

2.4 THE POTENTIAL OF HIGH PERFORMANCE, REGIONAL TOTAL LIGHTNING NETWORKS AND ENHANCED DISPLAY PRODUCTS FOR PUBLIC SAFETY AND BROADCAST METEOROLOGY APPLICATIONS

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1. INTRODUCTION

Vaisala has been operating a regional total (cloud and cloud-to-ground) lightning demonstration network in the Dallas-Fort Worth, TX area since 2001. This Lightning Detection and Ranging (LDAR II) network builds upon the Very High Frequency (VHF) lightning detection technology first developed at NASA Kennedy Space Center called LDAR (Maier et al., 1995). This same technology has also been modified by New Mexico Tech Institute of Mining and Technology (NMT) into the Lightning Mapping Array (LMA) (Rison et al., 1999). The Dallas-Fort Worth (DFW) LDAR II network detects over 90% of all cloud and cloud-to-ground (CG) lightning within 120 km of DFW International Airport. LDAR II's ability to map these lightning flashes in three dimensions, coupled with its high flash detection efficiency, allow a complete three-dimensional reconstruction of the lightning channels in a thunderstorm. Data from this network are currently being used for real-time thunderstorm monitoring at the Fort Worth National Weather Service Forecast Office. Vaisala also provides LS8000 VHF total lightning mapping networks that provide similar capabilities to LDAR II, except only in two-dimensions. LS8000 sensors employ interferometric lightning detection techniques. An example of data from this system will also be discussed in this paper.

Current media and safety display products show CG lightning. This information only conveys part of the CG lightning threat that exists to the public during thunderstorm activity. The DFW LDAR II network has regularly detected lightning flashes that extend over 50-100 km in length. These flashes pose a significant safety risk to the general public because, at any time, they are capable of producing a CG flash along their path. Many examples of these horizontally extensive lightning flashes will be shown using unique display tools developed by Vaisala. CG-only lightning displays are also not as useful as total lightning mapping displays for monitoring thunderstorm growth and dissipation and severe weather trends. Approximately 70% of all lightning stays in the cloud and never reaches the ground. In fact, some thunderstorms produce greater than 10 cloud flashes for every CG flash and a few may only produce cloud lightning for the first 60 minutes of a severe thunderstorm. Total lightning detection provides a

rich dataset that can be used with radar data to improve severe weather warnings and potentially increase the lead time for these warnings. Since the total lightning data is continuous, it can provide valuable information on thunderstorm growth and dissipation trends and severe weather development between radar volume scans.

Several unique storm animation tools will be presented. These tools provide easily-interpreted simultaneous displays of storm/cell location, total lightning rate, and/or CG lightning rate. These fields can be accurately superimposed on base maps of geo-coded information such as terrain height.

2. DFW LDAR II PERFORMANCE

The DFW LDAR II network consists of 7 sensors with 20 to 30 km baselines (Fig. 1). These sensors detect pulses of radiation produced by the electrical breakdown processes of lightning in 5 MHz VHF bands that currently have center frequencies ranging from 61 to 64 MHz. These pulses of radiation are used to reconstruct the path of individual cloud and CG lightning flashes in three dimensions. The DFW LDAR II network can map lightning flashes in three dimensions within approximately 150 km of the center of the network, degrading in performance with increasing range. Lightning flash detection efficiency is expected to be greater than 95% within the interior of the network (a range of 30 km from DFW



Figure 1. DFW LDAR II sensor sites. Each site is represented by a star, with its site identifier and site name located to the right of the star. County boundaries and names are also shown.

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International Airport – sensor A) and greater than 90% out to a range of 120 km from DFW International Airport. Expected 3-dimensional location accuracy for individual pulses of radiation is between 100 and 200 m within the network interior and better than 2 km to a range of 150 km from the center of the network.

3. VHF CLOUD FLASH MAPPING

Figure 2 shows a cloud flash that was detected over the southeast part of the DFW LDAR II network starting at 1004:31 UTC 11 April 2001. At about 1004:31.2 the initial upward electrical breakdown of this cloud flash occurs from about 5 to 9 km altitude, as indicated by the slight rise in elevation of sources in the altitude versus time panel of Figure 2 (top). The electrical breakdown along the whole path of this cloud flash and the charge reorganization within the clouds continue for the next 700 ms.

The vertical cross-section and plan-view panels clearly demonstrate the detailed three-dimensional mapping ability of the DFW LDAR II network (Fig. 2). The bi-level structure of the cloud flash can be seen by the sideways “H-type” pattern to the sources in both vertical cross sections. Many intricate branches

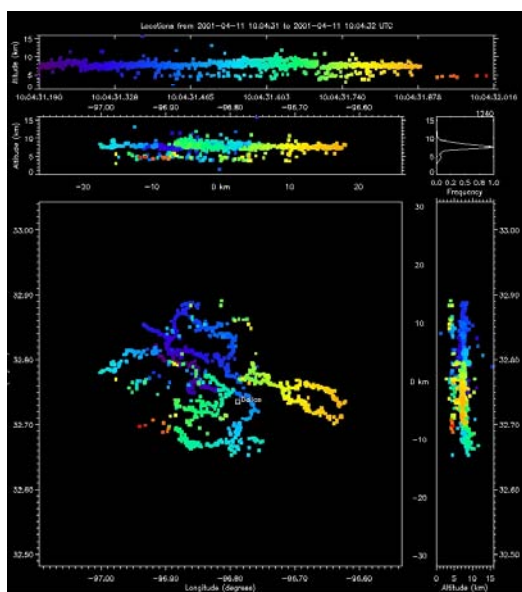


Figure 2. A cloud lightning flash detected by the DFW LDAR II network on 11 April 2001 between 1004:31-32 UTC. The top panel is an altitude (y) versus time (x) plot. The lower left is a plan view showing latitude (y) versus longitude (x). The lower right is a latitude (y) versus altitude (x) cross-section. The panel just above the plan view is an altitude (y) versus longitude (x) cross-section and the panel just to its right is an altitude (y) versus source frequency (x) plot. LDAR II sources are shown by dots.

and the true horizontal extent of the cloud flash are shown in the plan-view panel. This cloud flash covered an area of about 600 km².

As Figure 2 has shown, the presentation of LDAR II source data, while fascinating, could be difficult to interpret for today's television viewer. This is due to the knowledge required to mentally connect hundreds to thousands of dots on a display in order to visualize the branches associated with one lightning flash. “Connect-the-dots” algorithms have been developed at Vaisala in order to help solve this problem. Figures 3 and 4 show a horizontally extensive cloud lightning flash detected by the DFW LDAR II network. Figure 3 shows the flash as represented by hundreds of dots (sources), similar to what is seen in Figure 2. Figure 4 shows this same flash, except the sources are connected with lines according to the lightning's path of propagation. The interpretation of the intricate branching and extent of this lightning flash is much simpler because the TV viewer no longer has to mentally connect the individual points. This should make it easier for on-air meteorologists to show fascinating replays of horizontally extensive lightning flashes and numerous lightning flashes produced by interesting storms over specific time intervals.

4. CG LIGHTNING HAZARD

4.1 Stratiform precipitation lightning

Assessing the CG lightning threat region is critical for many applications that include, but are not limited to: (1) ground crew safety at airports, (2) outdoor events attended by large numbers of people, such as sporting events, (3) mission critical operations, including space shuttle launches, (4) operations involving explosives or highly flammable material, (5) golf courses and (6) recreation facilities.

CG lightning produced within stratiform rain regions that are attached to active thunderstorms are

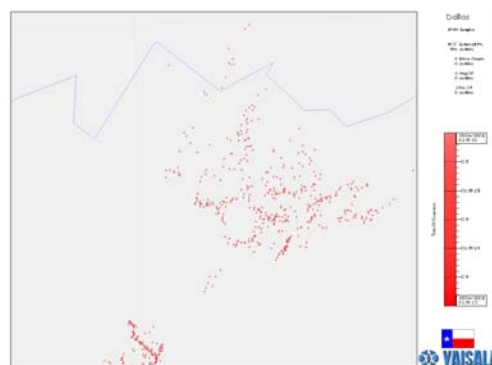


Figure 3. DFW LDAR II lightning sources detected within a horizontally extensive cloud flash 15 June 2001.

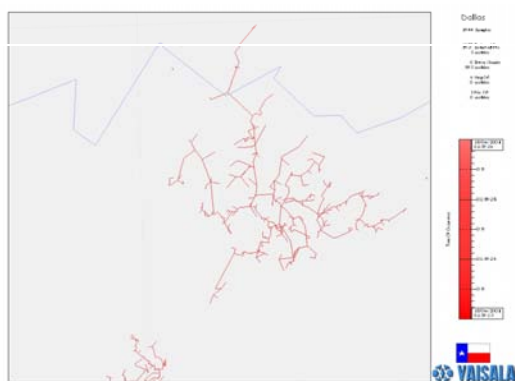


Figure 4. Same as Figure 3, except DFW LDAR II sources are connected using one of Vaisala's flash algorithms.

an important cause of lightning related injuries and fatalities (Holle et al., 1993). In these thunderstorm complexes, horizontally extensive cloud lightning flashes typically initiate in the convective thunderstorm cores and propagate through attached stratiform rain regions for distances sometimes exceeding 100 km. These horizontally extensive cloud flashes are particularly dangerous because they help produce isolated CG lightning discharges. Figure 5 shows the intricate 3-dimensional structure of one of these lightning flashes as detected by LDAR II. This lightning flash initiated approximately 40 km to the east-southeast of DFW Airport and propagated in a westward arc, terminating 25 km to the south of DFW Airport (plan view). A total of 337 LDAR II radiation sources were detected along its ~100 km path. According to Vaisala's National Lightning Detection Network (NLDN), this flash helped produce four isolated CG lightning strokes along its path. The final CG stroke injured a person at DFW Airport. Another impressive cloud flash was detected on 13 October 2001 (Fig. 6). It initiated just to the northwest of Waco and propagated north toward Fort Worth, before turning eastward and terminating near Dallas. This flash covered a path length of ~190 km and lasted over two seconds. To date, it is the longest flash found in the DFW data. NLDN CG lightning data indicated that this spider flash helped initiate two CG flashes with a separation of ~70 km (Fig. 6). The DFW LDAR II network can help address the problem of properly identifying the CG lightning hazard within the DFW area because it maps the horizontal extent of both cloud and CG flashes.

Figure 7 gives a dramatic example of the CG lightning risk within the trailing stratiform region of an MCS that passed through the DFW area on 15 June 2001. A comparison with Figure 8 shows that the NLDN flashes are mainly clustered along the leading convective line that is >50 km southeast of the center of the DFW LDAR II network (sensor A). However, the LDAR II sources indicate that cloud lightning is propagating over 100 km to the northwest of the

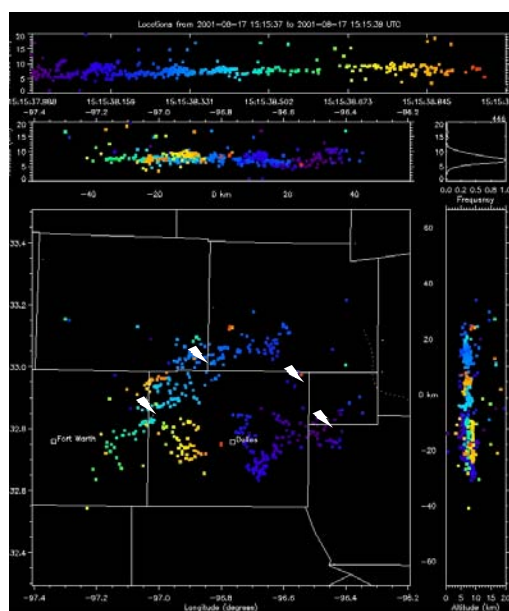


Figure 5. Same as Figure 2, except for a horizontally extensive cloud lightning flash detected by the DFW LDAR II network on 17 August 2001 between 1515:38-39 UTC. LDAR II sources are shown by dots and NLDN CG lightning stroke locations are indicated by the white lightning symbols.

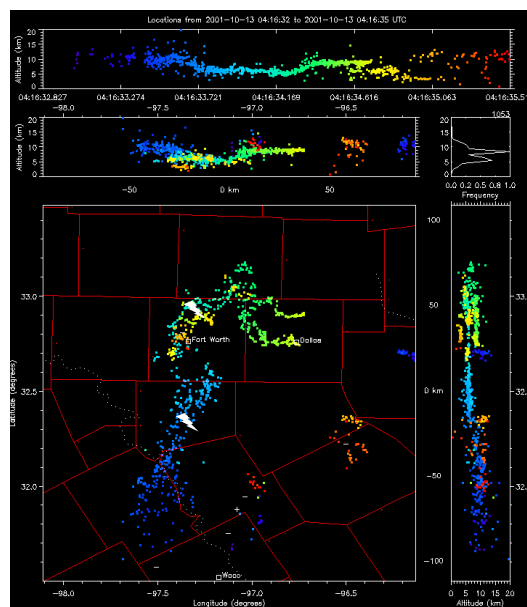


Figure 6. Same as Figure 2, except for a horizontally extensive cloud lightning flash detected by the DFW LDAR II network on 13 October 2001 between 0416:33-36 UTC. LDAR II sources are shown by dots and NLDN CG lightning stroke locations are indicated by the white lightning symbols.

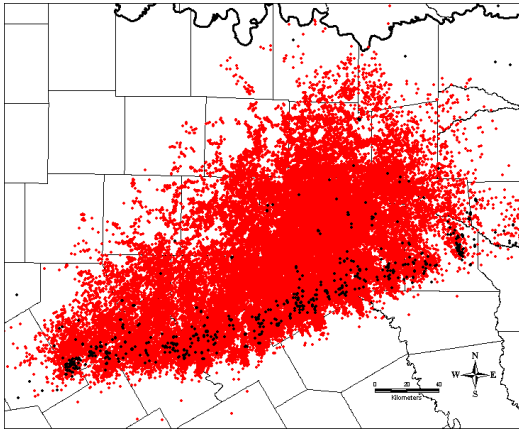


Figure 7. DFW LDAR II lightning sources (red) and NLDN CG lightning flashes (black) detected between 0312:30 and 0317:30 UTC 15 June 2001.

leading convective line, through the trailing stratiform region. The apparently random pattern of isolated CG flashes (sometimes located over 100 km from the leading convective line) produced by these trailing stratiform cloud flashes demonstrates the unpredictable nature of CG lightning in stratiform regions. Figure 7 shows that the whole DFW area is covered by trailing stratiform cloud lightning and therefore is at risk for isolated CG lightning discharges.

LDAR II and radar reflectivity observations from several MCSs that passed through the DFW area have shown that trailing stratiform regions do not necessarily have cloud lightning propagating throughout their entire area of coverage (Murphy and Holle, 2005). Therefore radar data alone can not define the isolated CG lightning threat through identification of the boundaries of the trailing

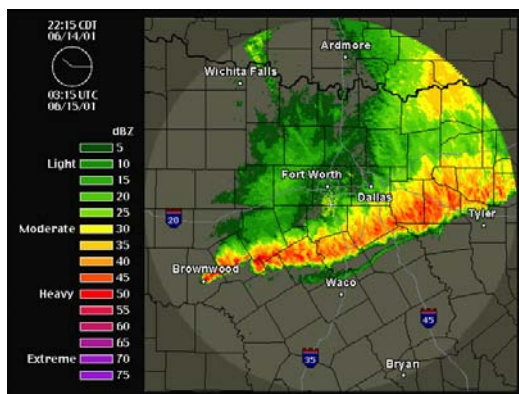


Figure 8. Fort Worth WSR-88D base reflectivity image from 0315 UTC 15 June 2001. The color key for reflectivity values is located on the left. (Image saved from The Weather Underground, 2001, www.wunderground.com)

stratiform region. It is critical to be able to map the horizontal extent of cloud lightning through the trailing stratiform region in order to properly define the isolated CG lightning threat.

4.2 Thunderstorm anvil lightning

CG lightning produced within anvil clouds attached to active thunderstorms are another important cause of lightning related injuries and fatalities (Holle et al., 1993). Depending on the magnitude of the vertical wind shear on a given day, anvil lightning can sometimes extend over 60 km in front of active thunderstorm cores. As with the stratiform region cloud lightning, anvil cloud lightning can produce isolated CG lightning flashes anywhere along its path.

Flash extent density (FED) is a product used by Vaisala to display VHF total lightning data. FED is defined as the number of lightning branches that passes through a 1 km² grid box per minute. Figure 9 shows a two-minute FED plot of supercell thunderstorms in the DFW area on 25 April 2005. Satellite and radar reflectivity images from this time period showed that strong southwesterly upper level winds were blowing thunderstorm anvils distances over 60 km toward the east-northeast. The highest total lightning activity is identified near the center of Figure 9 in shades of red, pink and white. Anvil lightning is shown in shades of purple, extending close to 60 km toward the east of the southernmost cell and 60 km toward the northeast of the cell located just northeast of the southernmost cell. Anvil lightning produced isolated CG lightning flashes during the lifetime of these supercells.

4.3 "Bolt from the blue" flashes

Observations from the NMT LMA have helped define another important application involving the mapping of total lightning flashes. Rison et al. (2003)

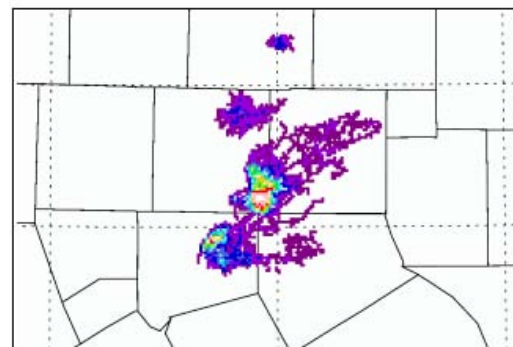


Figure 9. Total lightning FED (number of lightning branches that pass through a 1 km² area per minute) image from collected over a two-minute interval on 25 April 2005. Shades of red, pink and white identifies areas with high total lightning flash rates.

discuss numerous observations of the mapping of “bolts from the blue” within NMT LMA data (not shown). These flashes can sometimes extend over ten kilometers beyond the cloud boundary of thunderstorms and always go to ground. Rison et al. (2003) found that these flashes are quite common within storms observed with the NMT LMA and can represent the majority of CG flashes produced throughout the lifetime of a storm. A storm observed by the NMT LMA on 2 August 1999 produced 24 CG flashes throughout its lifetime, 18 of which were considered “bolts from the blue.” These observations imply that using radar reflectivity data in combination with the mapping of total lightning flashes will identify storms that are producing dangerous flashes at some distance from the radar echo.

4.4 Total lightning demonstration display products for CG lightning safety

Vaisala has created two demonstration display products that integrate VHF total lightning data with LF CG lightning ground locations in order to give a complete representation of the areas at risk for CG lightning. The first demonstration product uses a blue/red color scheme to identify areas at risk for CG lightning. Figure 10 shows a 15-minute FED plot of cloud and CG lightning in a mesoscale convective system (MCS) that passed through the DFW area on 16 June 2002. Areas containing cloud flash activity without CG lightning activity are shown in shades of blue. The darker the blue shade, the higher the cloud lightning rate. Areas containing both cloud and CG lightning data are shown in shades of red. The lighter the red shade, the higher the CG lightning rate as

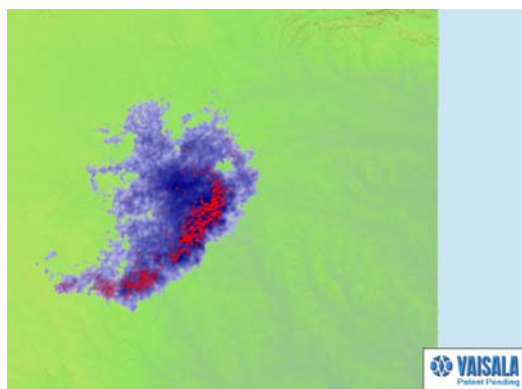


Figure 10. CG lightning hazard demonstration product showing 15 minutes of VHF total lightning mapping and CG lightning activity from 16 June 2002. Areas containing cloud flash activity without CG lightning activity are shown in shades of blue. The darker the blue shade, the higher the cloud lightning rate. Areas containing both cloud and CG lightning activity are shown in shades of red. The lighter the red shade, the higher the CG lightning rate as detected by Vaisala's NLDN.

detected by Vaisala's NLDN. The high CG lightning risk region is highlighted in red along the leading convective line of the MCS as it moved from west-northwest to east-southeast through the DFW area. Areas shaded in blue show that there remains an isolated CG threat from continuing cloud lightning activity in the trailing stratiform region located west of the leading convective line. Notice a number of scattered red areas showing isolated CG lightning flashes within the trailing stratiform region.

The second demonstration product combines CG lightning point locations with the cloud lightning connect the dots representation. Figure 11 shows 30 minutes of Vaisala NLDN CG lightning data plotted with VHF total lightning mapping data from an MCS that passed through the DFW area on 15 June 2001. The latest minute of CG (total) lightning data is shown in white (green) and turns to red (blue) when the data is 1 to 30 minutes old. Similar to the first demonstration product, the high CG lightning risk area is located in the leading convective line as this MCS moved from northwest to southeast through the DFW area. The continued isolated CG lightning risk is shown by the cloud and isolated CG lightning activity extending over 100 km to the northwest of the leading convective line, through the trailing stratiform region.

5. THUNDERSTORM GROWTH AND DISSIPATION

Total lightning rates detected at VHF are a much better indicator of thunderstorm updraft growth and dissipation than CG lightning detected at Low Frequencies (LF) used in Vaisala's NLDN. Since hundreds to thousands of VHF lightning sources are

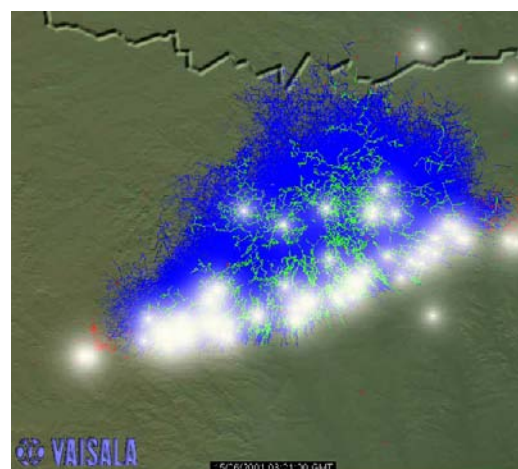


Figure 11. CG lightning hazard demonstration product showing 30 minutes of VHF total lightning mapping and CG lightning activity from 15 June 2001. The latest minute of CG (total) lightning data is shown in white (green) and turns to red (blue) when the data is 1 to 30 minutes old. (Patent pending)

detected within each flash by VHF total lightning mapping networks, flash initiation points (FIP) are used to help determine total lightning flash rates within thunderstorm cells. An FIP is defined as the first VHF lightning source detected within a lightning flash after VHF lightning sources are grouped into a flash by Vaisala's algorithms. Figure 12 shows a time series of radar and lightning parameters from an ordinary thunderstorm in the DFW area. Total lightning rates go through two periods of rapid increase and then rapid decrease. The first period covers about 20 minutes from 2115 to 2135 UTC and the second period covers only 5 minutes from 2140 to 2145 UTC. These increases in total lightning rates appear to be approximately correlated with increases in the maximum Vertically Integrated Liquid (VIL) from the WSR-88D radar. However, the negative CG lightning rates are very low and do not show any marked increases and decreases. These rapid increases (decreases) in total lightning rate are associated with a strengthening (weakening) updraft in the storm.

Vaisala has created a demonstration product that helps identify thunderstorm growth and dissipation using a three-dimensional representation of the total lightning rates within thunderstorms. Figures 13 and 14 show a number of thunderstorms that were occurring over Poland on 4 July 2002. Total lightning produced by these storms were detected by an older version of the LS8000 networks currently produced by Vaisala. Total lightning flash densities are converted from two to three dimensions by increasing the altitude of cloud-like features as total lightning flash rates increase. The color of the cloud-like feature also changes with increasing total lightning flash rates. At 0100 UTC, the total lightning flash rates of a number of storms are high and indicated by tall cloud-like features and shades of yellow and orange (Fig. 13). Sixty minutes later the

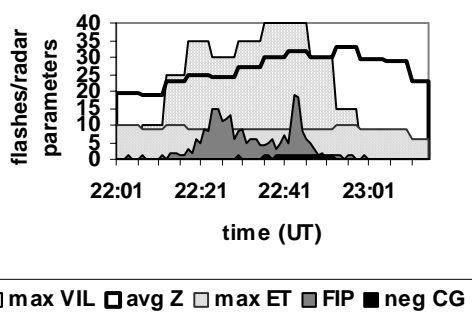


Figure 12. LDAR II total lightning rates calculated from flash initiation points (FIP), Vaisala NLDN negative CG lightning rates (neg CG), maximum VIL (max VIL), average low level reflectivity (avg Z) and maximum echo tops (max ET) from an ordinary thunderstorm in the DFW area.



Figure 13. A thunderstorm growth and dissipation demonstration product showing VHF total lightning mapping and CG lightning activity from Poland on 4 July 2002. "Cloud-like" features represent total lightning flash rates. The higher the altitude of the "cloud-like" feature and the brighter the color (from purple to red), the higher the total lightning flash rate. CG flashes in yellow show the exact location of the CG flash on the terrain map. The area covered by total lightning is shown by a shadow-effect on the terrain map. (Patent pending)

total lightning flash rates in all active thunderstorms are low to moderate and are shown by lower altitude "cloud-like" features and shades of light blue and green (Fig. 14). This display is also useful for other applications. A shadow is placed over all areas where cloud and CG lightning activity is observed. This helps address the CG lightning hazard application. Also, yellow lines are drawn from the "cloud-like" feature base to the exact positions at the ground where a LF CG lightning detection network located CG lightning flashes. Another useful element of this product is that lightning can be plotted on high resolution base maps that include such features as terrain altitude, cities, highways and even radar data.



Figure 14. Same as Figure 13, except 60 minutes later. (Patent pending)

6. SEVERE WEATHER APPLICATIONS

Total lightning data is very sensitive to changes in the strength of the updrafts within thunderstorms. Similar to radar reflectivity, increases in total lightning flash rates and the areas over which these increases are occurring are very useful indicators of storm strength. Patterns in VHF total lightning mapping data as identified in FED images can be very similar to radar reflectivity signatures. Often, one can identify bow echoes and echo free regions with FED data. Similarities to radar reflectivity signatures and sensitivity to changes in updraft strength make total lightning a tool forecasters could use to increase lead time for severe weather warnings, because total lightning data can be provided in a continuous data stream. The Fort Worth NWS Forecast Office is currently receiving two-minute FED plots. This means that for every 10-minute time period they receive five updates of information for thunderstorms in the DFW area, as opposed to two updates of radar information due to the five minutes it takes to complete a volume scan.

Figure 15a-c shows an example of how useful total lightning information can be when severe thunderstorms are evolving on time scales shorter than radar volume scans. Figure 15a shows FED data from a number of supercells that passed through the DFW area on 25 April 2005. The highest rates of FED data are shown in shades of red. There was a large supercell thunderstorm producing high total lightning rates near the center of the image. High total lightning rates were occurring along the white line oriented west-northwest to east-southeast which indicates the storm's path and projected future path, according to the Storm Cell Identification and Tracking (SCIT) algorithm used on radar reflectivity data. Two minutes later, moderate total lightning flash rates start to develop due to a strengthening updraft located south of the main storm track (Fig. 15b). Four minutes later, the new updraft that developed south of the storm track became the dominant updraft and total lightning rates increased dramatically (Fig. 15c). This is an example of a right-moving supercell thunderstorm. In this case, the total lightning information would allow a forecaster to identify strengthening updrafts in the storm and anticipate the right turn of the storm before the next radar volume scan arrived.

7. CONCLUSIONS

VHF total lightning mapping provides an invaluable data set for the thunderstorm nowcasting process. A significant safety risk currently exists to the public due to the lack of information regarding the spatial extent of cloud lightning activity within thunderstorms. Any cloud lightning flash, regardless of whether it is moving through a stratiform rain region, anvil cloud or clear air, can produce an isolated CG lightning flash anywhere along its path.

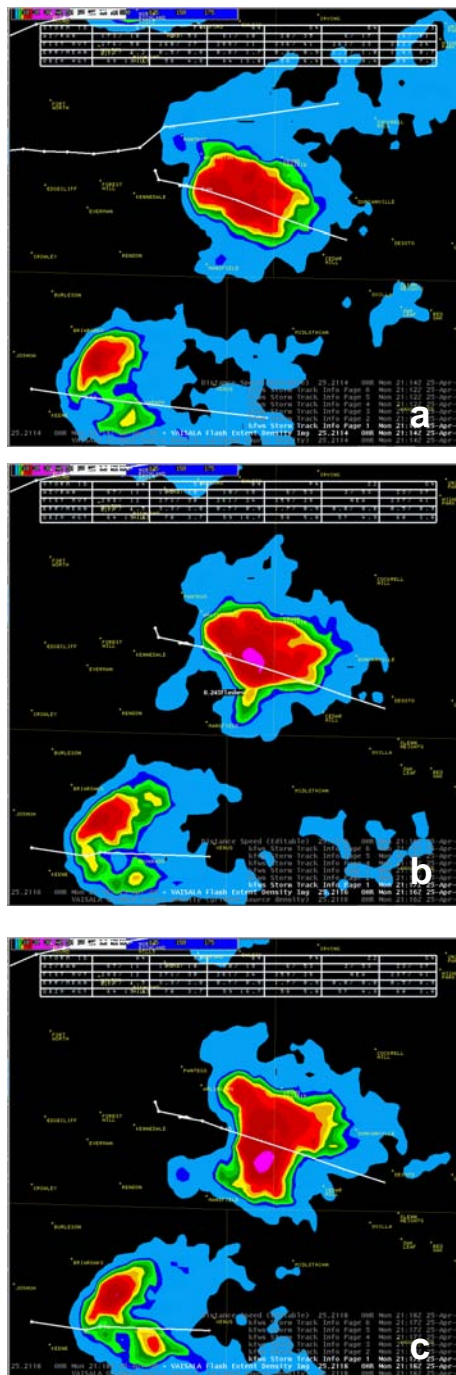


Figure 15. Total lightning FED (number of lightning branches that pass through a 1 km² area per minute) images from (a) 2114, (b) 2116, and (c) 2118 UTC 25 April 2005. Shades of red identify areas with high total lightning flash rates. Past and future projected storm tracks are shown as white lines. Future projected storm tracks are created by the SCIT algorithm.

Currently, no other data source can be used for continuously monitoring the true extent of all lightning activity in thunderstorms besides VHF total lightning mapping. Forecasters have radar reflectivity and velocity data, satellite imagery, CG lightning data and human reports that are all used to help identify severe weather. However, none of those data sources can show the forecaster the whole region at risk for CG lightning. Therefore, total lightning mapping fills the biggest gap that currently exists in thunderstorm hazard nowcasting.

VHF total lightning mapping is useful for identifying thunderstorm growth and dissipation, and severe weather trends that complement radar data and are updated more frequently than radar. Total lightning data could help add minutes of valuable lead time for severe weather events in situations where every minute may mean the difference between life and death.

In this paper, a number of unique demonstration products have been shown that should appeal to the viewer as well as convey important information regarding many hazards produced by thunderstorms.

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