new network is the Mesoscale Eastern Range Lightning Network (MERLiN) and is tentatively scheduled to be implemented by early 2013. Other possible future upgrades to lightning detection at 45 WS were also discussed.

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