7.3 RECENT IMPROVEMENTS IN LIGHTNING REPORTING AT 45TH WEATHER SQUADRON

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1. INTRODUCTION

The 45th Weather Squadron (45 WS) is the United States (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 AFB (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 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) (Murphy et al., 2008) included a major upgrade to the total lightning detection Lightning Detection And Ranging (LDAR) system (Boccippio et al., 2001). The 4DLSS was implemented operationally in April 2008. A map of the total lightning sensors of the 4DLSS is in Figure-1. The 4DLSS also upgraded the Cloud to Ground Lightning Surveillance System (CGLSS) (Boyd et al., 2005) and integrated it into the 4DLSS. A map of the cloud to ground lightning sensors of the 4DLSS is in Figure-2. The 45 WS also uses the Launch Pad Lightning Warning System (LPLWS) (Eastern Range Instrumentation Handbook, 2009), a network of 31 surface electric field mills that has a limited total lightning location capability. A map of the field mills in LPLWS is in Figure-3. The final lightning detection system used by 45 WS is a direct connection to the National Lightning Detection Network (NLDN) (Cummins and Murphy, 2009; Orville et al., 2002).

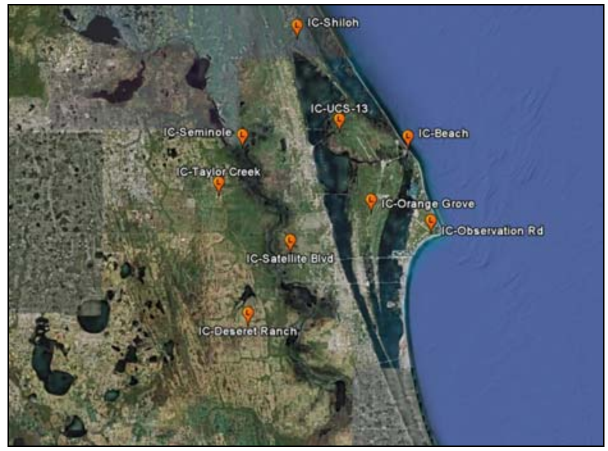

Figure 1. Map of the nine total lightning sensors in the Four Dimensional Lightning Surveillance System.

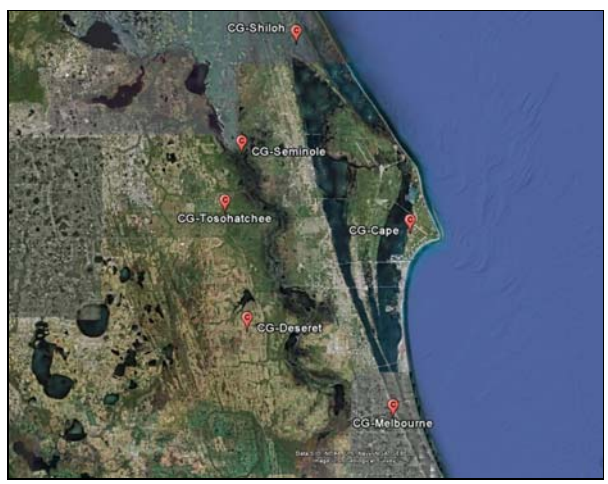

Figure 2. Map of the six cloud to ground lightning sensors in the Four Dimensional Lightning Surveillance System.

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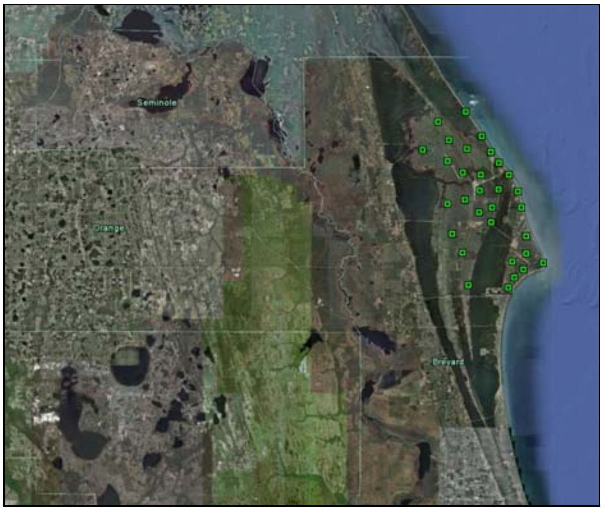


Figure 3. Map of the 31 surface electric field mills in the Launch Pad Lightning Warning System.

The 45 WS uses these lightning sensors for several applications (Roeder et al., 2005). One of these applications is the evaluation of 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). Another application is lightning watches and warnings for the safety of over 25,000 personnel and protection of over $20 billion of facilities (Weems et al., 2001). Yet another application is daily lightning reports to customers. Other applications include incident investigations, climatological studies for mission planning, and development of new or improved forecast tools.

The daily lightning reports include the distance and peak current of cloud-to-ground (CG) lightning strokes in the vicinity of key facilities. Even nearby lightning strokes can induce potentially damaging electric currents in the electronics in satellite payloads, space launch vehicles, ground support equipment, or key facilities. The daily lightning reports are used to decide if the various electronics should be inspected and, if so, what level of inspection is required. If damage occurred, it is essential to conduct those inspections to identify and implement required fixes to avoid potential degradation or early failure of the electronics that could result in degradation or mission failure, or in extreme cases even destruction of the space launch vehicle. However, it is also important to avoid unnecessary inspections due to their financial cost and delays to space launch schedule. This paper will describe the significant improvements to the 45 WS lightning reports since April 2008.

2. Recent Improvements To The 45 WS Lightning Reports

The 45 WS and their mission partners made five major improvements to their lightning reports from April 2008 through 2009: 1) reporting of all strokes, 2) providing lightning location error ellipses tailored to each stroke, 3) on-demand 24/7 availability of lightning reports, 4) fixed a truncation error of the peak current in the lightning database, and 5) KSC automated e-mail alerts and website.

2.1 Reporting All Lightning Strokes

The recent improvements to the 45 WS lightning reports began when the 4DLSS became operational in April 2008 (Murphy et al., 2008). One of the many benefits of 4DLSS is that all return strokes per flash are reported. The previous CGLSS lightning system used by 45 WS, now integrated into 4DLSS, only reported one stroke per flash. This improvement resulted in 4DLSS reporting 250% of the return strokes of CGLSS. Detecting and locating all return strokes is important since CG lightning has an average of 3.5 strokes per flash (Cummins et al., 1998) and 35% or more of these strokes have multiple ground strike locations (Valine and Krider, 2002) with a geometric mean spacing of about 3 km (mean = 1.7 km) and can extend up to 10 km (Thottappillil et al., 1992). Other studies have shown that 50% or more of flashes may have multiple ground strike points separated by up to 12 km. Reporting only one stroke per flash, as done by the former CGLSS, meant these other return strokes would not be reported and potentially necessary inspections would be missed.

2.2 Lightning Location Error Ellipses Tailored To Each Stroke

Another significant improvement in the 45 WS lightning reporting procedures was the inclusion of location error ellipses tailored to each individual stroke. This overcame several previous shortfalls.

2.2.1 Previous Shortfalls: Single Best-case 50% Confidence Location Accuracy

The previous 45 WS lightning location accuracy had several shortfalls. A single location accuracy was used for all lightning strokes in the center of the network and a 50th percentile confidence for the lightning location was provided. The 45 WS discovered that this location accuracy assumed all six CG lightning sensors were used in the solution. However, 4DLSS often has fewer than six sensors per solution, even if all six sensors are operating, resulting in larger location errors and more eccentric error ellipses than previously believed. The median number of sensors per solution is 4.80 for local lightning strokes detected by 4DLSS with a distribution shown in Figure-4. Reporting a single constant location accuracy implied circularity of the error, which was misleading. In addition, the customers had requested a 50th percentile location accuracy, but more recent discussion showed this to be inadequate for space launch applications.

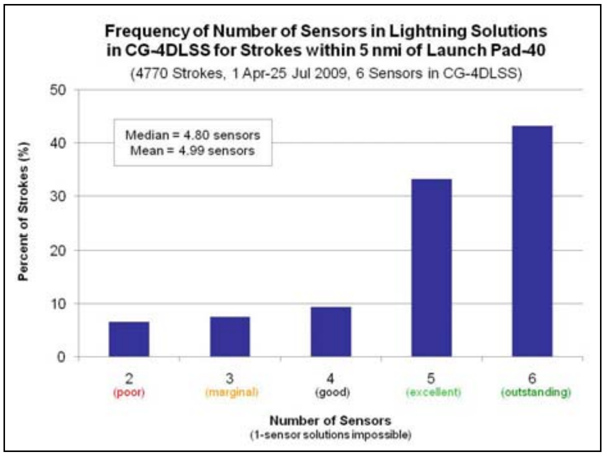


Figure 4. Distribution of number of sensors used in location solutions by 4DLSS for nearby strokes.

2.2.2 4DLSS Performance as a Function of Sensors Used in the Solution

As an interim step, 45 WS obtained the detection rate and location accuracy of the cloud to ground component of 4DLSS for all possible combinations of sensors in the lightning solutions. These 115 maps were used to estimate the expected performance for any strokes of interest. These plots were provided by Vaisala, Inc. from their system performance model. As an example, the detection rate and location accuracy when all six sensors are used in the solution are in Figure-5 and Figure-6, respectively. The 4DLSS is relatively insensitive to one or to a lesser degree even two sensors, not being used in the solution, unless one of them is the central “Cape” sensor on CCAFS (Table-1). A map of the sensor locations is at Figure-2. However, even with these performance plots, the error characteristics for each individual return stroke were still needed since these error characteristics varied based upon the geometry of the stroke location relative to the sensors used in the solution of that stroke.

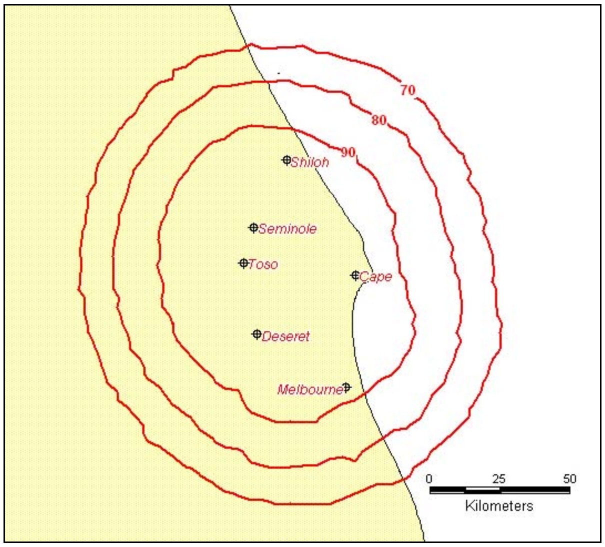


Figure 5. 4DLSS detection rate (%) of cloud to ground strokes if all six sensors are used in the lightning solution. This is the best performance possible. Similar maps for detection for all combinations of 5-sensor, 4-sensor, 3-sensor, and 2-sensor solutions were produced, but not shown in this paper. 1-sensor solutions are not possible. Maps were from the Vaisala, Inc. system performance model.

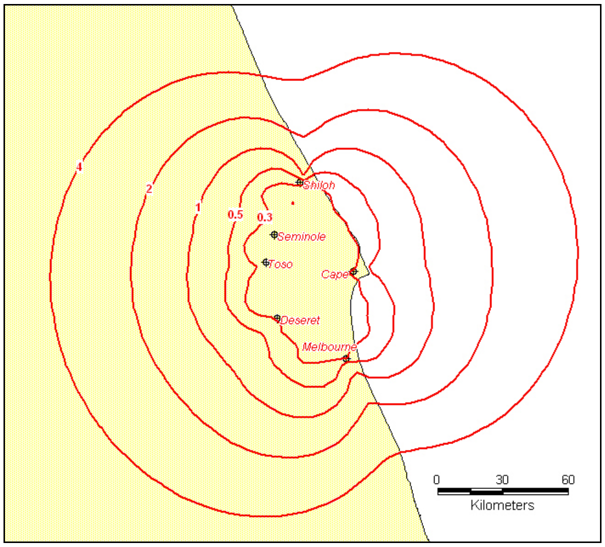


Figure 6. 4DLSS location accuracy (km) for cloud to ground strokes if all six sensors are used in the lightning solution. This is the best performance possible. Similar maps for detection for all combinations of 5-sensor, 4-sensor, 3-sensor, and 2-sensor solutions were produced, but not shown. 1-sensor solutions are not possible. Maps were from the Vaisala, Inc. system performance model.

TABLE-1.

4DLSS performance for cloud to ground strokes near the launch pads for all combinations of 5-sensor solutions, i.e. one sensor not used.

Sensor Missing	Detection Rate (%)	Location Accuracy (median) (m)
None	94%	300 m
Melbourne	93%	350 m
Deseret	93%	350 m
Tosohatchee	92%	350 m
Seminole	91%	400 m
Shilo	91%	450 m
Cape	89%	500 m

Performance is most sensitive to the Cape sensor not used in the lightning solution. Estimated from the performance maps provided by Vaisala, Inc.

2.2.3 Location Error Ellipses Tailored to Each Stroke with 99% and 95% Percentiles

A better solution than performance maps was subsequently implemented by 45 WS and their mission partners. This solution solved both the problems of a single best-case location accuracy being used for all strokes and a too low 50% accuracy being provided. The raw data from 4DLSS provides bivariate Gaussian error ellipses with location confidence of 50% tailored to each stroke based on the number of sensors used in the solution, the distance from the sensors to the stroke, and the geometry of the sensors relative to the stroke. The 45 WS and their mission partners tailored the confidence intervals to meet customer requirements and implemented them into the daily lightning reports. The KSC requires 99th percentile error ellipses while the rest of the space launch customers use 95th percentile error ellipses. In 99%/95% of the events, the best location of the stroke will be inside the error ellipse and in 1%/5% of the events the best location of the stroke will be outside the ellipse, respectively.

The lightning report includes the distance from each key facility to the best location of each nearby lightning stroke, i.e. the center of the error ellipse, the distance to the closest edge of the ellipse, and the peak current of the stroke, etc. A schematic diagram of these distances is in Figure-7. For each key facility, the customer specifies a critical distance within which lightning strikes merit additional investigation. If the distance to the stroke is larger than the inspection threshold, then the customer can be confident that inspection of the electronics is not needed. The inspection thresholds allow for the uncertainty in the peak current estimate. If the distance to the closest point of error ellipse is also larger than the inspection threshold for a stroke of that peak current, then the customer can be very confident that an inspection is not needed. A Google-Maps visualization is available on request (Figure-8). A copy of the lightning report is at Figure-9.

Customer points of interest include launch pads, payload/space launch vehicle processing facilities, and other facilities. The 29 key facilities supported by the 45 WS daily lightning reports are listed in Table-2.

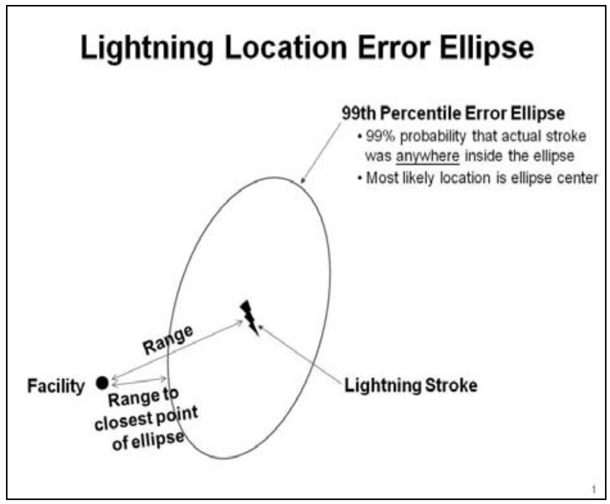


Figure 7. Schematic diagram of a lightning location error ellipse.

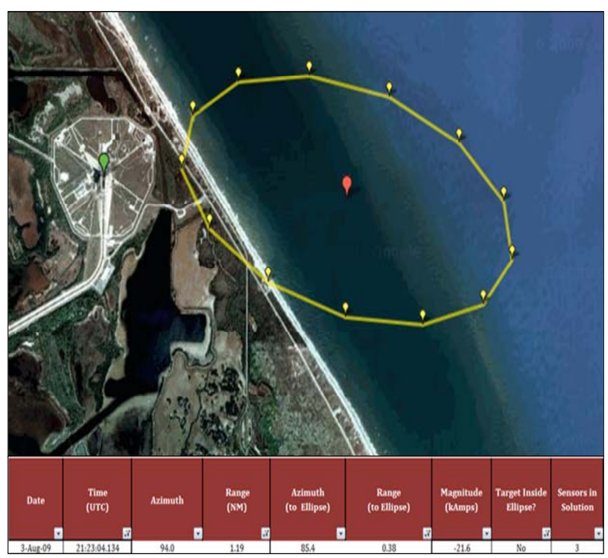


Figure 8. Example of the Google-Maps visualization provided when the lightning strike is within the critical distance. The 13 points used to approximate the location error ellipse are shown.

Confidence Ellipse Data

Number of strokes in which the center of the launch complex is inside the 99% confidence Ellipse: 3

Shuttle Complex 39A, 3 August 2009
Data from the 45th Weather Squadron
Cloud-to-Ground Lightning Surveillance System II (CGLSS II)

99% Confidence Ellipse Data

Date	Time (UTC)	Magnitude (kA)	Azimuth	Range (NM)	Azimuth (to Ellipse*)	Range (to Ellipse*)	Magnitude (kAmps)	Target Inside Ellipse*?	Sensors in Solution
3-Aug-09	21:10:40.527	-39.8	288.4	0.46	26.3	0.11	-39.8	Yes	3
3-Aug-09	21:10:40.601	-32.2	296.4	0.42	53.3	0.42	-32.2	Yes	2
3-Aug-09	21:10:41.240	-49.1	292.9	0.61	101.9	0.09	-49.1	Yes	4

Figure 9. Example of the daily lightning report provided by 45 WS. For KSC, lightning strokes that are inside the operationally critical radius of 0.45 nmi are highlighted in green. Points of interest that lie inside the error ellipse are highlighted in magenta to aid interpretation of the range to ellipse.

TABLE-2.
The 29 Key Facilities for which 45 WS issues daily lightning reports.

Key Facility	Primary Customer
Atlas Space Operations Center	Atlas
Area 59	Delta-IV
Astrotech	Commercial Satellite Processing Facility
Launch Complex-17A	Delta-II
Launch Complex-17B	Delta-II
Launch Complex-36	Space Florida
Launch Complex-37B	Delta-IV
Launch Complex-39A	Kennedy Space Center
Launch Complex-39B	Kennedy Space Center
Launch Complex-40	Falcon-9
Launch Complex-41	Atlas-V
Delta-IV Operations Center	Delta-IV
Falcon Launch Control Center	Falcon
Horizontal Integration Facility	Delta-IV
Joint Surveillance and Target Attack Radar System	U.S. Air Force
Operations & Checkout	Kennedy Space Center

Key Facility	Primary Customer
Patrick Air Force Base	45th Space Wing
Payload Hazardous Servicing Facility	Kennedy Space Center
Port	Navy
Range Control Center	45th Space Wing
Skid Strip	45th Space Wing
Shuttle Landing Facility-Runway North	Kennedy Space Center
Shuttle Landing Facility-Runway South	Kennedy Space Center
Shuttle Landing Facility-Mate/Demate Facility	Kennedy Space Center
Solid Motor Assembly Building	Kennedy Space Center
Shuttle Payload Integration Facility	Kennedy Space Center
Space Station Processing Facility	Kennedy Space Center
Vehicle Assembly Building	Kennedy Space Center
Vertical Integration Facility	Atlas-V

2.3 On-demand 24/7 Lightning Reports

The use of error ellipses was a significant improvement over the previous method. However, due to computer security requirements, the initial process required a system administrator to copy the data from the 4DLSS workstation and hand-carry it to 45 WS. Due to the system administrator's work schedule, this meant lightning reports could not be generated nights, weekends, or holidays if a nearby lightning strike occurred during a major non-launch operation and sometimes early during a launch countdown. A workstation was installed in the 45 WS operations area with a communications link to the 4DLSS workstation on 17 Aug 09. This allowed on-demand lightning reports in near real-time without system administrator support. Within minutes, the data are now available to 45 WS for calculation of the error ellipses. Just 10 days after the workstation was installed, the situation it was designed to mitigate occurred. During the nighttime countdown for the Space Shuttle STS-128 mission, lightning struck near the launch pad on 27 Aug 09. The on-demand lightning report showed inspection of the electronics was required. By providing the report immediately, rather than waiting for the next morning as done in the past, only a 24-hour slip of the launch occurred, rather than a 48-hour slip, providing a cost avoidance of over $1 million.

2.4 Fixed Truncation Error Of Peak Current

Another improvement to the 45 WS lightning reports was the discovery and correction of a truncation of the lightning stroke peak currents in the computer database used to generate the reports. The peak current was truncated, rather than rounded to the nearest integer kilo Amp (kA). With an average peak current of 20 kA, this truncation was causing up to a 4% underestimate of the peak current.

2.5 KSC Automatic E-mail Alerts And Website

On their own initiative, KSC provided automatic 24/7 e-mail notification in near real-time to customers whenever a lightning stroke exceeded that customer's distance and/or intensity threshold. These e-mails use a 30 minute cycle time, so customers are notified of important lightning with an average lag time of 15 min. KSC also displays stroke locations and distance/intensity data in near real-time at a customer accessible website.

3. On-going Improvements To The 45 WS Lightning Reports

Further improvements to the 45 WS lightning reporting process are being pursued or considered as future projects.

3.1 Probability That Any Nearby Lightning Stroke Is Within Any Radius Of Any Point Of Interest

A technique has been developed to calculate the probability that any nearby lightning stroke is within any radius of any point of interest (Figure-10). In practice, this provides the probability that a nearby lightning stroke was within a key distance of a facility, rather than the error ellipses centered on the stroke. This process takes the current bivariate Gaussian distribution of probability density provided by the current lightning location error ellipse for the most likely location of a lightning stroke and integrates it to get the probability that the stroke is inside any specified circle. This new facility-centric technique will be much more useful to the space launch customers and may supersede the lightning error ellipse approach discussed above. The technical details of this new technique are available at Huddleston (2010) and will be presented in a paper submitted to the 21st International Lightning Detection Conference, 21-22 April 2010 (Huddleston et al., 2010). The KSC was considering adding error ellipses to their website displaying nearby lightning strokes in near real-time and to their automatic e-mail notifications. That effort may be superseded by this new technique.

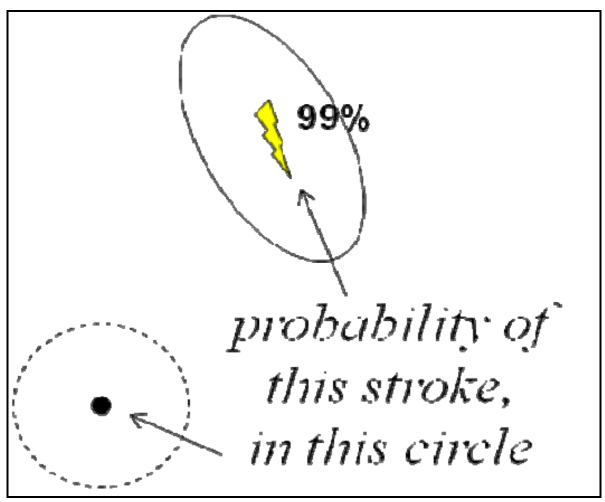


Figure 10. Schematic of the new facility-centric process of calculating the probability of any stroke within any radius of any point.

3.2 Distance To The Closest Point Of Lightning Location Error Ellipse

The closest point on an ellipse to any arbitrary point cannot be found analytically. This complicates calculating the distance from a key facility to the closest point of lightning location error ellipse. This distance was initially approximated by the distance to the closest of 13 evenly spaced points on the error ellipse. Only 13 points were used due to limitations of the Microsoft® EXCEL spreadsheet software. Unfortunately, this method can grossly overestimate the distance when the point of interest is near the ellipse and about equidistant between the 13 points (Figure-11). Under worst-case conditions, the error can be up to 1.5 nmi, which is very significant when the radius for an area of interest may be only a few tenths of a nmi.

A visual basic program was developed that iterates to a much more accurate solution for the closest point on the error ellipse to the point of interest. A schematic of this iteration process is shown in Figure-12. The process begins by calculating the distance from the point of interest to eight points on the ellipse, spaced every $\pi/4$ radians (45°) around the center of the error ellipse

Figure 11. The previous method of estimating the distance from the facility to the closest point on the error ellipse was done using the distance to the closest of the 13 evenly spaced points used to approximate the ellipse. This method would grossly over-estimate the distance when the facility was close to the ellipse and about equidistant from the two closest 13 points. This method was replaced by a far superior method as discussed in the text and shown in Figure-12.

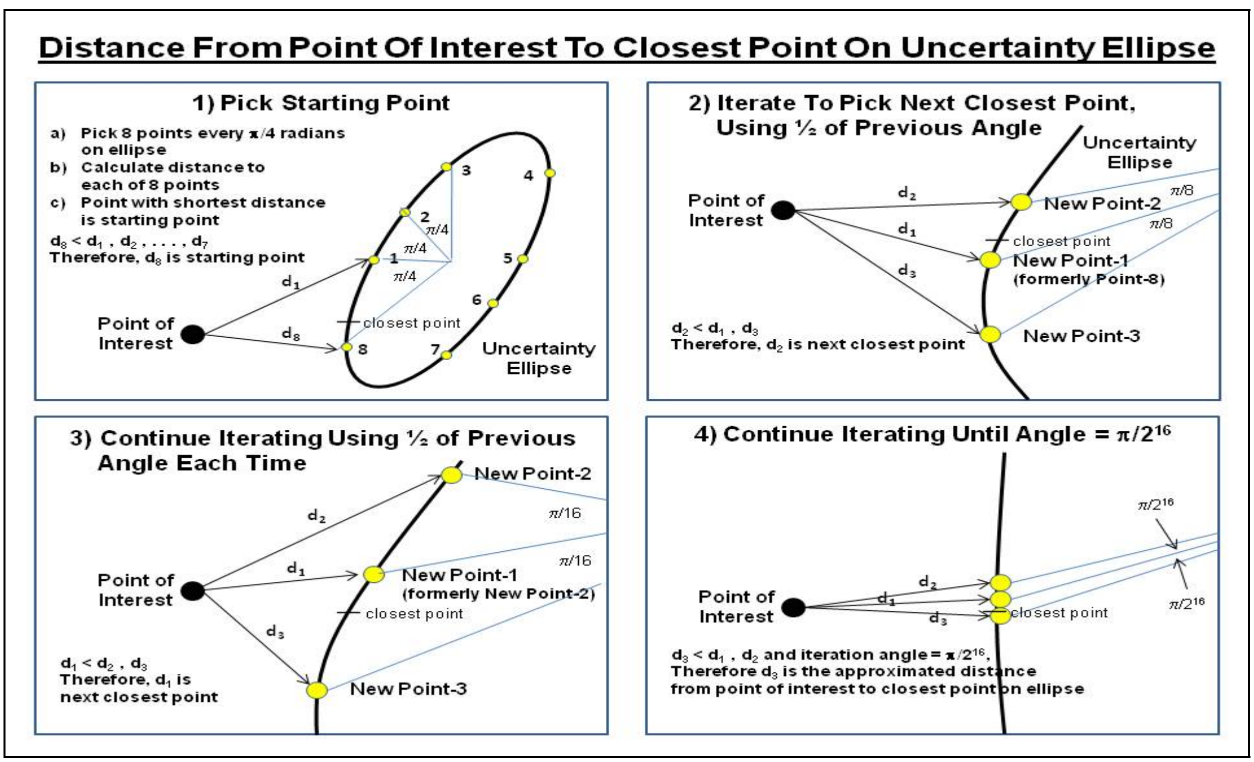


Figure 12. The new method estimates the distance from a facility to the closest point of the error ellipse. The new method is far superior to the previous method since it overcomes the problem of grossly overestimating the distance under some scenarios as discussed in the text and shown in Figure-11.

starting due west of the center of the ellipse. The closest of these eight points is chosen as the starting point. On the first iteration, three subsequent candidate closest points are selected on the error ellipse, the current chosen point and points spaced $\pi/8$ radians (22.5°) (half the previous angle) to either side of that point relative to the center of the ellipse. The closest of these three points is chosen. On the next iteration, three subsequent candidate closest points are selected on the error ellipse, the point chosen in the previous iteration and points spaced half the angle in the previous iteration angle to either side. The iteration is continued until the iteration angle is $\pi/2^{16}$ radians (0.002747°). The closest of the three candidate points in that last iteration is selected as the final closest point and the iteration is ended. This is equivalent to approximating the error ellipse with 65,000 points and choosing the closest of the points in just 50 iterations, which was a vast improvement over the previous method of choosing the closest of 13 evenly spaced points approximating the error ellipse. Even in a very unfavorable scenario, this method provides a location error no larger than 2.5 m, two orders of magnitude less than the best location error possible from the 4DLSS.

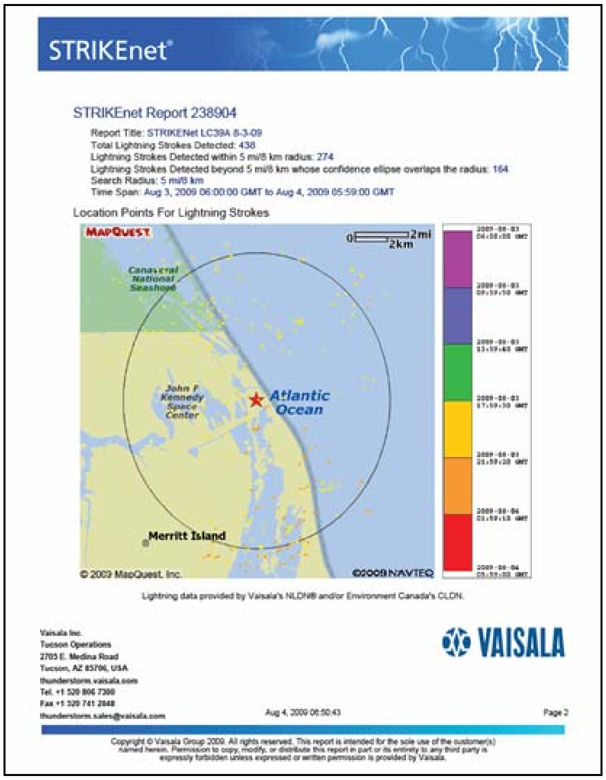
3.3 Strong Local Lightning Strokes Sometimes Not Detected

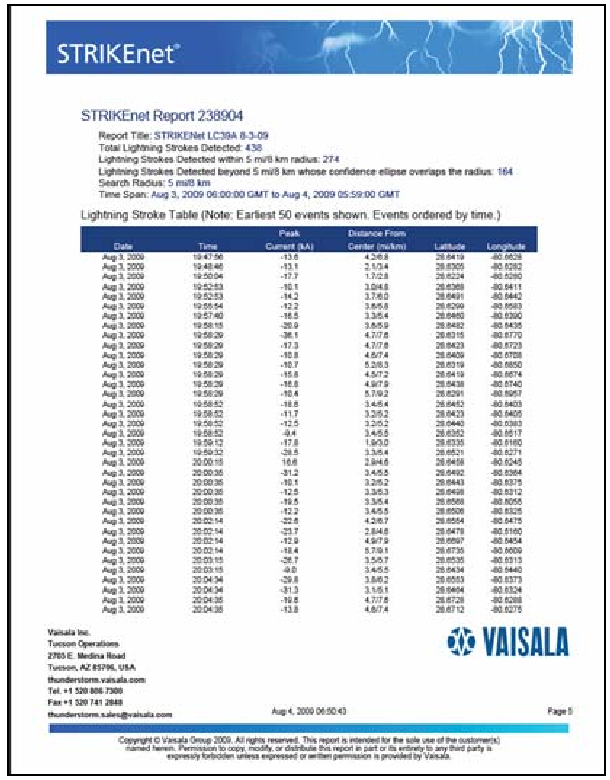
Recent research has shown that 4DLSS can be saturated by strong local strokes and fail to detect them, especially those with peak currents of 50 KA or greater (Ward et al., 2008). However, 4DLSS excels at detecting weak local strokes. On the other hand, the wider spacing of the NLDN sensors excels at detecting those strong strokes, but loses detection efficiency for weaker strokes near CCAFS/KSC, especially those with peak currents of 7 KA or less. This suggests that combining the sensor data from both systems in real-time could lead to improved performance. The 45 WS is pursuing integrating data from nine NLDN sensors into 4DLSS in real-time to improve the detection of strong local strokes. The nine NLDN sensors being considered are based on those closest to CCAFS/KSC and those with the best complementary geometry relative to CCAFS/KSC. The nine NLDN sensors being considered for incorporation into 4DLSS are all seven of the sensors in FL, one just across the state line in GA, and one in the Bahamas Islands. Integrating of the sensor data from those NLDN sensors into 4DLSS in real-time will also improve the location accuracy, detection efficiency, and provide smaller and less eccentric error ellipses when only a few of the 4DLSS sensors are used in the solution. The performance of 4DLSS will not be compromised when most of the 4DLSS sensors are used in the lightning solution.

As an interim measure, KSC is purchasing StrikeNet reports from Vaisala, Inc. when lightning strokes are detected or suspected near KSC points of interest. The StrikeNet reports include all the strokes detected by NLDN, as opposed to the more routinely available flash-only data, and so should include the strong local strokes missed by 4DLSS. The StrikeNet reports also allow cross-comparison with the 4DLSS lightning reports to identify strokes 4DLSS may have missed and to check for consistency in lightning locations and peak current. Some sample output of a StrikeNet report is shown in Figure-13. The StrikeNet solution is not as good as integrating the nearby NLDN sensors into 4DLSS for two reasons. First, the location, location error ellipses, and peak current solutions are not optimized with all the sensor data from 4DLSS and available NLDN for each stroke. Second, inconsistencies between the two reports may occur, requiring manual analysis to reconcile. However, the StrikeNet reports are available now, while the integration of nearby NLDN sensors into 4DLSS is still being developed. The 45 WS is pursuing funding to acquire StrikeNet reports to support their DoD, commercial, and NASA unmanned launch customers.

3.4 Fault Analysis Lightning Location System

The 45 WS considered acquiring the Fault Analysis Lightning Location System (FALLS) (Vaisala, 2009). The FALLS would have provided advanced analysis capabilities as well as display of the error ellipses. However, given the in-house lightning reporting improvements discussed above, the 45 WS decided FALLS was not cost-effective for their mission.




STRIKEnet®

STRIKEnet Report 238904

Report Title: STRIKENet LC39A 8-3-09
Total Lightning Strokes Detected: 438
Lightning Strokes Detected within 5 mi/8 km radius: 274
Lightning Strokes Detected beyond 5 mi/8 km whose confidence ellipse overlaps the radius: 164
Search Radius: 5 mi/8 km
Time Span: Aug 3, 2009 06:00:00 GMT to Aug 4, 2009 05:59:00 GMT

Lightning Stroke Table (Note: Earliest 50 events shown. Events ordered by time.)

Date	Time	Peak Current (kA)	Distance From Center (mi/km)	Latitude	Longitude
Aug 3, 2009	19:47:56	-13.6	4.2/6.8	28.6419	-80.6629
Aug 3, 2009	19:48:46	-13.1	2.1/3.4	28.6305	-80.6282
Aug 3, 2009	19:50:04	-17.7	1.7/2.8	28.6224	-80.6280
Aug 3, 2009	19:52:53	-10.1	3.0/4.8	28.6368	-80.6411
Aug 3, 2009	19:52:53	-14.2	3.7/6.0	28.6491	-80.6442
Aug 3, 2009	19:55:54	-12.2	3.6/5.8	28.6299	-80.6583
Aug 3, 2009	19:57:40	-16.5	3.3/5.4	28.6460	-80.6390
Aug 3, 2009	19:58:15	-20.9	3.6/5.9	28.6482	-80.6435
Aug 3, 2009	19:58:29	-36.1	4.7/7.6	28.6315	-80.6770
Aug 3, 2009	19:58:29	-17.3	4.7/7.6	28.6423	-80.6723
Aug 3, 2009	19:58:29	-10.8	4.6/7.4	28.6409	-80.6708
Aug 3, 2009	19:58:29	-10.7	5.2/8.3	28.6319	-80.6850
Aug 3, 2009	19:58:29	-15.8	4.5/7.2	28.6419	-80.6674
Aug 3, 2009	19:58:29	-16.8	4.9/7.9	28.6438	-80.6740
Aug 3, 2009	19:58:29	-10.4	5.7/9.2	28.6291	-80.6957
Aug 3, 2009	19:58:52	-18.6	3.4/5.4	28.6452	-80.6403
Aug 3, 2009	19:58:52	-11.7	3.2/5.2	28.6423	-80.6405
Aug 3, 2009	19:58:52	-12.5	3.2/5.2	28.6440	-80.6383
Aug 3, 2009	19:58:52	-9.4	3.4/5.5	28.6352	-80.6517
Aug 3, 2009	19:59:12	-17.8	1.9/3.0	28.6335	-80.6160
Aug 3, 2009	19:59:32	-28.5	3.3/5.4	28.6521	-80.6271
Aug 3, 2009	20:00:15	16.6	2.9/4.6	28.6458	-80.6245
Aug 3, 2009	20:00:35	-31.2	3.4/5.5	28.6492	-80.6364
Aug 3, 2009	20:00:35	-10.1	3.2/5.2	28.6443	-80.6375
Aug 3, 2009	20:00:35	-12.5	3.3/5.3	28.6498	-80.6312
Aug 3, 2009	20:00:35	-19.5	3.3/5.4	28.6568	-80.6055
Aug 3, 2009	20:00:35	-12.2	3.4/5.5	28.6506	-80.6325
Aug 3, 2009	20:02:14	-22.6	4.2/6.7	28.6554	-80.6475
Aug 3, 2009	20:02:14	-23.7	2.8/4.6	28.6478	-80.6160
Aug 3, 2009	20:02:14	-12.9	4.9/7.9	28.6697	-80.5454
Aug 3, 2009	20:02:14	-18.4	5.7/9.1	28.6735	-80.5609
Aug 3, 2009	20:03:15	-26.7	3.5/5.7	28.6535	-80.6313
Aug 3, 2009	20:03:15	-9.6	3.4/5.5	28.6434	-80.6440
Aug 3, 2009	20:04:34	-29.6	3.8/6.2	28.6553	-80.6373
Aug 3, 2009	20:04:34	-31.3	3.1/5.1	28.6464	-80.6324
Aug 3, 2009	20:04:35	-19.6	4.7/7.6	28.6729	-80.6288
Aug 3, 2009	20:04:35	-13.6	4.6/7.4	28.6712	-80.6275

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Page 5

Figure 13. Sample output from a StrikeNet report, which provides stroke data from NLDN.

3.5 KSC Automatic E-mail And Website

KSC is considering adding the location error ellipses to their automatic 24/7 e-mail alerts and display error ellipses at their website so the customers can see this important data in near real time. This effort may be superseded by the new probability of any lightning stroke being inside any radius of any location, as discussed in section-3.1.

4. Possible Future Improvements To The 45 WS Lightning Reports

There are two main avenues to improving the 45 WS lightning reports even further in the future: 1) improved peak current estimates and improved error estimates of the peak current accuracy, and 2) 4DLSS maintenance and upgrades.

4.1 Improved Peak Current Estimates And Peak Current Errors

There are five main factors in assessing the induced current hazard presented by nearby lightning: 1) the detection rate of the lightning detection system being used, 2) the distance to the stroke, 3) the error in the location, 4) the peak current of the stroke, and 5) the error in the peak current. Considerable work has been done over the years in improving and understanding the detection rate and location accuracy of lightning detection systems, including 4DLSS. However, more work is needed to improve the estimate of peak current as well as the error in the estimate of the peak current.

Anyone interested in helping conduct these peak current and peak current error studies is encouraged to contact the corresponding author.

4.1.1 Improved Peak Current Estimates

The 45 WS is interested in improving the estimates of the peak currents from 4DLSS. At present, the peak current estimate is calculated from the peak magnetic field at each sensor. The peak magnetic field is normalized to a range of 100 km and corrected for attenuation from ground propagation effects. The mean of the attenuation-corrected range-normalized peak magnetic fields is converted to peak current via a regression equation (Cummins et al., 1998). That regression equation was based primarily on data from rocket-triggered lightning. As a result, it is less representative for first strokes from natural lightning. 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. An appropriately instrumented tall tower in a wide open flat area with frequent lightning and subsequent analysis of that data should allow significantly improved peak current estimates, especially for the operationally more important first strokes. The CCAFS/KSC has a network of weather towers that would be a natural candidate for such an instrumented tower given the lightning frequency and terrain in that area. 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 near the coast. Shorter towers farther inland might be more likely to be struck by lightning since the climatological lightning flash density increases in-land. Funding for this project was not available at the time this paper was written (Jan 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 should be explored to avoid the additional uncertainties introduced by the range-normalization and the regression equation.

4.1.2 Improved Peak Current <u>Error</u> Estimates

The error estimate of the peak current for cloud to ground lightning strokes from 4DLSS has not been as well studied as the 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%, based on vendor recommendation, is used for all strokes, regardless of number of sensors used in the solution and distance of those sensors to the lightning stroke. Some lightning detection experts have suggested that the actual errors in peak current are larger than ±20% (Mata, 2009). It appears that most customers outside of space launch are much more interested in detection rate and location accuracy than in peak current and even more so peak current accuracy. As a result, more effort has been invested to quantify and improve the performance of the former, rather than the latter.

The 45 WS is interested in improved error estimates for peak current provided by 4DLSS. The best approach would be the instrumented tower discussed in section-4.1.1, which was also the best way to improve the estimated of peak currents.

Another possibility is to calculate the standard deviation of a peak current from the peak current linear regression. Error bars associated with a linear regression are easily calculated (Wilks, 2006). This would allow calculation of a standard deviation tailored to individual return strokes. Given the expected peak current and its standard deviation, the probability of exceeding any threshold(s) can be calculated. One application for space launch customers could be to calculate the peak current threshold(s) for different levels of inspections of elections given the distance to a nearby lightning stroke, then calculate the probability of exceeding that peak current(s). A similar approach was developed to forecast the expected peak wind and probability of exceeding wind warning thresholds at CCAFS/KSC (Barrett et al., 2008). There are likely more effective approaches to factor peak current uncertainty into the decision models for inspecting electronics, e.g. calculate the probability of exceeding the combined distance and peak current thresholds. Since no research is required, development of such applications could begin almost immediately, assuming the required parameters from the original linear regression are available. The assumption of Gaussian distribution of residuals should also be verified.

Another possible approach might be using the variability of the peak current estimated from each sensor used in the lightning solution. The standard deviation of the distribution of peak current from the sensors used to solve the stroke could be used to generate probabilistic confidence intervals. A total range or a percentile approach of the peak currents from individual sensors might also be useful, e.g. inter-quartile range, 95th or 99th percentile, etc. As before, the space launch customers could factor the uncertainty of peak current more effectively into their decision models.

4.2 4DLSS Maintenance And Upgrades

The 45 WS is interested in maintaining and upgrading 4DLSS since improved lightning detection will provide improved lightning reports. Four main possible approaches to upgrade CGLSS are available. First, conduct a new Network Performance Evaluation Program (NPEP) and schedule them periodically. Second, replace the 4DLSS sensors with the new model for long-term maintenance sustainability. Third, integrate any new nearby NLDN sensors into 4DLSS. Fourth, add a seventh sensor to 4DLSS. Unfortunately, none of these activities is currently funded.

4.2.1 New and Periodic Network Performance Evaluation Program

A Network Performance Evaluation Program (NPEP) was last accomplished for 4DLSS in summer of 2008, shortly after the system was installed. No major problems were found, but a minor radio noise problem was detected at one of the sites. A new NPEP should be conducted, since one is recommended every 1.5 years. If the previous minor radio noise problem still exists, a remediation may be worthwhile. Also the NPEP would check for any new problems. The NPEP should be repeated every 1.5 years for stable lightning detection systems that are performing well, as recommended by the vendor (Vaisala, 2008).

4.2.2 Replace 4DLSS Sensors with New Model

The current CG-lightning IMPACT Model 141-T sensors are no longer supported by Vaisala, Inc. This is already causing maintenance problems. For example, the Melbourne sensor was damaged by a lightning strike on 26 Jul 2009 and a replacement sensor was not available, so 4DLSS is in a temporary 5-sensor configuration at the time this paper is being written (Jan 10), rather than the nominal 6-sensor configuration. The Tosohatchee sensor was moved to the Melbourne location to replace the sole line of sight to CCAFS/KSC from the south and activated on 11 Aug 09 (see Figure-2 for sensor locations). The line of sight from the west provided by Tosohatchee is duplicated in part by the Seminole sensor. Fortunately, Vaisala is manufacturing the LS7001 sensor, which they plan to support for many years. This new sensor should be a simple plug-in replacement of the current sensors with no loss of performance and requiring no modification to the rest of 4DLSS. While a test of the new sensor model in 4DLSS is funded and being scheduled, the follow-on replacement of all the current sensors is not yet funded, pending results of that test. However, replacing the sensors is mission-essential to ensure sustainability of 4DLSS.

The testing of the new LS7001 sensor and subsequent replacement of the current 4DLSS sensors may be taking on heightened urgency. Preliminary analysis indicates that the performance degradation to cloud-to-ground lightning detection was larger than expected after the loss of the Melbourne sensor on 26 Jul 09 and relocation of the Tosohatchee sensor to the Melbourne site that was activated on 11 Aug 09 (see Figure-2 for site locations). Some summary performance metrics for both configurations are listed in Table-3. All four of the metrics indicate significantly degraded performance after transitioning to the temporary 5-sensor configuration. The median number of sensors per solution fell 46.3% and percent of solutions with only 2 or 3 sensors (poor or marginal performance, respectively) increased 395.7%. The distribution of number of sensors per lightning solution under both configurations is shown in Figure-14. The median area and of the location error ellipses increased 100.0% and the median eccentricity increased 5.9%. The degraded performance may not be inherent to the temporary 5-sensor configuration. It is possible that the relocated sensor requires calibration at the new site, e.g. its orientation may be misaligned by 1-2°.

Table 3. 4DLSS performance under the nominal 6-sensor configuration and the current temporary 5-sensor configuration with the Tosohatchee sensor relocated to the Melbourne site.

Performance Metric	6-Sensor Config.	5-Sensor Config.
Median Number of Sensors per Solution	4.80	2.58
Percent of Solutions with only 2 or 3 Sensors (poor-marginal performance)	14.1%	69.9%
Median Area of 99% Location Ellipse	0.102 nmi^2	0.204 nmi^2
Median Eccentricity of 99% Location Ellipse	0.87	0.91

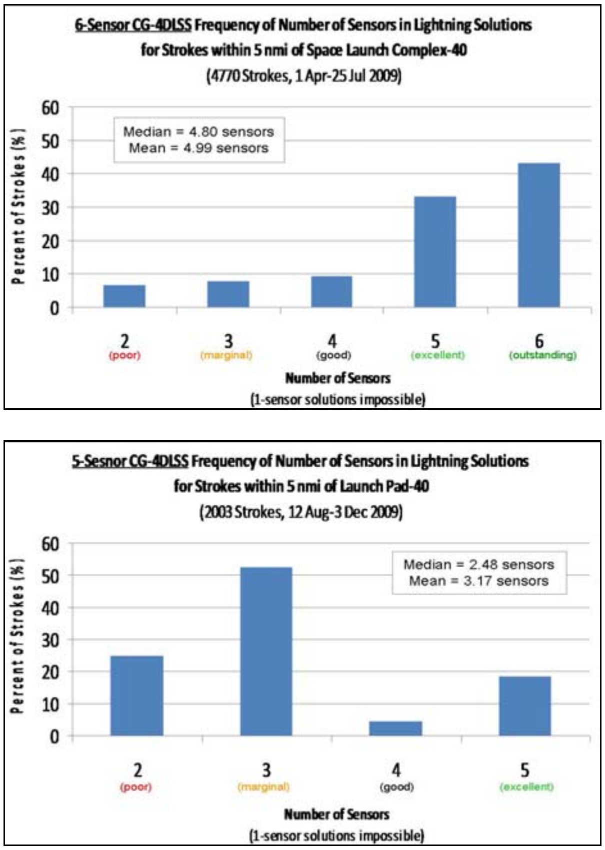

Figure 14. Frequency of number of sensors per lightning solution for strokes near the CCAFS/KSC launch pads under the nominal 6-sensor configuration *(upper figure)*, and the current temporary 5-sensor configuration *(lower figure)*. The 6-sensor end date of 25 Jul 09 was chosen to be the day before the Melbourne sensor was damaged (26 Jul 09). The 5-sensor start date 12 Aug 09 was chosen to be the day after the relocated Tosohatchee was activated at the Melbourne site (11 Aug 09). This ensured the 6-sensor and 5-sensor analyses included data only from those configurations.

4.2.3 Integrate any New Nearby NLDN Sensors

In section-3, the on-going effort to inject data from nine surrounding NLDN sensor data to 4DLSS was discussed. When that effort began in early 2009, Vaisala, Inc. was considering adding another NLDN sensor in central Florida, perhaps near Daytona Beach. If that sensor is added to NLDN, then it should also be incorporated into 4DLSS. Likewise, any other new NLDN sensors added in Florida, southern Georgia, or the Bahamas Islands should be considered for integration into 4DLSS.

If the new NLDN sensor is not added, the 45 WS may consider adding a new eighth 4DLSS sensor to 4DLSS at a distance of about 60 nmi from KSC/CCAFS. This new eighth sensor would be in addition to the new seventh sensor discussed in section 4.2.4. However, it may be more cost-effective to fund Vaisala to install and maintain such a sensor for 45 WS to ingest its data into 4DLSS. Either approach should help reduce the problem of strong local strokes sometimes not being detected by 4DLSS.

4.2.4 Add a New Seventh Sensor to 4DLSS

The performance of 4DLSS could be made more robust if a new seventh sensor was added. If this new seventh sensor is sited at a near center location, it should reduce the sensitivity to performance if the Cape sensor is not used in the solution (Table-1). In addition, the preliminary analysis of performance loss under the current temporary 5-sensor configuration suggests the gain in robustness with a new seventh sensor may be worthwhile. If this new seventh sensor is added, a location at the southwest edge of KSC should provide increased performance for lightning near the launch pads when the Cape sensor is used in the solution. In addition, if this new seventh sensor is added, moving the Seminole sensor a few miles to the northeast would optimize the performance of 4DLSS slightly, but this change may not be cost-effective. The addition of a new seventh sensor has not yet been formally recommended by 45 WS yet so funding has not been considered.

5. Summary

The 45 WS provides daily lightning reports to space launch customers at CCAFS/KSC. These reports are provided to assess the need to inspect the electronics of satellite payloads, space launch vehicles, and ground support equipment for induced current damage from nearby lightning strokes.

The 45 WS has made several improvements to the lightning reports during 2008-2009. The 4DLSS, implemented in April 2008, provides all lightning strokes as opposed to just one stroke per flash as done by the previous system. Recall that the 4DLSS integrated the previous Cloud to Ground Lightning Surveillance System.

The 45 WS discovered that the peak current was being truncated to the nearest kilo amp in the database used to generate the daily lightning reports. This error was corrected and led to elimination of the up to a 4% underestimate of the peak current for average lightning.

The 45 WS and their mission partners developed lightning location error ellipses for 99% and 95% location accuracies tailored to each individual stroke and began providing them in the spring of 2009. The new procedure provides the distance from the point of interest to the best location of the stroke (the center of the error ellipse) and the distance to the closest edge of the ellipse. This information is now included in the lightning reports, along with the peak current of the stroke. The initial method of calculating the error ellipses could only be used during normal duty hours, i.e. not during nights, weekends, or holidays. This method was improved later to provide lightning reports in near real-time 24/7. The calculation of the distance to the closest point on the ellipse was also significantly improved later. Other improvements were also implemented.

A new method to calculate the probability of any nearby lightning stroke being within any radius of any point of interest was developed and is being implemented. This may supersede the use of location error ellipses.

The 45 WS is pursuing adding data from nine NLDN sensors into 4DLSS in real-time. This will overcome the problem of 4DLSS missing some of the strong local strokes. This will also improve the location accuracy and reduce the size and eccentricity of the location error ellipses when few of the 4DLSS sensors are used in the stroke solution. This will not reduce 4DLSS performance when most of the 4DLSS sensors are used in the stroke solution.

Finally, several possible future improvements were listed, especially for improving the peak current estimate and the error estimate for peak current, and upgrading the 4DLSS. Some possible approaches for both of these goals were discussed.

6. Acknowledgements

Dr. Huddleston of the KSC NASA Orbiter Mechanical Systems office developed the program that calculates the probability of any nearby lightning stroke being within a radius of any point of interest. Dr. Huddleston also improved the calculation of the distance to the closest point of the error ellipse and improved the search routine of the spreadsheet that determines which lightning strokes were close enough to require a lightning report, making the spreadsheet run an order of magnitude faster. This work was done under the KSC Employee Development Program.

Mr. Jeremy Hinkley and Mr. Pete Hopman of United Space Alliance, one of the main contractors for Space Shuttle operations, developed the software to calculate the distance from the point of interest to the closest point on the error ellipse. They also developed the software that accelerated the search routine to filter out lightning strokes too far to be an induced current threat, which saved time processing the remaining strokes for threat assessment.

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