ACRP

REPORT 8

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AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP REPORT 8

Lightning-Warning Systems for Use by Airports

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AIRPORT COOPERATIVE RESEARCH PROGRAM

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FOREWORD

By Charles W. Niessner
Staff Officer
Transportation Research Board

This report provides a quantitative means to assess the operational benefits associated with delay reductions that lightning detection and warning systems can generate. The report will be of particular interest to airline and airport personnel responsible for aircraft ramp safety.

Air carriers and airports are concerned with the potential hazards of lightning. Safety policies and practices require that ramp operations be discontinued when the potential for lightning exists. Ramp closures significantly affect all facets of airport operations, including landside, terminal, and airside operations, and the National Airspace System. The severity of these effects could be reduced if current airport lightning-warning systems were enhanced to more precisely identify the periods when ramp closures must be in effect. For example, this could be accomplished by integrating measurements from other weather-observing systems, such as radar, into the lightning-warning systems. Research is needed to determine appropriate methodologies and expected improvements in warning capability.

Under ACRP Project 04-02, "Lightning-Warning Systems for Use by Airports," researchers at MDA Federal Inc., developed a quantitative means to assess the operational benefits associated with delay reductions that lightning detection and warning systems can generate. It enables an assessment of whether such systems are cost-beneficial on an individual airport or airline basis.

The researchers reviewed and evaluated existing/developing technologies for the measurement and prediction of lightning hazards, conducted a survey of selected airports and airlines to identify capabilities and limitations, assessed users' satisfaction with existing warning systems, and performed a cost analysis of operational costs resulting from airport ramp/apron closures. The current state of the industry for airport lightning detection and warning systems appears to be effective. However, there are a number of ways to refine and improve the systems by making better use of the currently available weather observations through the development of "smarter" software and analysis algorithms. These changes have the potential to further minimize the number and duration of ramp closure events and enhance ramp worker safety decision making.

AUTHOR ACKNOWLEDGMENTS

MDA Federal Inc. was the prime contractor for this study, and the National Center for Atmospheric Research was a subcontractor. Authors of this report are Lawrence Heitkemper, Vice President, MDA Federal; Ronald F. Price, Program Manager–Aviation Services, MDA Federal, who also served as the Principal Investigator; and David B. Johnson, Ph.D., Research Applications Laboratory, National Center for Atmospheric Research.

The project benefited from an expert panel organized by the Transportation Research Board. The panel was convened to review the working papers prepared during the course of the study and to meet with the MDA Federal team as we began to assemble our final report. The panel provided helpful and responsive feedback that enhanced the utility of the study research.

The authors also wish to express appreciation to the various staff of the airports and airlines surveyed as part of this study. They provided information concerning the lightning detection and warning systems that they employ and the processes and procedures they follow in managing the utilization of the aircraft ramp and personnel that are assigned to outdoor activities. These included representatives from the following airports and airlines:

- Airports
  - Charlotte-Douglas International Airport, North Carolina
  - Chicago-O'Hare International Airport, Illinois
  - Dallas-Ft. Worth International Airport, Texas
  - Denver International Airport, Colorado
  - Orlando International Airport, Florida
  - Phoenix-Sky Harbor International Airport, Arizona
  - Pittsburgh International Airport, Pennsylvania
  - Tampa International Airport, Florida
- Airlines
  - American Airlines
  - Northwest Airlines
  - United Airlines
  - United Parcel Service

The authors also acknowledge the assistance and support of Dan Breed and Frank Hage from the National Center for Atmospheric Research, as well as background discussions with Don MacGorman, NOAA National Severe Storm Laboratory (NSSL); Bill Beasley, University of Oklahoma; and Steve Goodman, NOAA's National Environmental Satellite, Data and Information Service (NESDIS). During the course of our study we visited Vaisala's Tucson Operations Center in Arizona and the offices of Weather Decision Technologies in Norman, Oklahoma. During our visits and in subsequent interchanges, we received valuable support and a wealth of information from Nick Demetriades, Martin Murphy, Ron Holle, Nic Wilson, and Geoff Bing (all from Vaisala), and from Mike Eilts, President and CEO of Weather Decision Technologies, Inc. We also received detailed product information from Jim Block (DTN/Meteorlogix) and from Mark Miller, Peter Neilley, and Kim Rauenzahn (all from WSI). Our appreciation is also extended to the American Meteorology Society, which permitted us to reprint definitions of lightning terms from their Glossary of Meteorology.

Finally, the authors express their sincere thanks to ACRP Senior Program Officer Charles Niessner for his assistance throughout the project and to Adrienne Blackwell, Senior Program Assistant, for facilitating the panel meetings and other aspects of producing the final research report.

NOTE

CONTENTS

SUMMARY

Lightning-Warning Systems for Use by Airports

Cloud-to-ground lightning strokes present a clear and immediate danger for ground personnel involved in outdoor ramp operations, such as aircraft fueling, baggage handling, food service, tug operations, and guiding and directing aircraft to their assigned gates. When this danger presents, airport ramp operations are suspended until the threat has passed. Airport staff engaged in outdoor activities are also subject to the impact of lightning strikes.

Decisions about ground personnel and ramp operations are made by the airports and airlines, not by the Federal Aviation Administration (FAA). Individual airlines, companies providing airport workers, and airport management often have very different procedures and standards for identifying and responding to potential lightning hazards.

Current Industry Practice

The impact of lightning events in the vicinity of, and on, airport operating areas has long been recognized as both a safety and an operational issue by airport and airline operators. Both have frequently invested in lightning detection and warning systems that serve to assess when ramp and outdoor activities should be halted and then resumed without compromising worker safety. The technology to support such decision making is offered by a number of commercial vendors, but appears to be effective given the limited reports of lightning-induced injuries and deaths in the airport setting. These systems combine the acquisition of lightning strike data from such sources as the National Lightning Detection Network (NLDN) with on-site electric field mills and other weather data inputs to produce visual and aural alarms with respect to the impending arrival of thunderstorms and lightning strikes. Airport and airline staff then broadcast the need for clearing of the ramp and other outdoor airport operational areas by their personnel. The return to work announcement is also facilitated by this equipment.

Although the number of aircraft ramp injuries and deaths attributed to lightning events is thought to be low, there has been no effort to collect such data into a systematic database. This is because there is no requirement to report such incidents to federal or state agencies, and most of the known data is derived from anecdotal reports and informal studies by individuals having an interest in the subject. While it is recognized that ramp closures affect the flow of aircraft operations and cause passenger delays that can ripple through the national air transportation system, neither government agencies nor airport and aircraft operators have compiled closure statistics that are available for public information.

The use of lightning detection and warning systems at airports is also dependent on the meteorological characteristics of the location and the geographical distribution of lightning strikes (cloud-to-ground) throughout the United States. Most lightning strikes occur in the eastern and central regions of the country. Consequently, the decision to install lightning detection and warning systems is dependent to a large extent on the potential for such events and their impact on airport and airline operations. Airports located along the west coast of the United States, for example, frequently question the cost of installing, operating, and maintaining lightning detection systems. Conversely, several relatively closely spaced airports in Florida each have their own lightning detection and warning systems in place.

The key objective and impetus for the installation of lightning detection and warning systems is worker safety. A secondary and near equivalent basis for the investment in these systems is the minimization of ramp closures during such events. In this latter regard, it was determined that the users of these systems employ differing standards with respect to broadcasting a "clear the ramp" or "return to ramp activity" message. The industry has focused on distance out and time since last event to establish bases that, respectively, govern stopping and resuming ramp activities. However, the distances and time intervals employed vary depending on the risk tolerance of the decision maker, which is generally influenced by past experience at the airport location, including weather characteristics and frontal passage speeds.

Liability

Another factor limiting the usefulness and standardization of lightning detection and warning systems is liability. Some airport operators share information that they obtain concerning lightning and other adverse weather phenomena with airlines and other tenants, while others have expressly avoided this level of cooperation. Those that disseminate information do so in one of several ways. Airports may allow tenants to subscribe to a data feed generated by their lightning detection and warning systems. Those tenants then employ their individual criteria for ramp closure and re-opening. Other airports broadcast a visual display—for example, flashing lights that are visible from all areas of the airline ramp—to warn personnel of a lightning threat. Again, the response from these workers is governed by their specific work rules and procedures. Alternatively, airports may also opt not to divulge weather data out of concern that they may overlook a tenant and be held liable in the event of injury or loss of life.

Individual airlines and airport tenants that have invested resources in their own weather monitoring technologies, including lightning detection and warning systems, use the data collected for their own decision making. In practice, the dominant airline at the airport where the threat of lightning events warrants the implementation of such systems typically sets the lead that other airlines may choose to follow. Ramp workers monitor the actions of their colleagues at other airlines, and they typically vacate and return to the ramp in unison. This practice can extend to airport employee decisions to stop and resume outdoor work activities. There can be instances when such "follow the leader" tactics are not observed, such as when relatively large distances separate airline ramp operations areas, and one airline continues to operate while others have suspended ramp activity, creating a situation that can be confusing to passengers of those airlines.

One airline, Southwest Airlines, has adopted special practices at certain airports to deplane passengers when the aircraft arrives at the gate and a ramp work shutdown is in effect due to lightning. The aircraft is marshaled to the passenger loading bridge position by the ramp supervisor, who is positioned in a vehicle with lights that indicate left/right of the lead-in centerline to the pilot during the taxi-in activity. Passengers are thus not exposed to the lightning threat and are allowed to deplane. Baggage handling activities are not conducted until the ramp is cleared for such activity. This has avoided the need to keep passengers on board the aircraft and engines engaged while the ramp shutdown is in effect. More airlines may adopt this and similar practices and procedures as a means of minimizing inconvenience to their passengers.

Standardization

Opinions varied on the value of standardizing technologies for lightning detection and warning system and their implementation. A majority of airports and airlines contacted expressed that a single system serving all users at an airport could be viable and might be funded through lease terms and conditions. Yet they also noted that stop/resume activity decisions could not be uniformly applied. Furthermore, liability issues would likely govern any decision for industry standardization.

It is said that lightning does not strike twice in the same place. This can also apply to the use and implementation of lightning detection and warning systems at airports. No two airports are alike, and a "one size fits all" approach does not appear to be viable. Airport geographical settings, weather phenomena characteristics, airport facilities layout, airline business models and operating procedures, labor union agreements, liability issues, and cost allocation processes are just some of the primary factors that do not lend themselves to standardization.

Operational Cost Analysis

An evaluation of the financial and operational impacts on the national air transportation system resulting from ramp closures associated with lightning strikes was conducted as part of this research study. The expectation was that incremental cost savings from modified or enhanced lightning detection and warning systems or from improved operator procedures could be achieved. Because reliable records on ramp lightning closures at airports are not available, lightning strike data from NLDN was obtained. This enabled the construction of a synthetic closure history for an airport based on a strict imposition of the "30/30" rule, which recommends that outdoor activities be curtailed following a cloud-to-ground lightning strike within 6 statute miles (corresponding to 30 sec of time delay between the visible lightning strike and the sound of the thunder) and not resumed until 30 min after the last lightning strike within six statute miles is observed. Based on the sequential time and location history of nearby lightning strikes, it is possible to calculate the distance of each stroke from the airport reference point and determine closure and all-clear times. Two airports were subjected to this exercise—Chicago O'Hare International and Orlando International. Chicago represents a high activity airport located in the upper Midwest in an area of large spring and summer storms. Orlando represents a medium activity airport in the southeast, near the climatological maximum for U.S. lightning activity. The number of affected aircraft and the diurnal pattern of flight operations at each airport were estimated from aircraft activity measures available from online resources (www.flightaware.com).

The cost analyses were aided by earlier research conducted for the FAA and summarized in Table S-1. There may be additional direct costs to airlines depending on whether they need to pay the ramp workers overtime and whether fuel is expended in planes waiting on the ramp for a gate position to become available. A second cost category evaluates the "ripple effect" caused downstream. These may include additional opportunity costs (passenger time) caused by missed connections and direct costs (flight time) of repositioning planes for the next day. The analyses were also conducted based on the use of an aircraft commonly used in passenger transport, the Boeing 737-500.

Table S-1. Standard economic values.

Item	Value ($)
Value of Human Life	3.0 million
Average Labor Cost Ramp Rate	13.03/hr
Hourly Cost of Aircraft Delay	1,524/hr/aircraft
Rate of Delay Per Aircraft (fuel, etc.)	2,290/hr/aircraft
Rate of Labor Delay	814/hr
Value of Passenger Time	28.60/hr
SOURCE: *Economic Values for FAA Investment and Regulatory Decisions, A Guide.* FAA, 2007 (*27*).	

A series of equations were modeled to quantify the "per minute" cost savings that could accrue through the use of improved decision making with respect to the timing of ramp closures and re-openings. These equations were applied to the synthesized lightning and aircraft activity levels at Chicago O'Hare International and Orlando International airports due to a shortening of the duration of each ramp closure event by 10 minutes. The savings represent those for a yearly period of activity and reflect the number of lightning events and aircraft delay statistics. As indicated in Table S-2, the potential savings from a ten-minute improvement in delay time during peak operating hours at Orlando is approximately $2.8 million, compared to the $6.2 million calculated for Chicago.

To evaluate the sensitivity of the predicted economic impact on the interval between the last lightning strike and a return to normal operations, an additional set of analyses reducing the "all clear" time from 30 min to 15 min after the last reported lightning strike within 6 mi of the airport was conducted. The reduced time interval may be more common at airports than the "standard" 30 min used for general outdoor activities. This "30/15" analysis was conducted for the summer months (June-August), when lightning activity is the most frequent.

The rule change from 30/30 to 30/15 results in a slight increase in the number of events due to the few cases when the airport would be opened and then quickly closed again under the 30/15 rule (causing two events instead of one to be recorded), while the airport would have stayed closed under the 30/30 rule. While this could represent an increased hazard for ramp personnel, it results in a significant reduction in delay time, totaling 354 minutes at Chicago and 1,568 minutes at Orlando.

The results for Chicago indicate a potential savings of approximately $3.4 million from hypothetical implementation of the 30/15 rule for the summer. The results for Orlando are perhaps more intriguing because the shorter "all-clear" time provides limited openings in the ramp closures and reduces the number of longer and more costly delays. In this

Table S-2. Lightning events, delay minutes, and savings.

Airport	Lightning Events (no.)	Total Annual Delay (min)	Savings Associated with a 10-min Reduction in Ramp Closure Interval ($)
Chicago O'Hare International	51	3,064	6,206,310
Orlando International	56	3,243	2,801,372

hypothetical analysis, this results in a potential savings of $6.3 million at Orlando for the summer of 2006.

The cost analysis indicates that delay cost impacts are complex. They are a function of several factors, including the activity levels and mix of aircraft operating at an airport, the number of lightning events, the timing of the lightning event, the type of lightning event (local convective or associated with broad-scale flow), the duration of the lightning event and the rules the airline/airport operators use in issuing the “all clear” signal to resume ramp activity. The analysis also indicates that the annual value of new technologies or new procedures that could reduce ramp lightning delays, although varying by airport, could be substantial. The potential savings produced by a reduction of even a few minutes would likely be sufficient to more than cover the cost of introducing improved technology or practices.

Because safety concerns for the ramp workers are paramount, it appears the airlines and airports will likely err on the side of caution in closing ramp operations. This suggests that the most likely path to improved operational efficiency is in being able to sound an “all clear” as quickly as possible after the initial event, as long as it can be done without compromising safety.

Future System Improvements

There are a number of promising ways to refine and improve lightning detection and warning systems for airports, airlines, and other tenants. These make better use of all the currently available weather observations through the development of “smarter” software and analysis algorithms, and by incorporating new technologies. Relatively more short-term opportunities for such enhancements and that are strong candidates for additional research and implementation include the following:

- Intelligent self-monitoring warning systems that check their own performance and evaluate the adequacy of the specific warning criteria being used.
- Incorporation of additional weather information, such as that available from the currently deployed Doppler meteorological radars.
- Adoption of total lightning systems that detect and locate both cloud-to-ground and intra-cloud lightning strikes.

Recommendations

The current state of the industry for airport lightning detection and warning systems appears to be effective. There are, however, potential ways to further minimize the number and duration of ramp closure events and enhance decisions involving ramp worker safety. We recommend the following action items:

1. Refine the warning algorithms and criteria through the use of self-monitoring software. While this approach is not necessarily guaranteed to shorten ramp closures, it would provide an objective standard for selecting warning criteria to balance safety and efficiency.
2. Incorporate additional meteorological data sets, primarily meteorological radar data and other remote sensing information, to better define the spatial and temporal limits of the lightning hazard. Using integrated data sets to define the geometrical extent of the lightning cells and then tracking their evolution and movement should be particularly valuable.
3. Continue demonstrations and tests of total lightning systems to enhance and refine the technology embedded in current lightning and detection systems.

4. Conduct research to enable the improved determination of those lightning events that are most likely to produce short-term (less than 1 min) impacts on ramp activity. This may include lightning cell tracking and echo movement vector analysis that can serve to minimize the number and duration of ramp closures.
5. Devise a system of collecting and reporting lightning events and their impact on aircraft ramp and outdoor activities. This will provide additional data to determine the extent of such weather impacts on aircraft operations and identify those improvements that are cost-beneficial.
6. Develop training programs for the use and application of lightning detection and warning systems that improve the ramp closure/re-open decision-making process.

CHAPTER 1

Background

Lightning Properties, Behavior, and Terminology

A nearby lightning strike is a dramatic event that immediately invokes fear and awe. As an obvious hazard for airport operations, it demands respect. Properly grounded buildings and well-designed electronics with surge protectors usually provide adequate protection to structures and electronic systems. Fueling operations, which are at risk from sparks or other electrical discharges, are normally suspended during lightning activity. The greatest lightning danger is to airport ramp workers, who need to be moved indoors until the lightning ends, which essentially shuts down ramp operations.

Lightning is a complex process that, even after decades of intense investigation, is still quite mysterious. The electric fields and currents that help drive lightning are global in scale, while many of the charge separation processes that lead to a lightning strike involve microscopic interactions between small particles of ice and water in the core of intense thunderstorms. For every generality about lightning behavior, there seem to be exceptions.

In this review of lightning properties and behavior we will start with a discussion of the earth's electric field and then move on to the clouds and thunderstorms that create lightning. This discussion involves a wide range of often unfamiliar words and specialized terminology. For reference, a glossary of lightning terms, extracted from the American Meteorological Society's *Glossary of Meteorology,* is provided in Appendix B (*1*). This discussion also makes extensive use of a number of standard reference books and Internet references (*2–11*).

The Earth's Electric Field and Cloud Electrification

The earth's atmosphere is an integral part of a natural electrical system in which the earth and its atmosphere can be thought of as a spherical capacitor, with the earth as the lower conducting surface and the atmosphere as a slightly conductive medium topped by a highly electrical region in the upper atmosphere, where unfiltered solar radiation effectively ionizes atmospheric molecules and atoms into a highly conductive region called the ionosphere. The ionosphere (sometimes also termed the electrosphere) is positively charged, while the earth's surface has a net negative charge. This charge imbalance creates an atmospheric electric field (roughly 100 V/m near the earth's surface) and a corresponding air-earth electrical current directed downward from the ionosphere to the ground, where the direction of the current is defined as the direction that a hypothetical positive charge would flow.

Without a mechanism to recharge the ionosphere, the air-earth current would quickly discharge this global capacitor. While historically there have been suggestions that charged particles from the solar wind might help maintain the positive charge in the ionosphere, most atmospheric scientists now accept that the global population of thunderstorms transfer electrical charges back to the ionosphere in a thunderstorm driven global circuit (see Figure 1). At any one time there may be as many as 2,000 thunderstorms occurring around the globe, generating a total of perhaps 40 lightning flashes every second. Our knowledge of atmospheric electricity is still expanding. Recent discoveries of a variety of electrical discharges extending upward from the tops of active thunderstorms have been termed *jets*, *sprites*, and *elves*.

The presence of the atmospheric electric field may contribute to the earliest phases of cloud electrification. Even though relatively weak, the field can induce a degree of charge separation in water drops and ice particles, helping them capture ions and other charged particles that are components of the fair weather current and giving them a net charge.

The relatively low level electrification of small, shallow clouds is not, in itself, a hazard. The development of lightning requires additional charge separation in strong convective clouds. Airplanes flying through seemingly benign stratiform

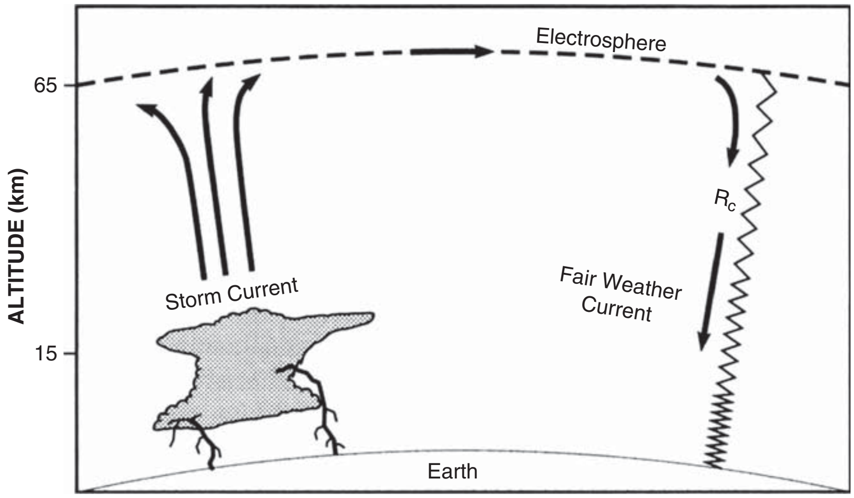


Figure 1. A simple conceptual model of the main global circuit. Thunderstorm "generators" drive current to the highly conductive electrosphere and back to the ground through the fair weather current (2).

clouds may, however, trigger an electrical discharge. Depending on their history, these clouds may have moderate electrical fields as a result of earlier convective activity or from electrification associated with the melting of precipitation. In-flight lightning strikes are relatively frequent (averaging about one strike for every 3000 hr of flight), but they seldom do much damage since aircraft are generally well shielded against lightning by their metal airframes (*12*).

Thunderstorm Electrification and Lightning

While small and mid-sized convective clouds may become electrified, they seldom produce natural lightning. Lightning requires a tremendous amount of charge separation before a discharge, and this generally happens only in the large convective storms we call thunderstorms. While there are still many unknown factors in the initiation of a lightning strike, years of studies have made it clear that the process involves collisions between super-cooled water and ice (including graupel and small hail) in the presence of strong updrafts and downdrafts. Most often, cloud tops have to cool to at least –20 °C before lightning begins, with the critical charge separation processes occurring in the portion of the clouds with temperatures between –5 °C and –20 °C (24 °F to –5 °F).

Particle collisions, combined with size sorting and strong updrafts and downdrafts, separate the positive and negative charges. The descending particles tend to collect negative charges, and the ascending particles are predominately positively charged. The idealized result of these interactions is a simple cloud dipole, with positive charges grouped at the top and negative charges grouped in the middle and lower areas of the cloud, in the –5 °C to –20 °C zone (see Figure 2).

In addition to the charge separation within the cloud, the lower area of strong negative charges induces a compensating area of positive charge to form immediately below the cloud on the earth's surface. Eventually, when the charges build up to a high enough level to cause an electrical breakdown in the air separating the charge centers, the built-up charges can discharge in a lightning stroke. This can either happen between the cloud and the ground, or between the positive and negative charge centers within the cloud. The majority of natural

Figure 2. An idealized small thunderstorm with charges separated into a simple electrical dipole (5).

lightning strikes (about 75% to 80%) occur within the storm cloud itself.

Anatomy of a Lightning Strike, Part I

Even in this simple model of a thunderstorm, lightning strikes are quite complex. Figure 3 shows the development of a typical negative cloud-to-ground lightning strike. Both negative and positive flashes can occur, but negative flashes are more common. Negative flashes bring negative charge to the ground, while positive flashes bring positive charge to the ground. In negative flashes, the descending current from the cloud moves downward in a series of short jumps, called a "stepped leader." The individual steps in this process branch out in different directions, looking for the path of least resistance toward the ground. As a leader gets close to the ground, a corresponding streamer of positive charge moves up from the surface to meet the descending negative current. When these two currents connect they provide a highly conductive channel for charge transfer between the cloud and the ground. The initial descending negative charge is followed by an even stronger "return stroke" of positive charge from the ground, which seems to move up the channel and into the cloud. The actual charge transfer is, however, done by free electrons so the return stroke is really just a progressive draining of negative charge downward, with the upper limit of the drained path moving upward as electrons flow to the ground. Multiple strokes of dart leaders and return strokes can follow, producing flickering strobe-like flashes of light (see Figure 4).

The entire multiple discharge sequence of a lightning strike is normally called a *flash* and is typically made up of two to four separate *strokes*. In some cases, as many as 15 or more strokes have been observed. The subsequent strokes generally follow the established conducting channel, but the final strike point on the earth's surface can jump around from strike to strike, with separations of up to several hundred meters or more.

These cloud-to-ground flashes are normally called *CG lightning*, or simply *ground lightning*.

Anatomy of a Lightning Strike, Part II

Electrified thunderstorms are seldom as simple as the idealized dipole shown in Figure 2. There are complex areas of charge throughout the cloud, resulting in complex electrical fields. Figure 5 illustrates a more normal situation and gives examples of a number of different types of lightning flashes, including discharges between clouds (intercloud) and within a single cloud (intracloud). Both of these classes of lightning can be grouped together under the single term *IC lightning*, or *cloud lightning*. Unlike CG lightning flashes, IC strokes are not followed by return strokes, and they do not carry as much current as is typical for a CG flash.

Cloud discharges and CG flashes both radiate energy over a wide spectrum of frequencies, predominately the radio frequency (RF) bands. During the "stepped" process that creates new channels, there are strong emissions in the very high frequency (VHF) range. High current discharges along previously established channels ("return strokes") generate powerful emissions in the low frequency (LF) and very low frequency (VLF) ranges. Medium frequency (MF) emissions are centered in the AM radio band and are responsible for the static we hear on AM radio during lightning storms. Figure 6 illustrates the relative energy spectrum of CG and IC flashes in the VLF, LF, MF, and VHF frequency bands.

Cloud and ground flashes produce significantly different RF emissions over different time scales, which can be used to distinguish between these two classes of lightning. With their high current and predominately vertically oriented return strokes that generate magnetic fields, CG flashes produce strong signals that can easily be associated with a single position near the point they strike the earth's surface. The strong LF and VLF pulses generally follow the curvature of the earth and can be detected for ranges of 300–600 km (185–375 mi). IC strokes, on the other hand, are identified by their VHF emissions, which are a line of sight transmission that can normally only be detected out to ranges of 200 to 300 km (125 to 185 mi).

In summarizing years of lightning research, the National Severe Storm Laboratory has concluded that taller, more complex storms produce more lightning and more CG flashes than do smaller, isolated storms. The first flashes produced by a storm are usually IC flashes, and if detected, they can signal the initiation of a thunderstorm. The ratio of IC flashes to CG flashes is quite variable, but cloud flashes predominate, often by a factor of five or more.

Lightning Climatology

Figure 7 shows two views of a lightning climatology for the continental United States (CONUS), Mexico, and southern Canada. The lightning data were extracted from a global database based on observations from two National Aeronautics and Space Administration (NASA) instruments in low-earth-orbit, the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS). The OTD data set was collected between May 1995 and April 2000, while the LIS data set was collected between January 1998 and December 2005—essentially a 10-year data archive. The satellite data are based on optical detection of lightning flashes, both during the day and at night, and represent the "total" lightning distribution, including both IC flashes and CG flashes as seen from space.

The summaries have been processed to display the number of flashes per square kilometer per year. The upper panel

The initial lightning strike: Stepped leaders, streamers, return strokes, and darts.

The initial "stepped leader" propagates down, towards The ground in a series of short steps, branching out, looking for the easiest path to reach the ground.

As the stepped leader nears the ground it strongly attracts positive charges, inducing positive channels from the surface, called "streamers," to reach up towards the descending current.

When these two currents connect they provide a highly conductive channel for charge transfer between the cloud and the ground. Negative charge starts flowing DOWN the channel from the cloud towards the ground.

This initial surge of current is followed by an even stronger "return stroke" that shoots UP the channel as a brilliant pulse from the ground to the cloud. If enough charge is still available in the cloud, another leader, termed a "dart leader" because it uses the existing channel and has a continuous path. The new stroke can be followed by additional return strokes, in a series of discharges between the cloud and the ground.

Figure 3. Anatomy of a lightning strike (5).

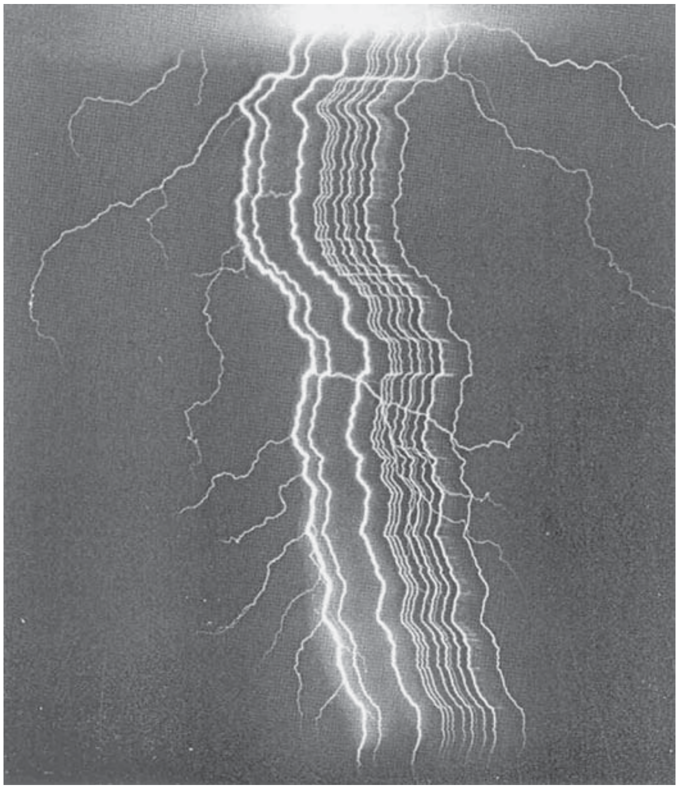


Figure 4. A well-known picture of a lightning flash made with a special lightning camera with film that moves rapidly during the exposure. Stepped leaders are frozen, while the multiple return strokes show up as separate strokes that follow exactly the same path (4).

shows the overall annual average flash density distributions. The main features are the concentration of the lightning flashes over land and a general gradient from low flash densities in the Pacific Northwest to very high flash densities over Florida. The annual pattern, however, reflects both the geographical and seasonal frequencies of thunderstorms, with the southern states having a much longer annual lightning season.

The lower panel shows the monthly average flash density for the month of August, displayed in terms of the expected annual lightning flash densities that would result if the August flash rates were continued for a full year. The August plot shows that during the late summer, thunderstorms are widespread throughout all areas of CONUS, with the exception of the extreme northwestern and northeastern states. Lightning can be a hazard every place in the lower 48 states; although not well represented in the satellite climatology, lightning storms are also a major hazard in Alaska during the long hours of summer sun, and they trigger a great number of forest fires every year.

In addition to the geographic and seasonal variations in the frequency of lightning hazards, there is also an important daily diurnal variation. Over continental areas, convective activity—including thunderstorms and lightning—peaks in the mid to late afternoon, with a secondary nighttime maximum across the Midwest.

Lightning Detection Technologies

Lightning flashes and strokes can be detected in many different ways. Most notably the discharge of thousands of amperes of current in a fraction of a second generates temperatures estimated to be as hot as 30,000 °C, hotter than the surface of the sun, with a brilliant flash of light and an acoustic shock wave we call thunder. At the same time, the surging electrical currents release a wide spectrum of electromagnetic radiation and modify the strength of the local atmospheric electrical field.

Flash and Bang

The flash and bang of nearby lightning strikes are hard to ignore, even without special instrumentation. Distant lightning flashes can often be seen by an alert observer, particularly at night. For applications involving safety, however, these techniques are not reliable and are only appropriate in the absence of more quantitative technologies.

While these "technology free" approaches can only estimate the position of a lightning flash in a general way, the difference in time between the observation of a flash and the arrival of the sound of thunder is a useful and practical way to estimate the distance (but not necessarily the direction) of the lightning. The lightning flash is seen virtually instantaneously, while sound travels at about 750 mph, or approximately 1 mi every 5 sec. The interval, in seconds, between the flash and the bang multiplied by 5 thus gives a useful estimate of the distance of the strike, in miles.

Unfortunately, many small airports do not have any lightning detection capabilities, and rules-of-thumb, such as the "flash-bang-multiply-by-5" estimate of the proximity of the lightning, provide the only information.

Acoustic detectors. While the sound of thunder is usually easy to recognize, it is difficult to use in any quantitative sense. Networks of acoustic detectors have been tested to try to locate lightning strikes, but with limited success, and acoustic detection systems have never been used operationally.

Optical detectors. The instantaneous flash of light associated with lightning can be difficult to see in the daytime and, until lately, has not often been used for quantitative applications. By using sensitive detectors and narrow bandwidth filters, however, optical lightning detection systems have been developed that can be used in the daytime and which have been incorporated into ground-based sensors in conjunction

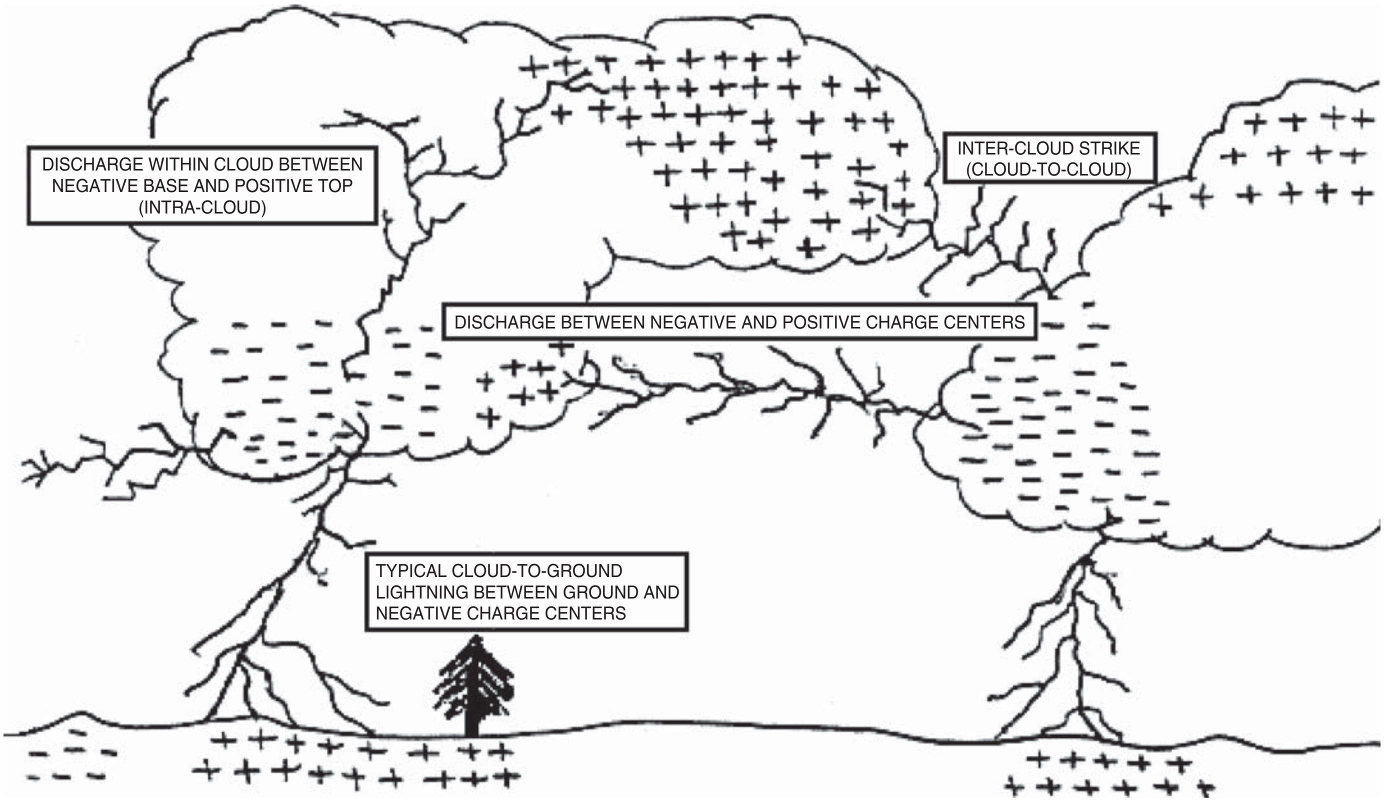


Figure 5. Multiple clouds with complex charge distributions. This figure illustrates the typical cloud-to-ground lightning flashes, as well as discharges between different portions of a single cloud and discharges between adjacent clouds (8).

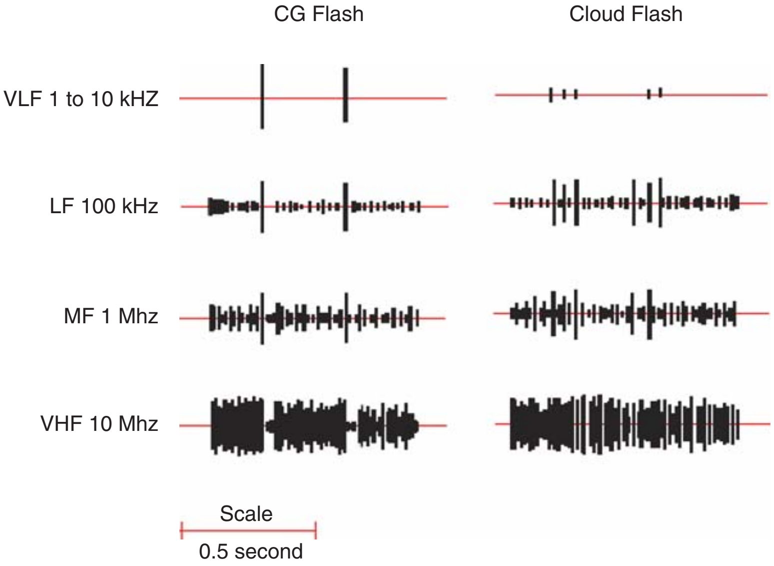


Figure 6. CG and IC flash emissions in various frequency ranges. VHF emissions are generally limited to line of sight propagation (200–300 km, or 125–185 mi.), while LF emissions propagate by ground waves that can follow the curvature of the earth and can be detected to ranges of 300–600 km, or 185–375 miles. VLF emissions can be reflected off the ionosphere and can be detected for thousands of kilometers, but in variably decreasing efficiencies (4).

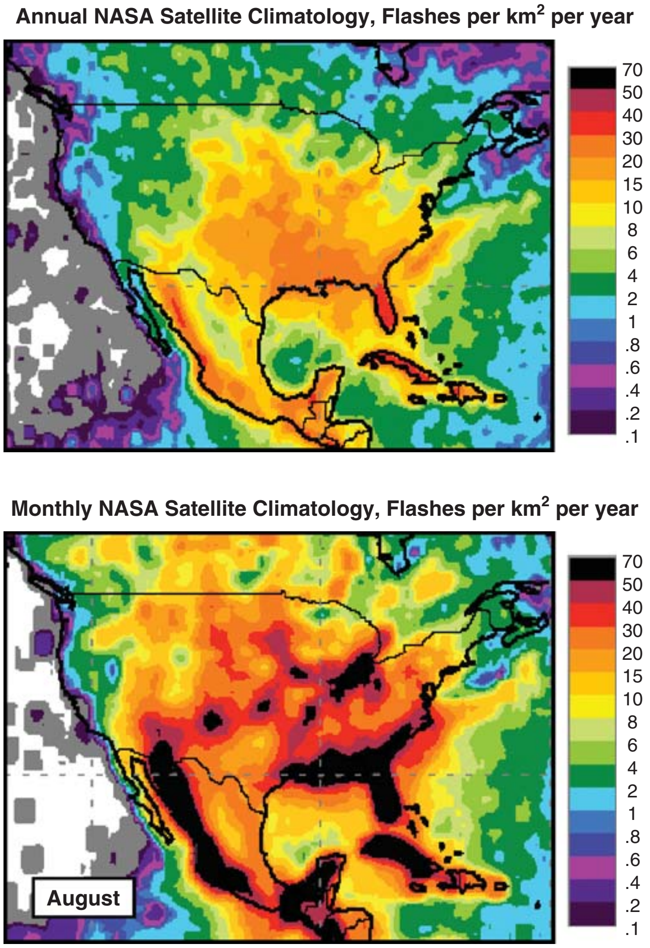


Figure 7. NASA satellite climatologies of "total" lightning (CG plus IC) flashes in terms of the average number of flashes per square kilometer per year, compiled over a 10-yr period. The upper panel shows the annual averages, while the bottom panel shows the monthly average flash density for the month of August (data provided by the Global Hydrology and Climate Center, NASA Marshall Space Flight Center).

with magnetic and electrostatic pulse analysis to reduce false alarms (for example, the Vaisala TSS-928 local-area lightning detection sensor). More important, optical detection systems have also been adapted for satellite-based lightning detection systems (satellite-based systems will be discussed in a separate section).

Atmospheric Electric Field Measurements

Figure 8. Electric field mill (from Boltek).

Electric field measurements have a long and important history of use by scientists interested in atmospheric electricity and lightning. The most common instrument to measure the atmospheric electric field is the field mill (see Figure 8), although there are other instruments, including some that are proprietary, that can also be used to monitor the electric field.

Nearby lightning discharges will produce sudden changes in the strength of the local electrical field, and these distinctive changes can be used to detect lightning—although without any direct way of measuring the distance or range to the lightning flash. Nearby charge centers, such as a cloud developing directly overhead, can dominate the local electric field and may limit the detection of distant lightning strikes. Perhaps more important than detecting lightning, electric field mills can also monitor the buildup in the local electrostatic field, which normally precedes a lightning strike. Most currently available lightning detection systems that employ field mills use them to alert users to the electric field buildup and to warn them of a potential lightning event. This application is unique in focusing on anticipating the lightning "threat" rather than on detecting lightning strikes after they occur. The technology, however, has a somewhat uncertain range and detection efficiency, along with a potential for false alarms.

Field mills are sensitive instruments that require periodic monitoring and cleaning; their readings can be influenced by blowing dust and by local air pollution. The strong electric fields that signal a potential lightning event, however, are normally easy to detect with fields mills that are properly maintained.

Lightning alert and lightning prediction systems making use of electric field mills are available commercially and are a key component of the lightning hazard and launch evaluation systems employed at NASA's Kennedy Space Flight Center.

Electromagnetic Emissions from Lightning Strokes

Most lightning detection systems currently available make use of the electromagnetic emissions, predominately RF, associated with the electrical discharge (see Figure 6). Lightning strokes produce RF static (mostly in the MF band) and are familiar to listeners of AM radios. CG strokes generate strong signals in the LF band, which can be detected at ranges of many hundreds of kilometers. IC strokes, on the other hand, predominately generate VHF, line-of-sight emissions.

Lightning detectors based on RF electromagnetic emissions range from relatively simple, low-cost, handheld devices to sophisticated sensors and groups of sensors organized into detection networks. Low-end systems, however, are of uncertain sensitivity and are subject to false detections. They are most commonly marketed for hikers, sports activities, and outdoor gatherings. The most basic systems do not try to identify the direction of the lightning, but may try to produce a rough estimate of the lightning distance by measuring the amplitude of the signal.

This technology can be enhanced by using more sophisticated receivers that can monitor the signal at multiple frequencies and analyze the time evolution and properties of the signal to minimize false alarms. Analysis of the incoming signal can also be used to distinguish between CG flashes and discharges from an IC stroke.

With the addition of orthogonally crossed loop antennas or other radio direction finding technologies (the SAFIR lightning detection systems developed in France, for example, use VHF interferometric dipole antennas for direction finding), it is also possible to determine the direction from the detector to the source of the lightning signal. Used individually, high-end receivers of this sort are employed to identify the direction of nearby lightning strikes and, with a simple signal amplitude algorithm, to also estimate the range. Such sensors are often included in automatic weather stations designed to produce fully automatic METAR reports (aviation routine weather reports) summarizing the current weather at an airport. For this application, the lightning detection system is used as an indicator of the nearby presence of a thunderstorm and gives an approximate indication of the storm's position and distance relative to the airport.

Lightning Detection by Networks of Electromagnetic Sensors

Networks of sophisticated electromagnetic sensors can provide very accurate position information for CG lightning strokes. The most immediately obvious approach is through triangulation of the direction information obtained by two or more sensors. Since the strong LF and VLF signals from ground lightning tend to follow the surface of the earth and are detectable at ranges of many hundreds of kilometers, it is possible to construct a network to cover a very large area with a reasonable number of detectors—something on the order of slightly over 100 sensors for CONUS. With this density of receivers, most lightning strokes can be detected by three to four different sensors.

Sensor networks can also locate the position of a lightning strike by making use of the high-accuracy time references provided by global positioning system (GPS) satellites to determine the difference in time between two or more detectors' observations of the same lightning stoke. Using sophisticated algorithms, the differences in the "time of arrival" of the signal can be used to identify the location and time of the lightning strike. Depending on the position of the lightning strike and the position and spacing of the detectors, time of arrival solutions can require as many as three or more detectors to record the signal from the same lightning stroke.

Using sensitive receivers designed to minimize false detections, lightning detection networks have been shown to be capable of detecting cloud-to-ground lightning strokes with a detection efficiency of over 90% and position accuracy of significantly better than 1 km (0.625 mi). Two such networks, run by commercial companies, currently provide lightning information for CONUS.

Ground-based lightning detection networks are primarily designed to detect CG lightning and can provide information about each individual stroke within a lightning flash. With recent improvements to these same detectors they can now detect a significant percentage of the nearby IC lightning strokes, but at a variable and as yet not well characterized detection efficiency that depends on the properties of the stroke and the distance from the network sensors. Since the IC lightning strokes are frequently horizontal and extend for great distances, it is harder to assign a single position to each stroke. CG flashes also extend over long distances inside the cloud, while the ground strike positions are normally well defined. Since there are significantly more cloud lightning strikes than ground strikes, and since within-cloud lightning is normally observed preceding the first ground strokes, cloud lightning detection systems that are optimized for VHF emissions have a great potential for enhancing our current detection capabilities. These systems will, however, require a significantly higher density of stations to provide uniform, high-detection-efficiency coverage for future applications. At present, there are a number of regional "total lightning" detection systems that are being used for research and for the testing of future application products.

Lightning Detection from Space

Space-borne sensors can also be used to detect lighting. While some satellite-based sensors can detect the electrical emissions from the lightning flash, the most promising space-borne approach is based on optical detection of the lightning strikes.

Optical detectors, normally filtered to look at a strong oxygen emission band in the near infrared (IR) and analyzed to detect short bursts of radiation such as expected from a lightning strike, can be used both day and night. In the 1970s and 1980s, Bernard Vonnegut designed an early handheld detector of this sort for use by U-2 research aircraft and Space Shuttle astronauts (*13, 14*). This approach was subsequently refined and employed in NASA's LIS on the TRMM satellite and in the OTD flown on the Microlab-1 satellite. Similar optical detection systems are currently being developed for use on the GOES-R series of U.S. operational geostationary weather satellites.

The Geostationary Lightning Mapper (GLM) being developed for GOES-R is expected to provide full coverage over the United States, South America, and adjacent oceanic areas. From geostationary orbit, the GLM lightning sensor will not be able to match the accurate positioning of the current ground-based networks, but will provide uniform, high-efficiency detection of total lightning, including both cloud and ground flashes over virtually all of the visible earth disk as seen from space. This new data set will not replace the current ground-based lightning networks, but will provide extremely valuable "total lighting" information to augment the high-resolution CG flash information currently available.

Warning Criteria

Detecting lightning strokes is a critical initial step in any lightning safety system, but needs to be combined with a set of warning criteria. In general, most dedicated lightning systems provide two levels of warning: an alert, saying that lightning may develop or move into the area in the near future, and an alarm, saying that lightning has been detected in the immediate vicinity or is expected to develop at any moment.

In systems based exclusively on measurements of the atmospheric electric field, unusually high fields will trigger an alert, with alarms being triggered by electric fields reaching a level where imminent discharges could be expected (typically 2000 V/m).

In systems based on detections of CG flashes, the warning criteria are based on the distance to the lightning strokes being detected and the time since the last stroke was detected within a specified distance from the area of interest. While there are no universally recognized standards for issuing alerts or alarms for airport ramp operations, the American Meteorological Society and the National Oceanic and Atmospheric Administration (NOAA) have endorsed the "30-30 rule." This rule states that outdoor activities should be limited or curtailed whenever there has been a lightning strike detected within 6 mi (based on 30 sec between an observed flash and the sound of the thunder) within the past 30 min.

Lightning warning system vendors often recommend this standard, but allow users to set their own criteria for alerts and warnings. In some cases, airport operators report using a standard as short as 10 min since the last lightning strike before going back to work (see Chapter 2). In any situation of this sort, there is a continual tension between providing an adequate warning to prevent injuries and not stopping work unnecessarily.

Advocates of conservative (safety first) warning criteria emphasize that lightning injury statistics show that injuries are most likely at either the very beginning of the lightning event or near its end (*15, 16*). Their goal is to be able to issue a lightning warning before the first strike reaches the ground and then to allow enough time before work is resumed to ensure that the hazard has passed.

This is a serious problem, since individual lightning strikes are essentially impossible to predict, either as to time or location. There are well-documented examples of "bolts from the blue"—lightning strikes that occur when an observer can see blue sky above (see Figure 9). On the other hand, current procedures are generally believed to provide a safe environment for ramp workers, as evidenced by the very low numbers of reported lighting deaths or injuries.

Review of Current Airport Lightning Detection Technologies

This section reviews and evaluates most of the lightning detection systems and technologies currently in use at airports or marketed for use by airports, airlines, and ramp workers. As a rather specialized market, it is surprising how many different commercial systems are available.

All the systems included in this discussion seem to be reputable and should be able to detect lightning strikes within ranges of concern to airport workers. There are, however, no formal standards for lightning detectors, and no agency or organization is responsible for routinely testing these instruments for accuracy, reliability, or durability. While it would be relatively easy to perform comparisons between instruments, this would require cooperation from the various system vendors. Lacking a requirement for a license or a certification process, this is not likely to happen. More important, verification and validation of lightning detection system performance requires an independent system for detecting ground truth. Some limited testing of this sort has been done, mostly to document the performance of the National Lightning Detection Network (NLDN) using triggered lightning strikes or triangulation of strike impact positions from simultaneous photographs taken by multiple cameras.

Handheld or Portable Systems Based on RF Emissions

Handheld systems are the entry-level product for lightning detection. These systems are relatively low cost (some priced

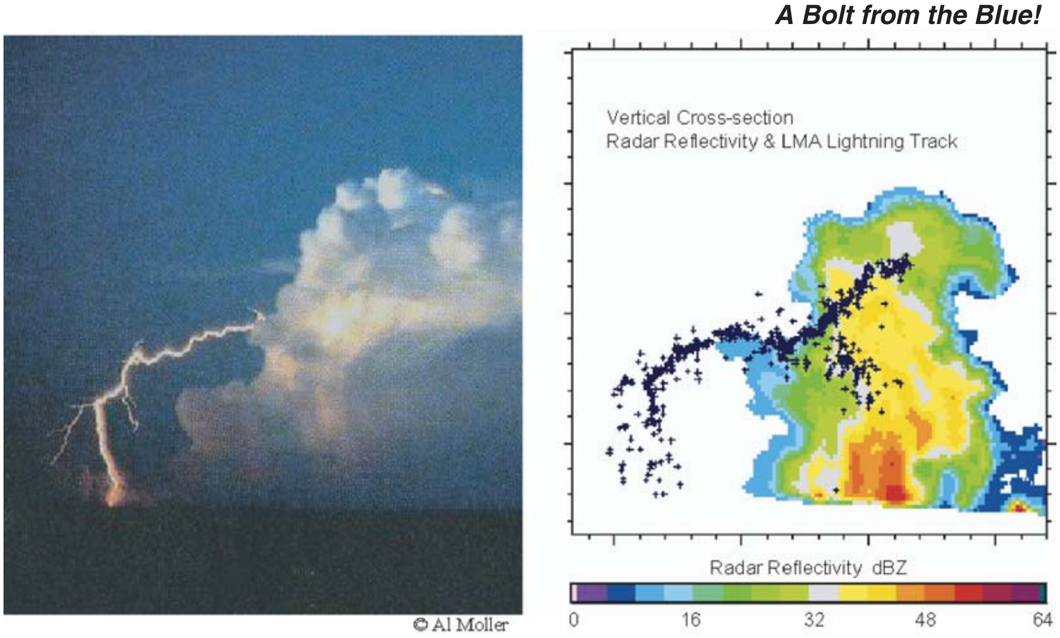


Figure 9. Two illustrations of lightning strikes that develop within a convective storm, but exit the side of the storm and strike the ground relatively far from the visible edge of the storm. These two illustrations are from different storms, but show a strikingly similar pattern. The picture on the left was taken by Al Moller. The illustration on the right, provided by Bill Rison from the New Mexico Institute for Mining and Technology, is a vertical cross-section of a storm, as seen by a research radar, overlaid with a full depiction of a lightning stroke based on a specialized lightning mapping system capable of detecting each step in the lightning stroke. In this case, the lightning strikes the ground about 5 km (3 mi) from the edge of the radar echo.

under $100) and only detect the RF static discharges of a nearby lightning strike. While the systems may not be uniformly sensitive in all directions, they have no way to detect or indicate the direction of the lightning strike. They do, however, generally try to give some indication of the relative range of the strike, based on the amplitude of the RF signal. These systems often monitor the amplitude of the lightning signals over time and indicate whether the lightning is getting closer or further away, based on the trend in the signal amplitude. This is not a particularly accurate way to estimate range, making the devices mostly useful as an "objective" detection system that might be carried by individual workers or used at a small airport to help them notice or evaluate a potential lightning hazard.

In general, these systems are not appropriate for workers at large airports or for airport operations managers.

Specific products in this category include

- StrikeAlert (www.strikealert.com),
- SkyScan (www.skyscanusa.com/main.html), and
- ThunderBolt (www.spectrumthunderbolt.com).

Directional Detectors Based on RF Emissions

These systems are a step up from the handheld or portable systems discussed earlier. The systems add a fixed antenna to identify the direction to the detected lightning strike. The distance to the lightning strike, however, is still estimated from the amplitude of the lightning signal. Products in this category can range from fairly basic systems using personal computers, which are primarily targeted at meteorological hobbyists or commercial users seeking a general awareness of nearby lightning activity, to sophisticated systems engineered for specific airport applications (for example, automatic thunderstorm detection for METAR reports).

As single sensor detection systems, these systems are somewhat limited for applications that require high-accuracy detection and tracking of lightning strikes in the vicinity of an operational facility, such as airport ramp operations. These systems can be quite useful, but they should not be used for applications for which they were not intended.

This category includes Boltek (www.boltek.com). Note, however, that there is a cooperative lightning detection network based on shared observations by Boltek system users—the StrikeStar Lightning Detection Network—but as a cooperative effort it is clearly and properly labeled as "Not for use for protection of life or property." The following two thunderstorm sensors designed for automatic weather stations are also in this category:

- All Weather Inc. Thunderstorm Detector, Model 6500 (www.allweatherinc.com/meteorological/lightning_detection_6500.html), and
- Vaisala Local Lightning Sensor TSS928 (www.vaisala.com/businessareas/measurementsystems/thunderstorm/producingsystems/tss9281).

The single-sensor thunderstorm detection systems intended for use with an automatic weather station may not be appropriate for high-resolution detection and tracking of nearby lightning activity. Two or more of these units could, however, be combined into a local lightning detection network that could provide a local-area, high-accuracy, real-time lightning detection capability. At present, no commercial vendors offer this type of system.

Electric Field Mills (or Other Electric Field Monitoring Systems)

By monitoring the buildup of the local electric field strength, electric field mills (or other electric field monitoring systems) can sense the increasing potential for a nearby lightning strike. In this sense, field mills are a rather unique product in that they offer the promise of being able to "predict" the first lightning strike and offer protection for airport personnel in the case of a storm that develops lightning directly overhead and does not move into range as a fully developed, active thunderstorm.

There are a number of manufacturers of field mills, mostly sold as individual units and not as an integrated lightning detection and warning product suitable for airport applications. Several commercial lightning detection systems employ, or have the option to employ, field mills as a component of their systems.

Only two vendors offer full commercial systems based exclusively on the monitoring of the atmospheric electric field: Thor Guard (thorguard.com) and TOA Systems (www.toasystems.com/TOASystems/ALWS.htm).

Thor Guard provides complete lightning warning systems, complete with horns and lights. Their standard installation is based on a single sensor, but for larger areas they provide systems with several sensors. They have an extensive customer list, including some small airports.

TOA Systems offers an Advanced Lightning Warning System (ALWS), based on three or more electrical field mills and designed to monitor an area 6 mi or more in range. Their field mill systems can also be integrated with lightning reports from a separate network (such as their own U.S. Precision Lightning Network, USPLN).

Field mills can offer important information on the initial development of electrical activity in the vicinity of an airport, but are probably best used as a component of a detection and warning system that also uses RF lightning detection technologies.

Commercial Lightning Detection Networks

At present, the United States is covered by two separate, independent lightning detection networks. These networks are intended to provide real-time lightning data for a wide variety of commercial and government applications.

The older of the two networks, NLDN, is now operated and maintained by Vaisala. NLDN (www.vaisala.com/weather/products/lightning/knowledgecenter/aboutnldn) was recently upgraded with new sensors that combine both magnetic direction finding (MDF) and time of arrival (TOA) technologies to increase system reliability, detection efficiency, and location accuracy. The current system is estimated to have a 90%–95% detection efficiency for CG flashes, with a median location accuracy of better than 500 m (*17*, *18*). In 2005, Vaisala's NLDN received a 5-yr contract to provide lightning detection data to the National Weather Service and other U.S. government agencies.

USPLN (www.uspln.com/index2.html) is owned and maintained by TOA Systems, Inc., in collaboration with its partner, WSI Corporation. WSI is responsible for sales and marketing of the data, including sales to value-added retailers. This recently completed network is based on a new generation of sensors, exclusively using time-of-arrival technologies. TOA Systems estimates that their national network provides greater than 90% detection efficiency and an accuracy equal to, or better than, 250 m.

Airport Lightning Detection Systems Based on National Lightning Networks

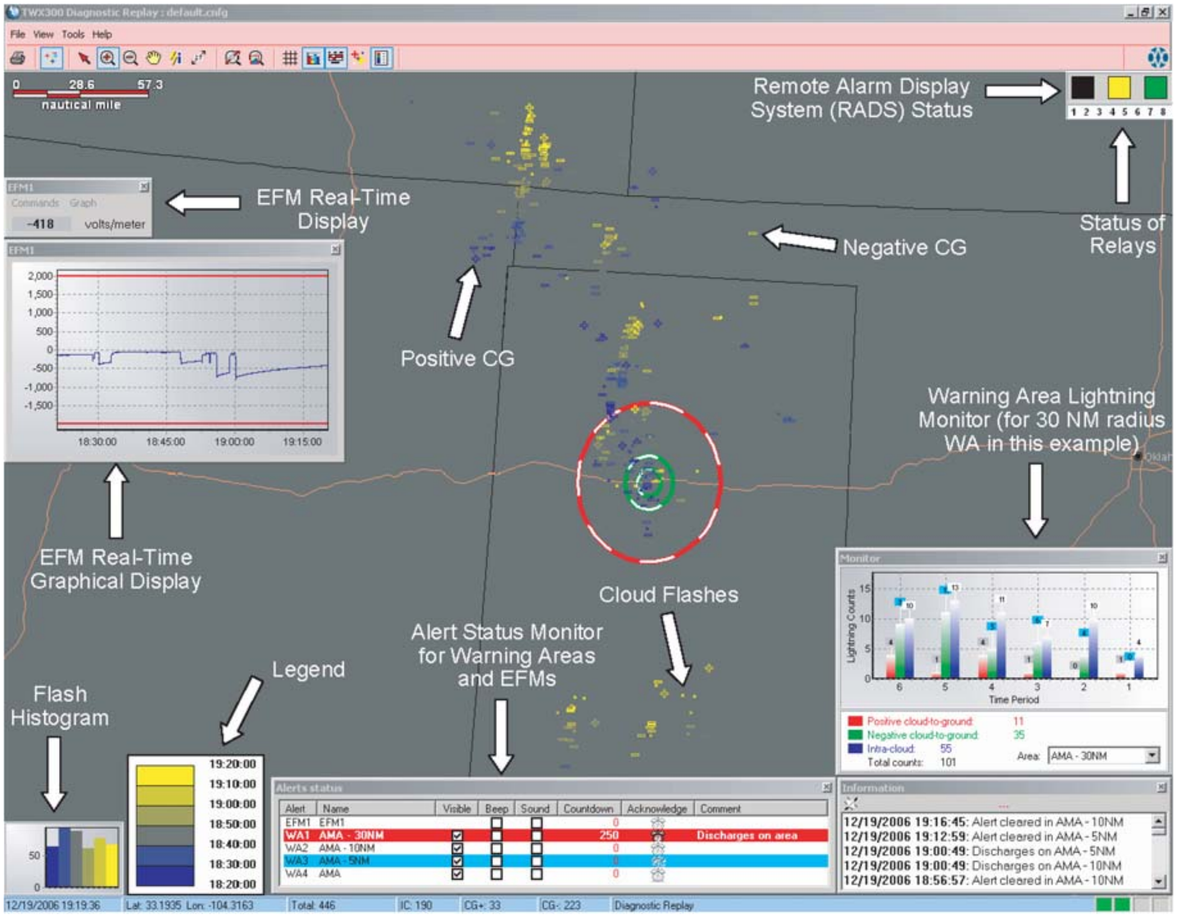
Given the availability, accuracy, and impressive efficiency of the national lightning detection networks, it is natural that most of the commercially available airport lightning detection systems are based on the network lightning data sets.

While some systems make use of the lightning data by itself, other vendors integrate the lightning data with other, more general-purpose weather information, including radar products. The lightning-specific products are clearly directed toward applications such as ramp operations, with the intent of providing a focused product that meets the specific user's needs. The more general integrated displays, on the other hand, are normally directed toward a broader audience, including users such as airline managers and dispatchers that need to monitor both flight and ramp operations. Ideally, an integrated product should provide separate displays or tools to switch focus between different, independently optimized views of the available data. Versatile systems, optimized for meteorologists, are often too complicated for focused applications such as ramp operations.

The Vaisala thunderstorm warning system is based on real-time lightning observations provided by Vaisala's NLDN. The system can optionally be augmented by the addition of up to seven electric field mills. The warning system provides an extensive set of custom displays showing the location of lightning strikes and generating specific alert and alarm messages. The warning system can be customized by visual and audible alarms and electronic notification. The most recent software upgrade supports an unlimited number of circular or polygon warning areas, with the alert and alarm criteria customized by the user (see Figure 10).

The current version of the Vaisala lightning warning system is the TWX300, which was released in 2007 (www.vaisala.com/weather/products/lightning/). Earlier versions of the Vaisala system were distributed as the Precision Lightning Warning System (PLWS), which was released in 1995, and the TWX1200, which was made available in 2004. All of these versions of the Vaisala system are currently in use at a variety of airports.

ARINC is a licensed installer and value-added reseller of Vaisala lightning equipment and can provide customized installations with external alarms (horns and beacons) and a variety of different options for communication links (www.arinc.com/products/weather/forewarn/index.html). ARINC's ForeWarn precision lightning system is based on Vaisala's Thunderstorm Warning System software, with user options.



🟥 Positive cloud-to-ground: 11
🟩 Negative cloud-to-ground: 35
🟦 Intra-cloud: 55
Total counts: 101
Area: AMA - 30NM

Alert	Name	Visible	Beep	Sound	Countdown	Acknowledge	Comment
EFM1	EFM1		☐	☐	0		
WA1	AMA - 30NM	☑	☐	☐	250		Discharges on area
WA2	AMA - 10NM	☑	☐	☐	0		
WA3	AMA - 5NM	☑	☐	☐	0		
WA4	AMA	☑	☐	☐	0		

```
12/19/2006 19:16:45: Alert cleared in AMA - 10NM
12/19/2006 19:12:59: Alert cleared in AMA - 5NM
12/19/2006 19:00:49: Discharges on AMA - 5NM
12/19/2006 19:00:49: Discharges on AMA - 10NM
12/19/2006 18:56:57: Alert cleared in AMA - 10NM
```

12/19/2006 19:19:36 | Lat: 33.1935 Lon: -104.3163 | Total: 446 | IC: 190 | CG+: 33 | CG-: 223 | Diagnostic Replay

Figure 10. A captured image of the main display screen of the Vaisala TWX300 lightning warning system (with annotations added). The age of the displayed lightning strokes is indicated by their color, while the bottom panel summarizes the current alarm and alert status. As the storm approaches the airport, the display can be zoomed in for a closer, higher resolution view (figure courtesy of Vaisala).

The Weather Decisions Technologies (WDT) real-time lightning display (www.wdtinc.com/pages/home_page/lightningDSS/realtimeLD/web_page.xml) provides a simple, direct view of nearby lightning strikes (see Figure 11). WDT's main focus, however, is on a more comprehensive Lightning Decision Support System (LDSS) that can be augmented to include lightning range alerting and a lightning prediction algorithm.

Weather Services International (WSI) has a number of systems designed to provide general-purpose weather information for airports and weather-sensitive applications (www.wsi.com/aviation/solutions). Their systems are based on a dedicated workstation at the airport with a satellite data feed that provides general weather information, including radar and satellite imagery, augmented by real-time NLDN or USPLN lightning observations. Their Weather Workstation product is used by Delta, UPS, and FedEx. Figure 12 shows a detail from the WSI Fusion Display, combining radar imagery, flight tracks, and real-time lightning observations.

DTN/Meteorlogix offers a general airport weather information system, featuring real-time NEXRAD radar data from NOAA. As one component of this system, NLDN lightning data are overlaid on top of the radar display, with an on-screen panel indicating the current alert or alarm status (defined in terms of lightning strikes within a user-specified warning and advisory area, indicated by a circle centered on the airport). The WeatherSentry system (www.meteorlogix.com/industry/aviation.cfm) is provided as an online web application (see Figure 13).

The Integrated Terminal Weather System (ITWS) is a U.S. government–sponsored development of a comprehensive terminal area weather system (www.ll.mit.edu/AviationWeather/sitdisplay.html). It is intended for installation at large airports that have been provided with Terminal Doppler Weather Radar (TDWR). The basic ITWS display is relatively complex, but includes a simple "lightning within 20 nautical miles" display light based on real-time access to NLDN data (see Figure 14). It would be relatively easy to enhance the lightning warning features of this system in an environment that has the capacity to integrate lighting observations with other meteorological data sets.

Lightning Prediction Technologies

Lightning warning systems often make a distinction between lightning *detection* and *prediction*. Detection systems, as the name implies, simply detect and report lightning

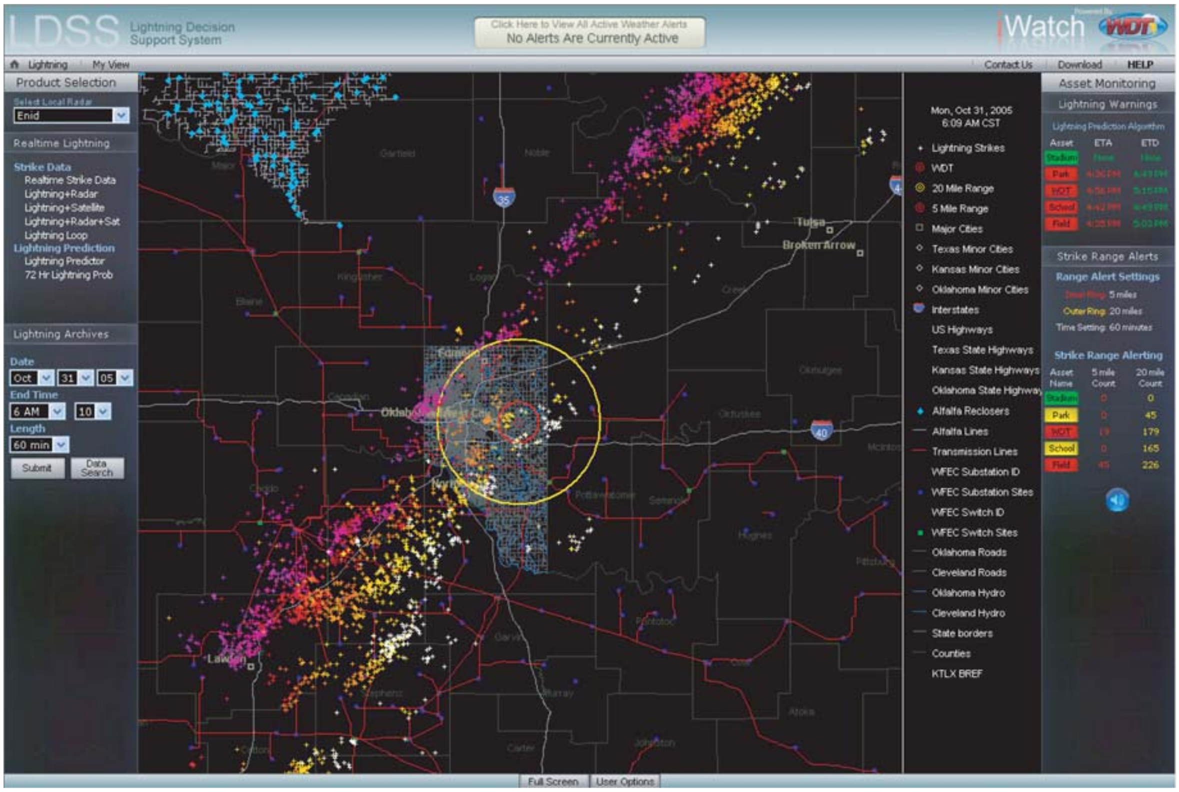


Figure 11. An example of the WDT real-time lightning display. The age of the displayed lightning strokes is indicated by their color on a zoomable map display (figure courtesy of WDT).

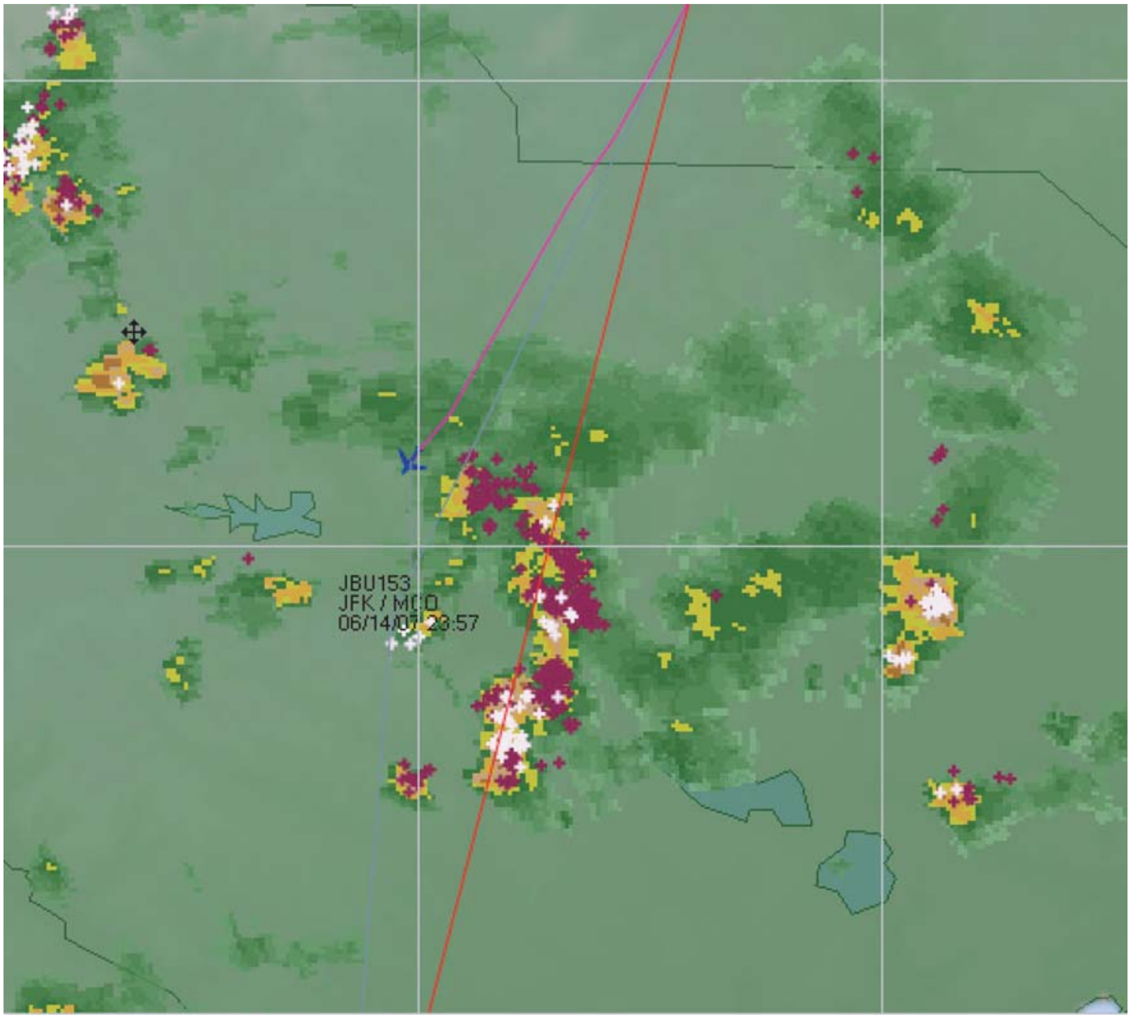


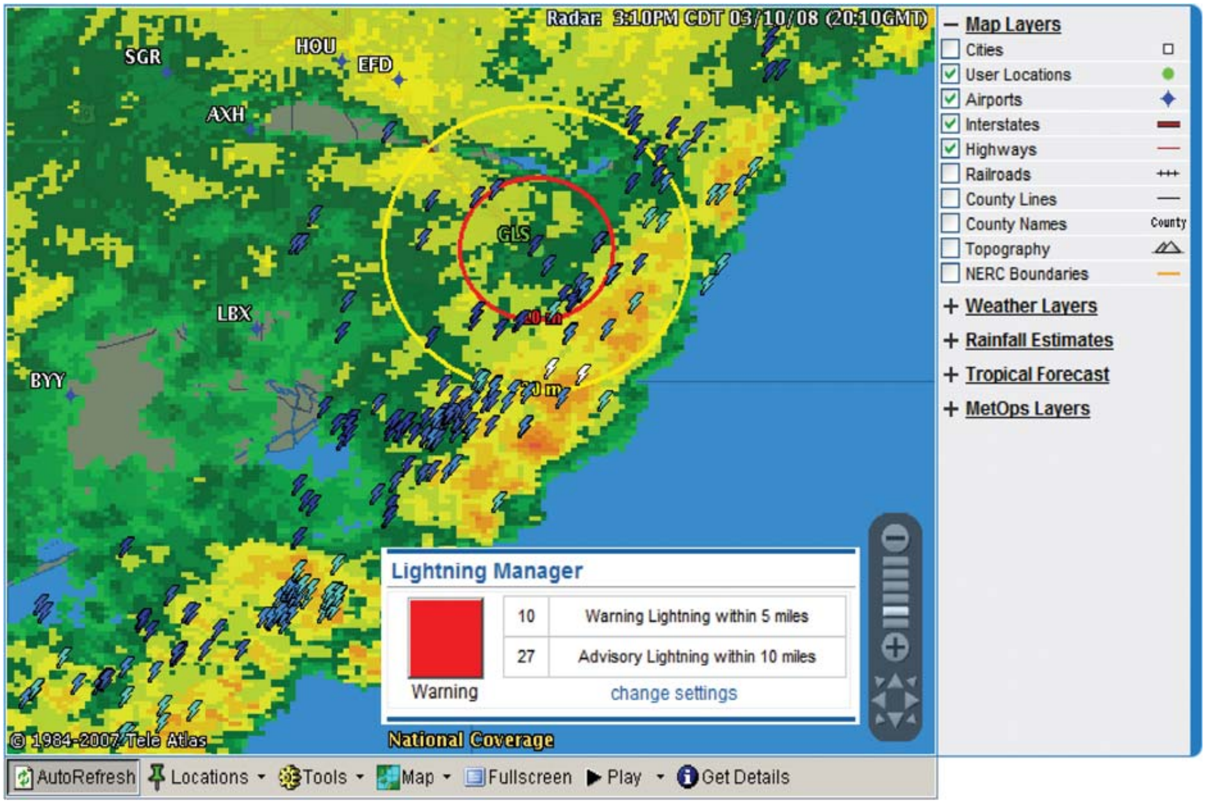
Figure 12. Detail of a screen image from the WSI Fusion Display, showing a combination of aircraft track, flight plans, and radar imagery (in shades of green) as a background for CG lightning strikes that are color-coded, with the most recent strikes plotted as white "plus" signs (figure courtesy of WSI).

strikes after they occur. Prediction systems, on the other hand, provide warnings that a lightning strike is likely to occur. Most of the time there is not much of a difference between the two approaches. If an active thunderstorm moves towards an airport, lightning detection technology will continually monitor the locations of the CG lighting strikes. When the activity reaches a specified distance from the airport, the system will generate an alert or warning—essentially a prediction, based on the proximity of the lightning, that the storm presents an imminent threat and hazard. In some cases, however, a lightning storm may develop directly over an airport, and the very first strikes can put airport workers at risk. In this case, a prediction system may be able to provide a uniquely valuable warning.

Even the best predictions only give a general indication that a lightning strike is likely to occur in the immediate vicinity. The timing and path of an individual lightning stroke are, for all practical purposes, unpredictable.

There are two distinctly different approaches to predicting lightning hazards. The first, based on monitoring the buildup of the atmospheric electric field in response to nearby charged clouds, represents a true prediction. Electric field measurements will not, however, necessarily predict all nearby lightning strikes, and they can be expected to produce occasional false alarms (*19, 20*).

The other approach to lightning prediction is to monitor the growth and movement of the systems that develop into thunderstorms using techniques that have been developed for short-term weather forecasts ("nowcasting"), using general storm properties that can be monitored by radars or satellites as a proxy for lightning activity. This approach can provide significantly longer advance warnings of pos-



– Map Layers
☐ Cities
☑ User Locations
☑ Airports
☑ Interstates
☑ Highways
☐ Railroads
☐ County Lines
☐ County Names
☐ Topography
☐ NERC Boundaries

Lightning Manager

Warning

10	Warning Lightning within 5 miles
27	Advisory Lightning within 10 miles

change settings

Figure 13. A screen image of the DTN/Meteorlogix online Lightning Manager, showing a combination of radar and lightning data, with a user-configured warning and advisory pop-up window (figure courtesy of DTN/Meteorlogix).

sible lightning activity than other approaches, but with less accuracy.

The convective nowcasting approach is well-suited for hazardous operations such as missile ranges and weapons testing, which require a long lead time to shut down or reschedule operations and a high probability of detection of a potential hazard. These systems will, however, normally have a correspondingly high false alarm rate. With respect to commercial airport operations, most long-range predictions of this sort would be considered only as an advisory forecast; they would not mandate that activities be rescheduled or that operations be shut down.

Shutting down ramp operations at a busy airport is a major decision that cannot be taken lightly; there is thus a low tolerance for false alarms. In most cases, there will likely be a natural hesitancy to clear the ramp on the basis of a "prediction" without some additional evidence of nearby lightning strikes.

While most studies of lightning prediction have naturally concentrated on forecasting the initial onset of lightning activity, the same observing systems may also be able to provide valuable information about the cessation of a lightning hazard as storms are dying down and moving out. In those cases, the technologies may be able to provide objective criteria for shortening the duration of ramp closures after a warning is sounded.

Monitoring the Local Atmospheric Electric Field

As already discussed, electric field measurements can detect the presence of high levels of charge separation in nearby clouds that suggests a strong likelihood of current or future lightning activity. These systems have the unique potential to provide advance warning of the first lightning strike from a developing storm.

This ability to offer an advance prediction of the first lightning strike makes these systems particularly attractive for applications where response time is critical, such as athletic fields and golf courses with limited access to sheltered areas and stadiums that would take a long time to clear of spectators.

Monitoring and Predicting Overall Storm Evolution

Lightning activity is an integral part of the life-cycle of a thunderstorm. For example, Figure 15 shows a summary of

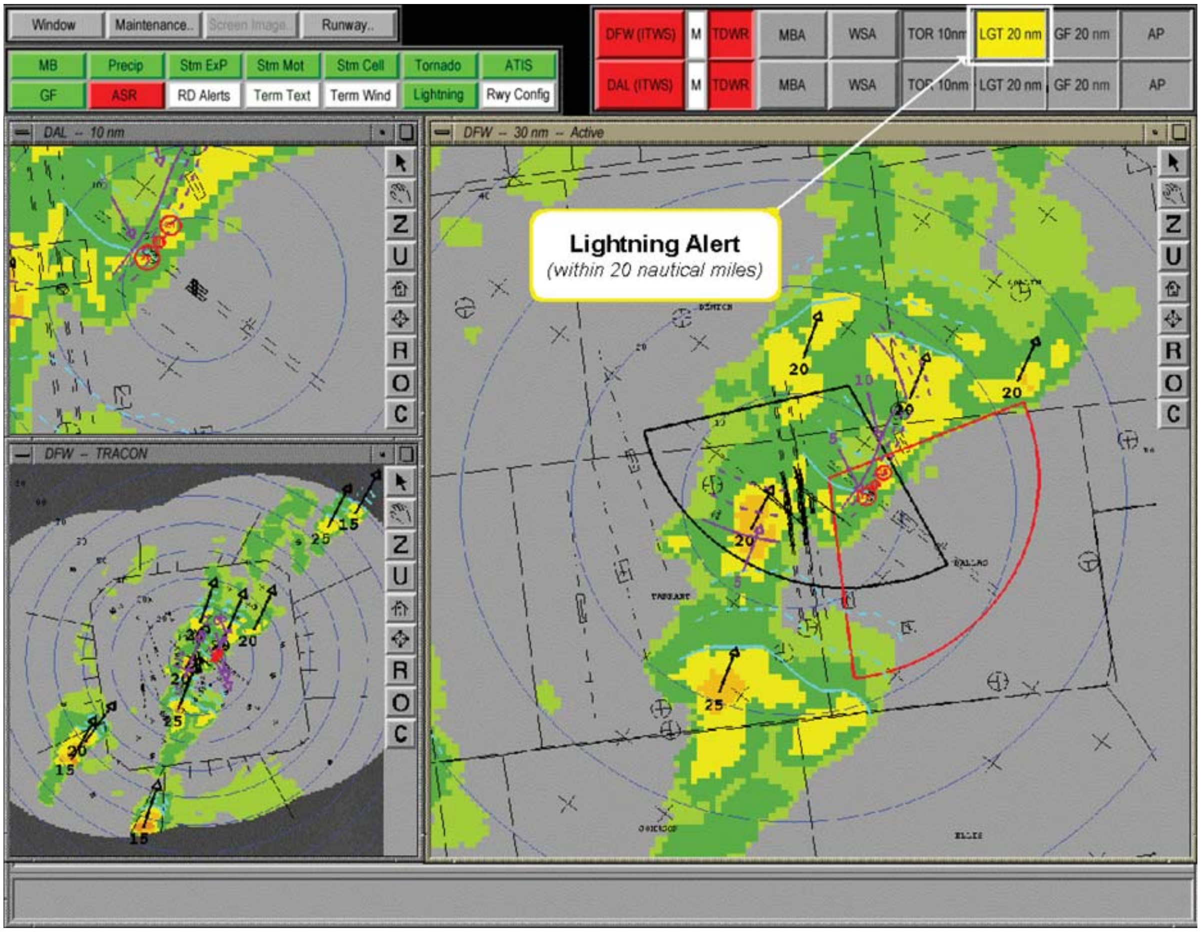


Figure 14. A screen image of the main ITWS weather display, including a simple lightning alert button.

the evolution of an intensely studied, microburst-producing thunderstorm. The bottom two panels show vertical profiles of the time evolution of the storm radar reflectivity and updraft strength, while the top panel shows the IC and CG lightning activity.

In this storm, the initial mid-level strengthening of the radar echo preceded an intensive growth period, with the highest lightning flash rates well correlated with the period of the maximum updrafts. This storm's ratio of IC to CG lightning strikes was unusually high, but follows the normal pattern of IC lightning developing several minutes before the first CG stroke.

Storm studies such as shown in Figure 15 indicate that lightning data, particularly IC lightning data, are a valuable indicator of the updraft strength and can play an important role in short-term prediction of storm behavior. At the same time, observations of storm strength and evolution can be used as an approximate indicator of lighting activity. In recent years, there have been a number of significant advances in the short-term forecasting of thunderstorm activity, including predicting areas of new growth and explosive development (*22*). Using standard meteorological data sets, including output from numerical models, radar, and satellite observations, storm nowcasting has proved to be a valuable tool for understanding and predicting storm behavior and evolution. Given the importance of timely predictions of hazardous weather, it is natural that storm forecasters are now beginning to generate short-term, high-resolution lightning forecasts (*23*).

Figure 16 shows a graphical depiction of the results of a lightning prediction algorithm included in WDT's Lightning Decision Support System (LDSS). This algorithm combines real-time lightning observations with storm-cell motion tracks to identify separate moderate and high threat areas out to 30 min in advance. A similar system, which combines radar and lightning observations to provide lightning warnings for a variety of public service applications, including airport ground operations, is currently under development in Australia (*24*).

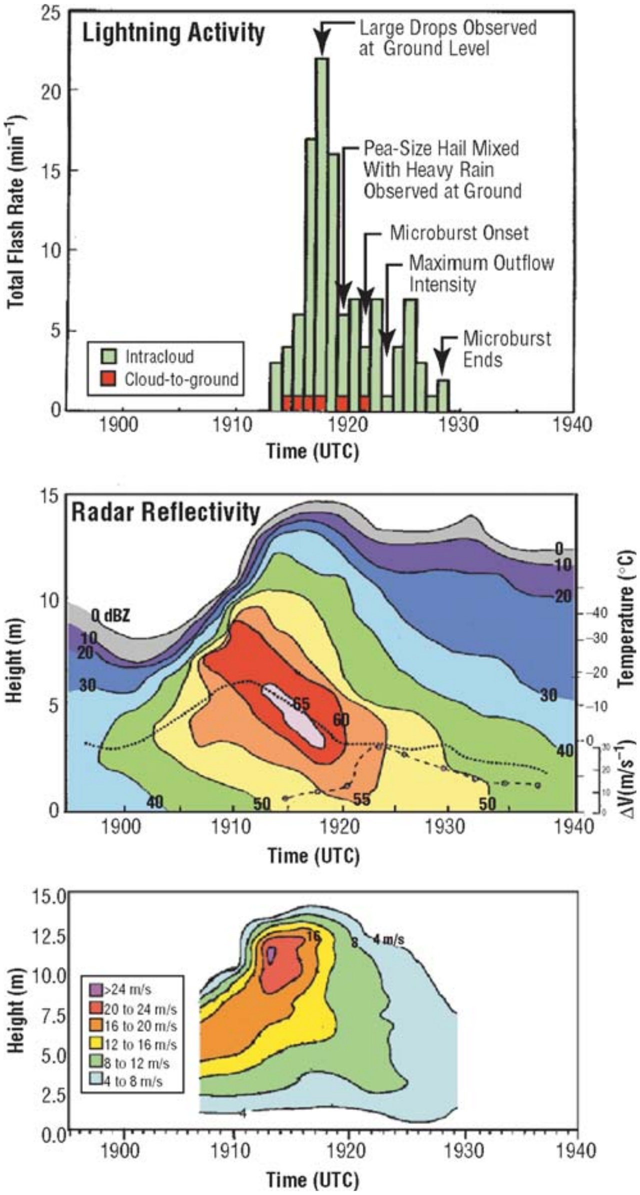


Figure 15. Lightning and precipitation history of a severe thunderstorm (21). The bottom panel shows the updraft strength in the main cell as a function of time and height. The middle panel shows the corresponding evolution of the radar reflectivity, while the top panel shows the lightning activity correlated with significant features in the storm's evolution.

Total Lightning as a Predictor for Ground Strikes

The CG lightning events that are the focus of the NLDN and the USPLN lightning detection networks make up only a small fraction of all lightning activity. Studies, such as the one depicted in Figure 15, show that systems that can monitor all lightning strokes will be able to perform detailed monitoring of the time-resolved flash rates and the areal extent of a storm's lightning activity. Since IC lightning is normally a precursor to the first CG strokes, total lightning systems can be used to identify storms that are entering an active lightning-generation period and act as a predictor for subsequent CG lightning strikes (*25*).

While it is important to remember that it is the CG lightning flashes that represent the actual hazard to ground operations, IC lightning activity is a direct indicator of a given storm's lightning potential and thus should be a uniquely valuable short-term predictor of the CG hazard. As a predictor, total lightning is also attractive since it is based on an observed event, rather than dependent on extrapolated storm behaviors.

While current lightning detection networks can detect some IC lightning flashes, high-efficiency detection of IC lightning events will require the network sensors to be enhanced, combined with a significant increase in the number of network sensors. As an attractive alternative to a nationwide enhancement of the current lightning detection networks, a number of regional total lightning networks could well be embedded within the national CG networks. The regional total lightning systems could provide improved storm monitoring and prediction capabilities as well as enhanced lightning detection capabilities for a wide variety of community-based applications.

Sometime after 2014, the next generation of U.S. geostationary meteorological satellites is expected to include a large-area optical lightning mapper. From geostationary orbit, this instrument will provide total-lightning observations at a spatial resolution of about 10 km. While this is much lower resolution than would be provided by a dedicated regional sensor network, the 10-km resolution would still provide a valuable measurement of the extent of the IC lightning and help define the areal extent of the lightning hazard. Perhaps more important, data from the satellite-based system would be available via free, real-time broadcasts from space.

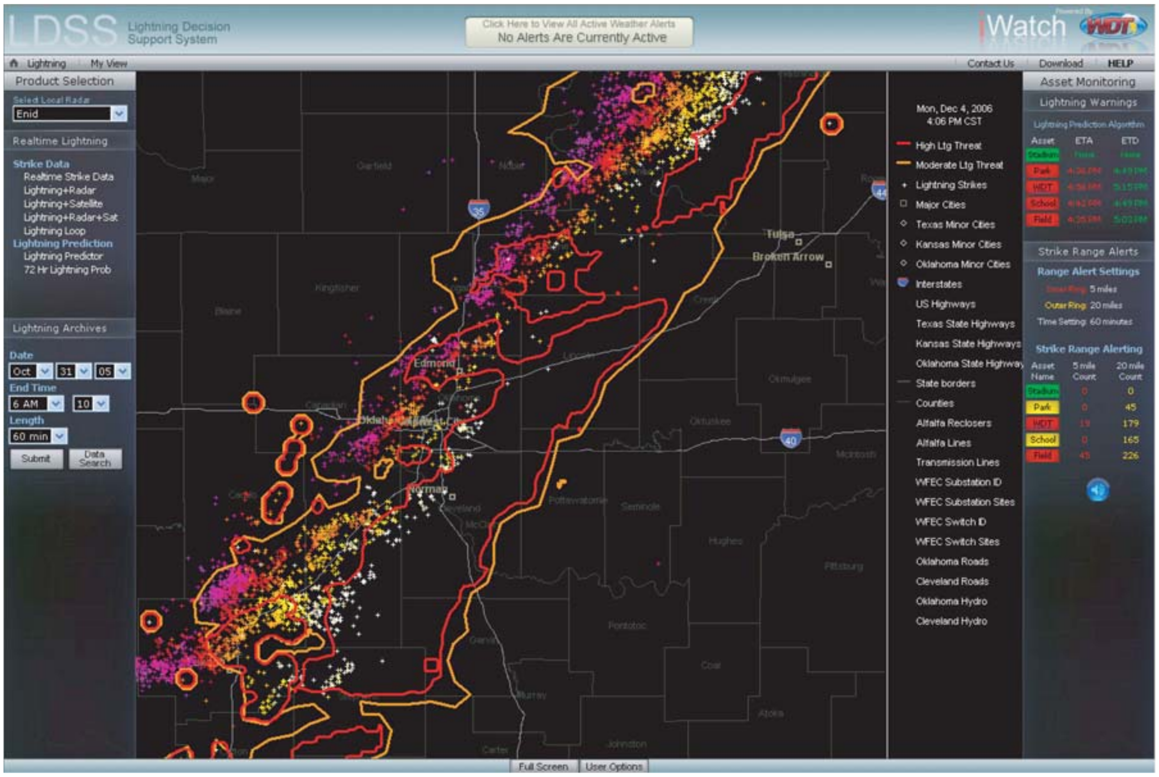


Figure 16. An example of the WDT lightning prediction algorithm running within the WDT LDSS. The algorithm is based on the current lightning observations, coupled with the expected evolution of the storm, as reflected by its radar signature and indicates the location and magnitude of the expected lightning threat 30 min into the future (figure courtesy of WDT).

CHAPTER 2

Airport and Airline Surveys

Introduction

The science of lightning and technologies that detect lightning events were briefly reviewed in Chapter 1. This chapter describes how airport and airline management uses those technologies to control ramp activities and afford a safer working environment when lighting occurs at the airport.

Survey candidates were jointly identified by the project panel and the MDA Federal team. the candidates included several airports that have installed lightning detection and warning systems to support their operations, as well as several airlines.

The airports surveyed included

- Charlotte-Douglas International Airport, NC (CLT),
- Chicago-O'Hare International Airport, IL (ORD),
- Dallas-Ft. Worth International Airport, TX (DFW),
- Denver International Airport, CO (DEN),
- Orlando International Airport, FL (MCO),
- Phoenix-Sky Harbor International Airport, AZ (PHX),
- Pittsburgh International Airport, PA (PIT), and
- Tampa International Airport, FL (TPA)

The following four airlines were also surveyed:

- American Airlines (AA),
- Northwest Airlines (NW),
- United Airlines (UA), and
- United Parcel Service (UPS).

Survey Results

In general, the airports and airlines were questioned with respect to

- Type of lightning detection and warning system equipment installed;
- Complementary weather data support systems;
- Defined threat and risk alert levels;
- Means of alerting airport staff and operators on aircraft ramps to lightning events (airport surveys);
- Means of alerting airline staff and other airport ramp operators to lightning events (airline surveys);
- Deficiencies in lightning detection systems and associated warning procedures;
- Effectiveness of the equipment, threat and risk levels, and notification process; and
- Applicability of standardization to lightning detection and warning system procedures.

For comparative purposes, the input obtained from each airport and airline is grouped by query item. The responses reflect the use of certain types of equipment to monitor lightning threats and the variety in how that data are interpreted and used to control ramp operations.

In general, lightning detection systems convey information to users through computer monitor displays, as illustrated in Chapter 1. These systems apply algorithms to advise users as to the potential for, or the actual existence of, a lightning event; the warnings are conveyed to field crews and personnel in a number of ways, as summarized in the following sections.

Lightning Detection Equipment

Charlotte-Douglas International Airport (CLT)

Vaisala Precision Lightning Weather System (PLWS), a predecessor of the TWX1200 (Vaisala Thunderstorm Warning System 1200) with NLDN feed and two electric field mills (EFM).

Chicago-O'Hare International Airport (ORD)

No airport-owned or provided equipment. Users rely on self-installed equipment.

Dallas-Ft. Worth International Airport (DFW)

No airport-owned or provided equipment. Users rely on self-installed equipment.

Denver International Airport (DEN)

No airport-owned or provided equipment. Users rely on self-installed equipment.

Orlando International Airport (MCO)

Vaisala TWX1200 with NLDN feed and two EFMs. This system is referred to locally as "ForeWarn II," which is the brand name used by ARINC when it sells and installs the Vaisala product. MCO is planning to add a third EFM and use its local area network to transmit alarms to remote alarm display (RAD) units.

Phoenix-Sky Harbor International Airport (PHX)

Vaisala TWX300 with NLDN feed and two EFMs.

Pittsburgh International Airport (PIT)

Vaisala PLWS with NLDN feed and two EFMs. System to be upgraded to TWX300.

Tampa International Airport (TPA)

Vaisala PLWS with NLDN feed and two EFMs. System to be upgraded to TWX300.

American Airlines—DFW Only

Vaisala TWX300 with NLDN and two EFMs.

Northwest Airlines—Systemwide (eight airports)

DTN/Meteorologix Aviation WX Sentry and one EFM.

United Airlines—ORD Only

Vaisala TWX1200 with NLDN feed and two EFMs. System to be upgraded to Vaisala TWX300.

United Parcel Service—Louisville, KY, Only

UPS has operations at about 100 airports. Two airports (main hubs)—at Rockford, IL, and Louisville, KY—have their own lightning detection systems. Approximately 12 airports have lighting information provided by the airport authority or other airlines.

At Louisville, UPS utilizes the WSI Weather Workstation, which provides weather radar observations, weather maps and forecasts, and NLDN real-time cloud-to-ground lightning observations that are monitored 24/7 at the ramp operations center. The system automatically generates a pre-alert, fuel ban alert, and operations alert at the center with visual cues when lightning is detected within the predefined ranges.

UPS is considering switching to the TOA System's USPLN in the expectation of faster throughput of observations, lower costs, and possible improved warnings through the USPLN's reports of within-cloud lightning strikes, in addition to cloud-to-ground strikes.

Complementary Weather Data Support Systems

Charlotte-Douglas International Airport (CLT)

Weather radar feed.

Chicago-O'Hare International Airport (ORD)

Uses outside contractor and media reports. Has access to weather radar feed.

Dallas-Ft. Worth International Airport (DFW)

Utilizes an outside contractor for weather forecasts and warnings.

Denver International Airport (DEN)

"Borrows" observations taken by a weather observer stationed in the Ramp B tower and retained by another party. Also subscribes to the Weather Support for Deicing Decision-Making (WSSDM) provided by Vaisala in conjunction with the National Center for Atmospheric Research (NCAR). The WSSDM system includes lightning observations from the NLDN, but the lightning data path is not secure and is not intended for lightning safety applications.

Orlando International Airport (MCO)

No airport-owned or provided equipment. Users rely on self-installed equipment.

Phoenix-Sky Harbor International Airport (PHX)

No airport-owned or provided equipment. Users rely on self-installed equipment.

Pittsburgh International Airport (PIT)

Weather radar display from Meteorlogix.

Tampa International Airport (TPA)

Satellite weather radar antenna.

American Airlines—DFW Only

Has access to American Airlines Meteorology Department at headquarters, but relies on Vaisala TWX1200 system.

Northwest Airlines—Systemwide (eight airports)

Internet with Google map overlay. Surface radar and visual observations.

United Airlines—ORD Only

Has access to data collected at the nearby off-airport United Airlines Operations Center, including real-time radar observations, satellite imagery, and forecasts.

United Parcel Service—Louisville, KY, Only

Has access to weather data and forecasts at their on-airport airline operations center.

Defined Threat and Risk Alert Levels

The majority of users of lightning detection systems employ visual warning cues to signal lightning events and a course of action with respect to ramp activities.

Because of the range of activity centers at an airport, users may opt to equip management/operations centers with RAD systems that readily convey the required course of action based on the data input received and evaluated at the central location. Visual displays typically use color-coded signal lights to convey whether no lightning is anticipated or being monitored, the potential for termination of ramp activities, or ramp closure. The colors green, yellow, red, as well as combinations of those colors, are well suited to convey the required course of action with respect to ramp activity. An example of a RAD system is shown in Figure 17.

Figure 17. RAD system manufactured by Vaisala.

Charlotte-Douglas International Airport (CLT)

Utilizes the light signals automatically presented by the Vaisala TWX1200 based on customized software, as follows:

- Green indicates EFMs do not exceed alarm thresholds and no lightning within 12 mi, or no EFM alarm and no lightning in past 5 min.
- Green/yellow indicates one EFM at alarm threshold, or lightning strike within 12 mi.
- Yellow indicates two EFMs at alarm threshold, or lightning strike within 12 mi and one EFM at alarm threshold, or lightning strike within 6 mi.
- Yellow/red indicates two EFMs at alarm threshold and a lightning strike within 12 mi, or lightning strike within 8 mi and one EFM at alarm threshold.
- Red indicates lightning strike within 3 mi, or a lightning strike within 8 mi and two EFMs at alarm threshold.

The light signals are intended to convey current conditions for thunderstorms and potential for lightning strikes as follows:

- Green indicates no activity that will affect local operations.
- Green/yellow indicates conditions favor thunderstorms, or one or more storms are nearby and are active or forming.
- Yellow indicates activity is close and will influence, or may have already affected, operations.
- Yellow/red indicates activity is close enough that a red light can be anticipated within 5 to 10 min, or storm is just beginning to display less influence.
- Red indicates storm is having a direct impact on operations. An interruption can normally be anticipated.

Chicago-O'Hare International Airport (ORD)

None. May rely on observed action of airlines.

Dallas-Ft. Worth International Airport (DFW)

None.

Denver International Airport (DEN)

DEN Communications Center issues

- Lightning advisory when lightning is observed 10 mi out,
- Lightning warning when lightning is observed 5 mi out, and
- Lightning "secure" when no lightning is observed within a 5-mi radius for 15 min.

Orlando International Airport (MCO)

Utilizes the light signals automatically presented by the Vaisala TWX1200 based on customized software, as follows:

- Green indicates EFMs do not exceed alarm thresholds and no lightning within 6 mi.
- Green/yellow indicates one EFM at alarm threshold, or lightning strike within 6 mi.
- Yellow indicates two EFMs at alarm threshold, or lightning strike within 6 mi and one EFM at alarm threshold, or lightning strike within 4 mi.
- Yellow/red indicates two EFMs at alarm threshold and a lightning strike within 6 mi, or lightning strike within 4 mi and one EFM at alarm threshold.
- Red indicates lightning strike within 2.5 mi, or a lightning strike within 4 mi and two EFMs at alarm threshold.

Phoenix-Sky Harbor International Airport (PHX)

Utilizes the light signals automatically presented by the Vaisala TWX1200 based on customized software, as follows:

- Green/green on both monitors indicates lightning at least 17 mi distant,
- Green/yellow on one or both monitors indicates lightning within 17 mi, and
- Yellow/red on one or both monitors indicates lightning within 5 mi.

Pittsburgh International Airport (PIT)

Utilizes the light signals automatically presented by the Vaisala TWX1200 based on customized software, as follows:

- Green indicates no lightning within 17 mi, and no EFM alarm threshold reached.
- Green/yellow indicates lightning within 17 mi but greater than 12.5 mi, or one EFM at alarm threshold.
- Yellow indicates lightning within 17 mi but not within 12.5 mi and one EFM at alarm threshold, or two EFMs at alarm threshold and no lightning strike within 17 mi, or lightning strike within 12.5 mi but not within 5 mi and no EFM at alarm threshold.
- Yellow/red indicates lightning within 12.5 mi but not within 5 mi and one EFM at alarm threshold.
- Red indicates lightning strike within 5 mi, or lightning within 12.5 mi but not within 5 mi and two EFMs at alarm threshold. After a 10-min delay, system moves to the next appropriate threat level.

Tampa International Airport (TPA)

Utilizes the light signals automatically presented by the Vaisala TWX1200 based on customized software, as follows:

- Green indicates no cloud-to-ground lightning within 18 mi, and no EFM alarm threshold reached.
- Green/yellow indicates lightning within 18 mi.
- Yellow indicates lightning within 18 mi and one EFM at alarm threshold, or lightning strike within 4.8 mi.
- Yellow/red indicates lightning within 18 mi and two EFMs at alarm threshold, or lightning within 4.8 mi and one EFM at alarm threshold.
- Red indicates lightning strike within 3.1 mi, or lightning within 4.8 mi and two EFMs at alarm threshold.
- After a 5-min delay and no change, system moves to next lower threat level.

American Airlines—DFW Only

American Airlines Safety Department, with input from labor unions, uses the following standards:

- If a lightning strike is within 5 mi, use hand signals on the ramp;
- If a lightning strike is within 3 mi, shut down all ramp operations; and
- Minimum time to restart ramp activity is 10 min without a lightning strike within 3 mi.

Northwest Airlines—Systemwide (eight airports)

Northwest uses the following standards:

- If a lightning strike is within 5 mi, stop fueling and cease all headset communications;
- If a lightning strike is within 3 mi, cease ramp operations; and
- Ramp activities can be restarted only when there have been no lightning strikes within past 10-15 min (using judgment).

The 5-mi and 3-mi limits are those recommended by the Air Transport Association and the International Air Transport Association. The impact on ramp activities associated with these standards was determined with input from the labor unions.

United Airlines—ORD Only

The following standards were set with input from United Airlines headquarters and labor unions:

- If lightning is detected within 50-mi radius, alert status is activated;

- If lightning detected within 25-mi radius, aircraft are grounded and preparations begin to clear ramp personnel;
- If lightning is detected within a 10-mi radius, strobe lights and electronic flight information display system (EFIDS) are automatically activated and the ramp is cleared of personnel; and
- If lightning is beyond 50-mi radius, then normal activity.

Note: unions had requested increase from 7 mi to 10 mi and installation of EFIDS.

United Parcel Service—Louisville Only

UPS default operating rules are as follows:

- Provide a pre-alert to all personnel when lightning is within 12 mi;
- Ban fueling when lightning is within 5 mi; and
- Ban ramp operations when lightning is within 3 mi.

These rules can be modified by local station operating management depending on the history of storm events at each airport and the distances that ramp personnel need to cover to reach an area of safety. These rules can also be amended by time of year, to account for differing storm characteristics.

The aircraft mechanics union has expressed concern with respect to lightning issues and encourages the use of “reliable systems” to support decision making.

Notification Process

Charlotte-Douglas International Airport (CLT)

Fully automated system based on customized software that activates

- Master alarm distribution system (MADS) at CLT Operations Control Center (OCC),
- RAD system at airlines’ operations center and North Carolina Air National Guard, and
- Red/yellow/green traffic signals for ramp vehicles.

The CLT OCC notifies general aviation and fixed base operator by telephone. No audible alarms are sounded.

Chicago-O’Hare International Airport (ORD)

- Advises ORD staff by radio and telephone.
- Does not alert airlines or other airport tenants.

Dallas-Ft. Worth International Airport (DFW)

DFW Operations Communications Center initiates radio calls to staff and coordinates with American Airlines ramp tower staff.

Denver International Airport (DEN)

DEN Communications Center has a briefing phone hotlinked to airlines, air traffic control tower, terminal radar control center (TRACON), aircraft fuelers, caterers, cargo operators, and the DEN Public Affairs Department, which uses a phone-tree to contact other DEN property tenants and terminal tenants. DEN field staff are contacted by radio.

Orlando International Airport (MCO)

Fully automated system based on customized software that activates

- MADS at MCO Communications Room; and
- RAD system at MCO Operations, participating airlines’ operations, and 13 locations in Terminal A and Terminal B.

No visual alarms are installed.

MCO field staff are contacted by radio, but not always reached.

Aircraft fuelers are not served by RAD system; instead, they rely on wireless data transmission from MCO Communications Room.

Phoenix-Sky Harbor International Airport (PHX)

PHX Communications Center initiates a 800 MHz radio all-call to field staff.

- Airlines and ramp users are not notified.
- No visual or audible alarms are activated.

Pittsburgh International Airport (PIT)

- Warning lights in sets of yellow and red are strategically placed on all four wings of the airside terminal, the fingers of the E-gates, and the hangars. At least two sets of warning lights are visible from anywhere on the aircraft ramps.
- Radio calls are made to all PIT staff.
- Automated telephone calls are made to certain tenants.
- PIT hosts a lightning warning committee three times per year to review procedures and appropriate actions.

Tampa International Airport (TPA)

Fully automated system based on customized software that activates

- MADS at TPA Communications Center,
- RAD system at participating airlines' operations, and
- Remote enunciators (horn and beacon) at participating airline airsides A, C, E, and F; at A baggage sort; and at landside terminal baggage makeup.

American Airlines—DFW Only

American Airlines' fully automated system activates strobe lights and ramp information displays at all gate positions. The DFW Operations Communications Center is telephoned, and advice is provided to other airlines and tenants in response to direct queries.

Northwest Airlines—Systemwide (eight airports)

Northwest Airlines' notification process includes

- Activating blue lights at ramp locations,
- Initiating radio and telephone calls to notify other Northwest personnel, and
- Advising air traffic control tower operators.

United Airlines—ORD Only

United's notification system consists of

- An alarm activated at station manager's office, which must be acknowledged;
- 800 MHz radio call to employees who are unable to see strobe lights or EFIDS;
- Radio and telephone calls to fuelers, caterers, air freight, and other ramp operators that support United operations; and
- A Blackberry message to vendor contractors.

United Parcel Service—Louisville Only

When the WSI system signals a lightning event, ramp operations center (RCC) personnel manually activate a radio communications system that blocks all frequencies for intra-airline use to a receive-only mode. A voice message announces a pre-alert, fuel ban, or operations ban.

Deficiencies and Effectiveness

Respondents made the following comments regarding notification deficiencies and effectiveness.

Charlotte-Douglas International Airport (CLT)

Satisfied with the system in place. Airlines rely on CLT for alarm notification through the automated system (RAD system). Those airlines that are not provided with RAD system generally follow the lead of the hub carrier, USAirways.

Chicago-O'Hare International Airport (ORD)

System and program in place does not allow for identifying the location of lightning strikes. Airlines, primarily American and United, operate independent lightning detection and warning systems.

Dallas-Ft. Worth International Airport (DFW)

Relies on system installed by American Airlines, which activates flashing strobes at terminal facilities and hangars. American Airlines telephones the primary fixed base operator. Other airlines and ramp users follow the lead of American Airlines. However, these ramp users apply independent judgment as to stop/restart activity. FedEx and UPS may have independent lightning detection and warning systems for their use.

Denver International Airport (DEN)

The contract weather observer in the Ramp B tower initiates the lightning advisory, warning, or "secure" message based primarily on visual reference. This can generate an earlier than necessary notification. The observer would benefit from the use of newer technology equipment.

Orlando International Airport (MCO)

Prefers current arrangement, which provides a central location for data inputs and alarm notification.

Phoenix-Sky Harbor International Airport (PHX)

Notification system is adequate for PHX personnel. However, there is no communication with airlines or other airport tenants. Unsure how these tenants make stop/restart decisions when lightning threatens.

Pittsburgh International Airport (PIT)

Airlines and other airport tenants generally follow lead of primary carrier, USAirways, but there are deviations in application. Airlines or other tenants have not installed independent lightning detection and warning systems.

Tampa International Airport (TPA)

Some users allow for more time than the system suggests to restart ramp activity despite 5-min built-in delay.

The warnings provided by TPA are advisory only. Airlines and other tenants make independent stop/restart decisions that can vary among them.

American Airlines—DFW Only

No deficiencies in their operations. System in place at DFW is the most advanced of those used in other American Airlines stations with at least 30 daily flights. A remote display system may be leased at other airports where such capability exists as generally provided by the airport owner.

Northwest Airlines—Systemwide (eight airports)

None noted. Other airlines tend to follow Northwest Airlines lead at airports where it is the primary carrier. FedEx has an independent lightning detection and warning system at Memphis International Airport, TN.

United Airlines—ORD Only

No deficiencies noted; no deaths, injuries, or loss of equipment in past 5 years. Noticed that other airlines at ORD use differing risk threshold levels.

United Parcel Service—Louisville Only

Concerned about reliance on totally automated systems, which are described as often being overly cautious. This generates ramp activity stoppages that can be expensive to their time-sensitive operations.

Standardization

Respondents made the following comments regarding standardization of lightning detection and warning system technologies and practices.

Charlotte-Douglas International Airport (CLT)

Due to the uniqueness of each airport, the process does not lend itself to standardization.

Chicago-O'Hare International Airport (ORD)

Airlines had requested a central system operated by ORD. Under the advice of legal counsel, however, ORD has declined due to liability concerns.

Dallas-Ft. Worth International Airport (DFW)

Prefers a single system for airport and tenants to rely upon. Could be implemented on a cost-share basis as defined in a new operating lease.

Denver International Airport (DEN)

Favors a common approach to issuance of lightning threats at airports.

Orlando International Airport (MCO)

Some tenants have requested that MCO make the stop/restart decision. However, MCO has resisted because of liability concerns.

Phoenix-Sky Harbor International Airport (PHX)

Believes that liability issues will limit implementation of central system.

Pittsburgh International Airport (PIT)

Does not believe this is a significant issue. Airlines and unions usually have differing points of view as to stop/restart ramp activities.

Tampa International Airport (TPA)

The lightning detection and warning system at TPA has evolved over time, and the airlines have participated with TPA staff in deciding best practices, type and location of equipment to be installed, and the alarm level thresholds. Nonetheless, adherence is voluntary, and airlines and others with ramp access exercise autonomy in deciding whether to stop ramp activity and when to restart. Standardization of the system can be a goal, but in practice is not achievable due to the variances in airline and ramp user policies and business models.

American Airlines—DFW Only

American Airlines' risk levels have been regarded as too conservative by some airlines. Inasmuch as they have not standardized a system for their other airport stations, standardization would seem to be even more impractical for other users. Views liability concerns as overriding justification for a central system.

Northwest Airline—Systemwide (eight airports)

Supports a single system provided by the airport, with establishment and operating costs included in airline and other user leases. Users would execute a waiver with respect to the accuracy of the data provided, acknowledge such information as advisory, and recognize that they have responsibility for its application to their operating decisions.

United Airlines—ORD Only

Supports a single system provided all users can agree to the risk levels and associated responses.

United Parcel Service—Louisville Only

Supports the installation of lightning detection and warning systems by the airport, but users must have flexibility in the interpretation and application of the data. Recognizes that each airport has a different operational environment, distances between activity centers (cargo terminals versus airline passenger terminal complexes), and that meteorological conditions and lightning climatology also differ from airport to airport.

Survey Observations

The preceding information yields several points of interest for each category of investigation.

Lightning Detection Equipment

With the exception of one airport (DEN) and one airline (UPS), all the airports and airlines contacted utilized a lightning detection system complemented with one or two EFMs. Those employing the Vaisala TWX1200 (or predecessor versions) or other weather monitoring systems also obtain the feed from the NLDN.

Weather Data Support Systems

Each of the airports has access to other sources of weather data on which to base their decisions about stopping and restarting aircraft ramp activities. There is variability in the use of such weather data sources that may be airport-owned or readily obtained from tenants. For example, airports with operations communications centers have television news broadcasts continuously turned on and can thus monitor the Weather Channel and other programs when warranted. AM and FM radio broadcasts are also readily available at these centers. In addition, links to weather radar displays, contract services, and regular telephone contact with airline station operations personnel are employed. Airline station managers may have some of these sources onsite and also can contact their flight dispatch and operations centers for impending weather data that could affect their specific flight activity.

Threat and Risk Levels

Decisions to more aggressively monitor lightning potentials, stop ramp activity, and restart operations have been made by all the airports and airlines surveyed. There is variability in the threat and risk levels, and there is also an element of judgment, especially with respect to restarting ramp activities. It is interesting to note that airport- and airline-defined threat and risk levels focus on the distances within which a lightning strike occurs and, at times, when the EFMs reach their alarm threshold limits.

Ramp restart levels usually include a period of time during which no lightning events occur within a specified distance. The decision to restart ramp activity varies among the users surveyed and highlights the subjectivity employed. Use of the "30-30 rule," which suggests that outdoor activities be limited or curtailed whenever a lightning strike is detected within 6 mi and within the past 30 min, does not appear to be employed in practice.

The threat and risk levels are determined by consideration of the following two primary factors:

- Typical direction of thunderstorm movements and passage time, and
- Input from labor unions representing the interests of those operating on the ramp

Notification Process

The responses to questions about means by which airport, airline, and other tenants are advised of pending, onsite, and passing lightning events reflected the greatest degree of variability. Airports were focused on contacting their personnel by radio communication. This includes those personnel operating in open areas on the airport distant from terminal facilities, such as those maintaining airport grounds or operating heavy and noisy machinery. Most airports also shared their lightning detection outputs on an advisory basis to the airlines and other tenants that have ramp access, such as fuelers, caterers, and aircraft cleaning crews. Audible and visual alarms were used at some airports. Other airports have purposefully avoided the use of these means of notification and rely on "all-call" or direct telephone contacts. Other airports have installed remote alarm units at airline operating areas in accordance with lease agreements. One airport (ORD) has a policy of not advising any tenant of lightning events because of liability concerns.

Airlines act to notify their staff, and they accomplish this by one or more actions involving visual alarms (beacons at gates and work areas, electronic message displays at the ramp/passenger boarding area, telephone, and pager.)

At all airports contacted, it is common practice and a natural tendency for all airlines to follow the lead of the primary air carrier, especially if that airline has invested resources to facilitate its decision making. This accounts, in part, for the variability in stop/restart times among multiple airlines operating at an airport. In addition, airport terminal areas can encompass very large land masses, and airlines are generally grouped in certain areas. This also contributes to the variance observed among airline operators. Airline business models (i.e., quick-turn or more traditional layover times), availability of visual aircraft docking guidance systems, and union agreements are other factors that influence stop/restart work decisions for ramp activities.

Observed Deficiencies and Effectiveness

The airports and airlines contacted were satisfied with the equipment installed and the warning notification procedures they have implemented. Some have upgraded their systems to take advantage of new technologies and have modified their threat and risk levels to reflect a longer time history of events to aid in their decision making.

The technology used either by airports or by airlines is meeting the need to protect life and property on the ramp during lightning events. Whether the airport or the airline, or both, make the investment in lightning detection and warning equipment, ramp activities are managed individually and are generally consistently applied. Although data on lightning strike injuries at airport ramps do not appear to be available, those airports and airlines contacted have noted a decline in injury occurrences.

Standardization

Opinions varied on the value of standardizing lightning detection and warning system technologies and their implementation. A majority of airports and airlines contacted expressed that a single system serving all users could be viable and funded through lease terms and conditions. Yet they also noted that the stop/restart activity decisions could not be uniformly applied. Furthermore, liability issues would likely govern any decision for industry standardization.

Conclusions

It is said that lightning does not strike twice in the same place. This can also apply to the use and implementation of lightning detection and warning systems at airports: No two airports are alike, and a “one size fits all” approach does not appear to be viable. Airport geographical settings, weather phenomena characteristics, airport facilities layout, airline business models and operating procedures, labor union agreements, legal liability issues, and cost allocation processes are just some of the primary factors that do not lend themselves to standardization.

What has been learned is that the technology is working, is relied upon, and serves a useful means to make decisions about ramp operations. The industry has focused on distance out and time since last event to establish bases that govern stopping and restarting ramp activities, respectively, and these seem practical and useful.

Data on deaths, injuries, loss of property, and downtime caused by lightning events at airports does not appear to be maintained in a common database. Contacts with the Occupational Health and Safety Administration, Department of Labor Bureau of Labor Statistics, National Weather Service, NOAA, National Transportation Safety Board, and FAA did not yield any database of aircraft ramp incidents or accidents related to lightning strikes. Individual industry members may log lightning events and losses, including downtime; however, industrywide data that can be utilized for standardization or other purposes are not available.

In the chapters that follow, the MDA Federal team will examine these parameters, attempt to identify the essential technology that should be employed, evaluate if and how data related to lightning events and losses may be collected and reported on an industrywide basis, and establish a basis for determining a benefit/cost relationship for implementation of a lightning detection and warning system. The means by which airports and their tenants use the information developed by these technologies appears, however, to withstand standardization at this time.

CHAPTER 3

Cost Analysis

Introduction

The objective of this research project was to review current lightning detection and monitoring technology and airport ramp operating procedures, and then use that information to identify areas for possible improvements in efficiency and in enhanced safety. Lightning monitoring systems were reviewed in Chapter 1. The results of a survey of airport and airline ramp procedures for nearby cloud-to-ground lightning events and of the lightning technology employed were summarized in Chapter 2.

The objective of Chapter 3 is to perform a cost analysis, including both the direct and indirect operational costs resulting from the closure of ramps and aprons and the financial and operational impacts to the National Airspace System. The analytical process examines the incremental cost savings that could be expected from modified or enhanced lightning detection and warning systems or from improved operating procedures. The implications of the ripple effects of aircraft arriving late at destinations are incorporated into the analysis.

Airport Operations During Lightning Events

Cloud-to-ground lightning strokes present a clear and immediate danger for ground personnel involved in outdoor ramp operations, such as aircraft fueling, baggage handling, food service, tug operations, and guiding and directing aircraft to their assigned gates. When this danger presents, airport ramp operations are suspended until the danger has passed.

Decisions about ground personnel and ramp operations are made by the airports and airlines, not by the FAA. Individual airlines, companies providing airport workers, and airport management often have very different procedures and standards for identifying and responding to potential lightning hazards, as was documented in Chapter 2.

Because airlines and airports do not report suspensions of ramp operations to the FAA, there is little hard data available on actual suspensions of ramp operations. Short-term suspension of airport ramp operations does not generally close the airport or cause en route delays or ground holds of traffic destined for the affected airport. If ramp operations are suspended for a long time, however, all the available ramp space may become occupied, leaving no space to handle incoming new arrivals. In this case, the airport manager may have to take the rare action to close the airport and report the closure to the FAA. It should be noted that such closures are not a direct response to the lightning hazard, but rather a response to not having the ramp capacity to accept new arrivals. Except for busy airports with limited ramp space, we would suspect that this is uncommon, although we have no firm data to support this conclusion.

While the suspension of ramp operations does not directly or immediately affect flight operations, planes scheduled for departure will not be able to load or leave their gates. Although arriving planes may be able to taxi to their arrival gates (if the gates are not already occupied), baggage typically will not be able to be unloaded. After all the gates are occupied, newly arriving aircraft will have to park elsewhere on the airport.

Specific Impacts and Costs of Suspending Ramp Operations

Ramp operating procedures vary from airline to airline. In general, however, ramp closures mean

- No new passenger enplaning or deplaning,
- No new loading or unloading of baggage,
- The baggage already loaded onto carts stays put,
- No servicing of aircraft (fuel, food service, etc.),
- Passengers and flight crew remain on the aircraft (or stay in the terminals waiting to board),

- Aircraft not already connected to a generator or ground power unit keep their engines running (at least minimally) to maintain cabin and instrument power, and
- Available gates fill up and additional arrivals park elsewhere.

Many of the costs could be classified as "wasted time." While we considered it appropriate to consider such wasted time as a cost, it is important to distinguish between "lost opportunity" time (time that could have been spent doing something else), delay or annoyance time (passengers not being able to get to their next destination, or crew not being able to move to their next flight assignment), and direct costs, such as fuel costs for idling engines, which entail real dollars that have to be paid by the person or entity incurring the cost.

While it is reasonable to include some effective hourly "cost" associated with passenger delay time, nobody really pays the delayed passengers cash (or even provides flight coupons). Flight crews may well waste some time during a ramp closure, but to the extent they are salaried or paid by flight time (and not total time), ramp delays do not necessarily involve a true cost to the airline unless flight personnel reach their daily or weekly service limits. Baggage handlers may well be idle during a ramp closure, but unless they get so far behind that they have to work overtime, they may be able to get caught up during their normal scheduled work hours at no extra cost to the airline. Unexpected or unscheduled overtime, on the other hand, could represent a very significant "real" cost.

It would seem that flight delays would always entail some very significant real costs, but the analysis of the costs is not straightforward. Passengers and crew making intraline connections at the affected airport should still be able to make their next flights, since all loading and unloading at the airport for that airline is suspended across the board. Flights (or passengers, or crew) making interline connections to their destination airports, on the other hand, could miss connections, resulting in required rescheduling or rebooking of flights, under-capacity flights, possible special movements of aircraft, and flight personnel shifted to cover for delayed airline employees. Furthermore, depending on contract terms, airline crews who experience extended wait periods as a result of lightning (or other weather) delays may become restricted in their ability to maintain their flight schedules. Reserve crews may be available at base airports, which would minimize the impact on flight operations. At other airports, flights may need to be canceled to allow the crews the requisite daily rest period. This could result in impacts on flight schedules and produce a real cost to the airline. Table 1 presents a summary of potential costs incurred by events of varying duration.

With the exception of the possible total closure of an airport because of the lack of ramp capacity to accept landing aircraft, lightning-based ramp closures should not result in FAA-imposed en route delays or ground holds. There may be some exceptions, but most downstream impacts from ramp closures will be due to delayed aircraft departures by the affected airline, resulting in some missed connections to destination airports (because many passengers will not be connecting at the destination airport, they won't miss any connections, even though they arrive late). These delays would be similar to simple mechanical delays that can affect individual flights. Perhaps the largest of such impacts might be from aircraft not reaching their final scheduled destination of the day, which would mean that the airline's aircraft will not be positioned for the next day's flights.

Approach to Cost Savings Analysis

There are many possible ways to address this sort of analysis. Initially, we examined the use of a "queue" delay reduction approach or a "linear" delay reduction approach, as described in *Delay Causality and Reduction at the New York City*

Table 1. Cost effects for delays of various duration.

Cost Item	Short Duration Delay	Medium Duration Delay	Long Duration Delay
Passenger Time	Yes	Yes	Yes
Direct Cost to Airline	Minimal	Some	Likely
Ripple Effect	Some	Some	Likely
En Route Delay	None	Unlikely	Possible
Notes:			
Short duration is defined as less than or equal to 60 min.			
Medium duration is defined as greater than 60 min and less than or equal to 135 min.			
Long duration is defined as greater than 135 min.			

Airports Using Terminal Weather Information Systems (*26*). An analysis of that study found that this approach is more appropriate for evaluating the impact of thunderstorms along the flight path, rather than the effect of cloud-to-ground lightning strikes in the vicinity of the airport on ramp operations.

The key issues are the tradeoffs between safety (close ramps as needed to prevent injuries or deaths from lightning) and efficiency (minimize ramp closures). Safety is clearly the driving factor in airport and airline investment in lightning detection and warning systems, but it is difficult to quantify since there are so few reported deaths and injuries caused by lightning. Because our survey did not identify any specific concerns about missed warnings or unsafe working conditions, we concluded that the basic safety requirements are well met by the current systems and procedures.

The most appropriate approach is thus to concentrate on ways to improve efficiency through decreasing ramp closure times, without compromising safety. To do this, we will attempt to quantify the actual closure costs, with emphasis on the closure costs "per minute" after the initial ramp shutdown. These closure cost estimates will ultimately be used to evaluate any proposed improvements to current lightning detection and warning systems either to not initiate an unneeded closure or to try to get an airport back into full operation as soon as possible when lightning strikes no longer present a danger. Given the general unpredictability as to where and when a lightning strike will occur, there will always be a required minimum closure time before ramp operations can be resumed safely. This implies that there will always be a significant cost associated with the initial alarm declaration and the clearing of the ramp.

Analysis of Costs

Two main cost categories were segmented for analysis. The first concentrates on the costs at the local airport where the lightning is occurring. These costs will include the opportunity cost of lost passenger time, which are applicable in events of any duration. There may also be direct costs to the airline, depending on whether they need to pay the ramp workers overtime or whether extra fuel is used by planes waiting on the ramp for a gate to become available.

The second cost category evaluates the "ripple effect" that is caused by downstream delays. These may include additional opportunity cost of passenger time caused by missed connections, as well as direct costs of extra flight time incurred in repositioning planes for the next day.

The best economic estimates we found originate from an FAA report (*27*). The remaining input values would be sensitive to each particular situation, depending on airport and airline. The estimated values made available in the FAA report are presented in Table 2.

The hourly cost of aircraft delay shown in Table 2 is a representative value. Costs will vary by aircraft type. Various aircraft and their block hour operating costs as of 2001 and 2002 are shown in Table 3.

Case Studies

Closure costs will always be a function of the amount of aircraft operations affected, the geographical area and lightning climatology, and flight schedule. To get a balanced perspective, we chose two airports for detailed case study analysis—Chicago O'Hare International Airport (ORD) in Illinois, and Orlando International Airport (MCO) in Florida. As shown in Table 4, ORD is a high-activity airport located in the upper Midwest in an area of large spring and summer storms. MCO is a medium-activity airport in the southeast, near the climatological maximum for U.S. lightning activity.

Lightning Delay Analysis

Because reliable records on ramp lightning closures at airports are not available, we obtained from Vaisala NLDN lightning strike data within 10 statute miles of both ORD and MCO for the calendar year 2006. We then constructed a synthetic closure history for each airport based on a strict imposition of the 30/30 rule. As discussed in Chapter 1, the 30/30 rule recommends that outdoor activities be curtailed following a cloud-to-ground lightning strike within

Table 2. Standard economic values.

Item	Value ($)
Value of Human Life	3.0 million
Average Labor Cost, Ramp Rate	13.03/hr
Hourly Cost of Aircraft Delay	1,524/hr/aircraft
Rate of Delay Per Aircraft (fuel, etc.)	2,290/hr/aircraft
Rate of Labor Delay	814/hr
Value of Passenger Time	28.60/hr

Table 3. Aircraft block hour operating costs.

Aircraft Type	Block Hour Cost ($/hr)
Commercial Passenger Service	
Airbus 319	1,960
Airbus 320	2,448
ATR 72	1,401
Beach 1900	676
Boeing 727-200	2,887
Boeing 737-100/200	2,596
Boeing 737-300/700	2,378
Boeing 737-500	2,271
Boeing 737-800	2,201
Boeing 757-200	3,091
British Aerospace 146	2,776
Canadair CRJ-145	1,072
Canadair CRJ-200	864
Dehavilland Dash 8	970
Embraer 120 Brasilia	861
Embraer ERJ-145	996
Fokker 100	2,406
Jetstream 31/32	544
Jetstream 41	759
McDonnell Douglas 9-30 (DC 9-30)	2,280
McDonnell Douglas 80 (MD-80)	2,630
McDonnell Douglas 87 (MD-87)	2,300
General Aviation—Corporate and Air Taxi	
Small Business Jet	500
Mid-Size Business Jet	750
Large Business Jet	1,000
General Aviation—Private	
Single-Engine Piston	100
Multi-Engine Piston	200
Multi-Engine Turboprop	300
Rotorcraft	250

6 statute miles (corresponding to 30 sec of time delay between the visible lightning strike and the sound of the thunder) and not resumed until 30 min after the last lightning strike within 6 mi.

Based on the sequential time and location history of nearby lightning strikes, we calculated the distance of each stroke from the airport reference point and determined closure and all-clear times for both airports. The results of this exercise are summarized in Appendix A.

It should be noted that all data contained in the following analyses and shown in Tables 5 through 12 were derived using the synthetic lightning duration technique employed on the Vaisala lightning detection data and therefore do not represent actual reported lightning duration delays.

O'Hare International Airport

The results for ORD indicate there would have been 68 ramp closures in 2006, with a total closure time of 70.8 hours, or approximately 1% of the time. Figure 18 presents the full histogram of the length (time duration) of each ramp closure based on this simulation. The synthetic closure distribution is strictly based on the 30/30 rule in a hypothetical system without electric field mills.

Table 5 shows the distribution of synthetic lightning induced ramp closures for ORD stratified by time of day and season of the year. When events overlapped a time period, the event was assigned to the time period it most affected. Table 5 indicates a slight preference for lightning events to occur in the late afternoon. As would be expected, lightning events are most frequent in the summer and least frequent in the winter. We caution, however, that this analysis contains only 1 yr of data, so it may not be generally representative of the long-term diurnal duration climatology. Nonetheless, based on NOAA's 2006 climate summary and 30-yr normals for thunderstorm events, 2006 was a relatively normal year, with 42 thunderstorm events compared with a normal of 40 events. This suggests that the 68 lightning-induced ramp closures at ORD that we deduced from the data are consistent with the climatological record of thunderstorms for the area.

As illustrated in Figure 18, a majority of the closures are estimated to have been for 45 min or less, with only 14 closures exceeding 90 min and only 3 closures exceeding 3 hr. The data also indicate several days when there was more than one closure because of recurring lightning events. We conclude that these results indicate that occurrences of long-duration delays that could potentially cause en route delays and ground holds in the National Airspace System are infrequent, but may occur. It is important to note, however, that in most cases these extreme events will be caused by large mesoscale convective systems that are either stationary over the airport, extend over large areas, or generate repeated lines of storms across the airport. These events will generally result in en route and terminal airspace delays irrespective of their effect on ramp operations. Because these events are infrequent and are likely to be associated with a general disruption of the National Airspace System, these costs are more appropriately addressed in an analysis of thunderstorms along the flight path rather than lightning

Table 4. Aircraft operations levels at selected airports.

Airport	Operations/Day
Chicago-O'Hare International Airport, IL (ORD)	**2,662**
Dallas-Ft. Worth International Airport, TX (DFW)	1,915
Denver International Airport, CO (DEN)	1,603
Phoenix-Sky Harbor International Airport, AZ (PHX)	1,494
Charlotte-Douglas International Airport, NC (CLT)	1,421
Orlando International Airport, FL (MCO)	**977**
Tampa International Airport, FL (TPA)	716
Pittsburgh International Airport, PA (PIT)	649
Note: Operations/day includes those operations conducted by air carrier, air taxi, general aviation, and military aircraft. An aircraft operation is either a takeoff or a landing.	

strikes in the vicinity of the ramps, and thus were not included in our cost analysis.

Table 6 summarizes the per-minute values used to estimate the closure costs resulting from lightning events. Using these values, we calculated per-minute cost values for a sample short duration (less than 60 min), medium duration (61 to 135 min) and long duration (greater than 136 min) event. The number of affected aircraft and the diurnal pattern of flight operations were estimated from the material available on the FlightAware website (www.flightaware.com). The pattern consists of minimal operations activity (an operation is defined as a takeoff or a landing) between the hours of 12 a.m. and 5 a.m. Then there is an increase in operations, reaching approximately 100/hr by 7 a.m. Hourly operations levels remain in the 80 to 100 range throughout the day until approximately 10 p.m., when activity declines rapidly. The number of aircraft affected at ORD was estimated at 90 planes per hour based on the typical daily operation statistics shown FlightAware's graphics for ORD.

In our analysis, we assumed there would be no direct operating costs to the airlines for short duration events because they should be able to catch up without incurring additional costs. For medium and long duration events, the direct local airport costs were obtained by multiplying the number of planes affected times the number of ramp workers per plane times the overtime rate of ramp workers times one-half of the delay. The reason for using one-half of the delay was to

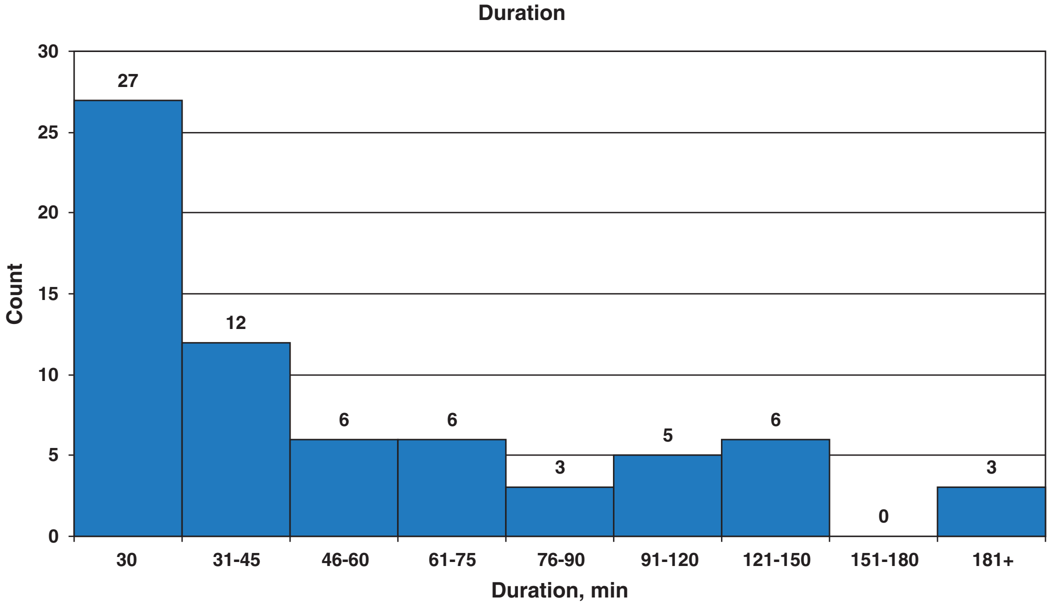


Figure 18. Duration of lightning delays at ORD during 2006.

Table 5. ORD lightning event frequency stratified by time of day and season of year.

Hour	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Total
0-3		2	1	1	4
3-6			3	4	7
6-9		1	3	1	5
9-12	2	2	2	2	8
12-15	3	1	3	3	10
15-18		4	4	5	13
18-21		3	6	3	12
21-24		3	4	3	10
Total	**5**	**16**	**26**	**22**	**69**

Table 6. ORD per-minute cost values.

Cost Item (Based on Boeing 737-500)	Value
Passengers per plane	$100
Value of passenger time	$0.478/min
Passenger time ripple effect	1.5 times local airport passenger effect
Ramp workers standard pay rate	$13.03/hr
Ramp workers overtime pay rate	$19.55/hr
Average ramp workers per plane	6
Operating cost for Boeing 737-500	$2,271/hr
Aircraft repositioning time	0 for short duration 1 hr for medium duration 2 hr for long duration
Note: The typical duration of an event was deduced from the ORD 2006 NLDN data.	

account for the fact that airlines would be able to catch up somewhat faster after a delay without occurring the full duration of delay in overtime cost. The above factors are presented in the following equation:

$$DLAC = 1/2(NPA * NRPP * ORRW * DD)$$

where

$DLAC$ = direct local airport costs,
NPA = number of planes affected by delay,
$NRPP$ = number of ramp workers per plane,
$ORRW$ = overtime rate of ramp workers, and
DD = duration of delay.

The ripple effect direct costs are caused by the added end-of-day cost of repositioning planes. This cost was calculated by multiplying the operating cost of the Boeing 737-500 times the number of planes affected times the repositioning time (as shown in Table 6).

$$REDC = N(OCOP_N * NPIR_N) * RT$$

where

$REDC$ = ripple effect direct cost,
N = number of aircraft affected of type N,
$OCOP_N$ = hours operating cost of aircraft type N, and
RT = repositioning time.

The local airport opportunity costs were calculated as the per-minute value of passenger time multiplied by the number of passengers per aircraft times the number of aircraft affected by the delay times the duration of delay. Based on information contained in the ATC-291 report (*26*), the ripple effect cost or opportunity ripple factor applied for passenger time was assumed to be 1.5 times the local airport effect, as shown in the equation below:

$$LAOC = VPT * NOPID * DD$$

where

$LAOC$ = local airport opportunity cost,
VPT = value of passenger time,
$NOPID$ = number of passengers incurring delay, and
DD = duration of delay.

The ripple effect opportunity cost may be determined from the following equation:

$$REOC = LAOC * ORF$$

where

$REOC$ = ripple effect opportunity cost,
$LAOC$ = local airport operating costs, and
ORF = opportunity ripple factor.

The monetary per-minute cost calculations are shown in Table 7. The last column indicates the per minute cost and is calculated as:

$$PMC = TC/DD$$

where

PMC = per minute cost,
TC = total cost of delay, and
DD = duration of delay.

These results indicate the per-minutes costs increase with the duration of delay. Fortunately, medium and long duration delays during the period 7 a.m. to 10 p.m. at ORD are relatively infrequent, occurring only 16 times during 2006, as shown in Table 7.

Medium and long duration events present higher incremental per-minute potential savings because more costs come into play and more aircraft and people are affected. However, short duration events are more frequent. The potential delay reduction is likely not correlated to the duration of the event. Using the 2006 data, we estimated the potential savings of a 10-min reduction in delay for each duration lightning event. It should be noted that we did not include in this analysis lightning events between the hours of 10 p.m. and 7 a.m. because operations during those hours are much less than during the core 7 a.m. to 10 p.m. local time. Reduction in lightning delays during these "off" hours should provide minimal cost savings.

The potential minutes saved for each duration event were calculated by multiplying the number of events times the assumed 10-min savings. As shown in Table 8, the total potential savings over a period of 1 yr (using 2006 as the proxy) would be slightly over $6 million.

The savings for each duration are calculated by multiplying the per-minute costs (savings) for each duration by the minutes saved. The total minutes saved and the total dollar savings are then obtained by adding the savings for each duration. The average per-minute savings is then calculated by dividing the total dollar savings by the total per minute savings. In equation form, this is

$$TPMSA = (SDMS * SDV + MDMS * MDV + LDMS * LDV) / (SDMS + MDMS + LDMS)$$

where

$TPMSA$ = total per minute savings,
$SDMS$ = short duration minutes saved,
SDV = short duration per-minute value,
$MDMS$ = medium duration minutes saved,
MDV = medium duration per minute value,
$LDMS$ = long duration minutes saved, and
LDV = long duration per-minute value.

Table 7. Typical monetary values for various duration events during the core 7 a.m. to 10 p.m. period at ORD.

Type of Event	Typical Duration (min)	No. of Aircraft Affected	Local Airport Cost ($)		Ripple Effect ($)		Total Cost ($)	Per Minute Cost ($)
			Direct	Opportunity	Direct	Opportunity		
Short	30	45	0	64,350	0	96,525	160,875	5,362
Medium	120	180	21,109	1,029,600	408,780	1,544,400	3,003,896	25,032
Long	210	315	55,409	2,702,700	715,365	4,054,050	7,527,524	35,845

Table 8. Estimate of potential savings from a 10-min improvement in lightning delays during the 7 a.m. to 10 p.m. core period at ORD.

Type of Event	Number of Events	Total Annual Minutes Delay	Potential Annual Minutes Saved	Per-Minute Cost ($)	Total Annual Potential Savings ($)
Short	35	1,275	350	5,362	1,876,700
Medium	13	1,258	130	25,032	3,254,160
Long	3	531	30	35,845	1,075,350
All	**51**	**3,064**	**510**	**12,169***	**6,206,210**

*Weighted average, calculated with Total Annual Potential Savings divided by Potential Annual Minutes Saved.

Orlando International Airport

Paralleling our analysis for ORD, we analyzed 2006 NDLN data from Vaisala to produce a synthetic ramp closure data set for MCO using the same process as described for ORD. The synthetic delay information for MCO is presented in Appendix A. The results of the Orlando lightning event duration analysis for 2006 are shown in Figure 19. As would be expected because of the location in the most active lightning region in the U.S., Orlando (MCO) had almost twice as many lightning events as ORD (126 compared with 68). The total minutes of delay were also higher (143 hr for MCO compared to 71 hr for ORD). The duration pattern of MCO, summarized in Table 9, indicates a tendency for longer duration events than occur at ORD. At ORD, 66% (45/68) of 2006 lightning events were less than 1 hr in duration, whereas MCO reported 60% (75/126) of the lightning events in 2006 were less than 1 hr.

There is also a higher frequency for summertime lightning events at MCO (62%) compared with ORD (38%). While the peak period for storms at ORD is 3 p.m. local time, the peak period for storms at MCO is 6 p.m. to 9 p.m. local time. These differences are probably the result of the different climate zones for two airports. ORD is in a continental climate, affected more frequently than MCO by synoptic type storms, whereas MCO is affected by more local weather factors, such as summertime sea breeze convergence zones.

MCO reports approximately 33% of the daily flight operations that ORD reports, with MCO averaging approximately 40 flight operations per hour between the hours of 7 a.m. and 8 p.m., with a rapid decline in operations after 8 p.m. Minimal activity is seen overnight, and flight operations begin to increase at approximately 5 a.m.

As shown in Table 10, 52 of the 2006 lightning events occurred overnight between the hours of 9 p.m. and 6 a.m. Because flight operations are very limited during these hours, approximately 41% (52/126) of the synthetic 2006 lightning delays would have resulted in minimal economic costs to the airport and airlines.

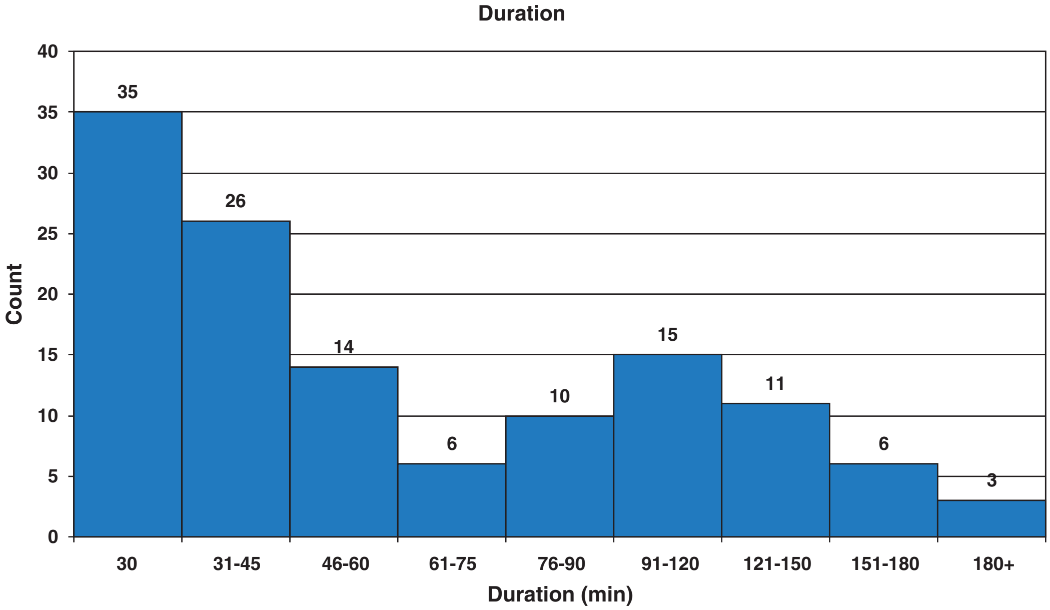


Figure 19. Duration of lightning delays at MCO during 2006.

Table 9. MCO lightning event frequency stratified by time of day and season of year.

Hour	Dec-Feb	Mar-May	Jun-Aug	Sep-Nov	Total
0-3	1	1	5	3	10
3-6	1	2	2		5
6-9		1		1	2
9-12	2		1	1	4
12-15	2	1	1		4
15-18	1		11	1	13
18-21	2	2	38	9	51
21-24	3	5	20	9	37
Total	**12**	**12**	**78**	**24**	**126**

Following the approach taken for ORD, monetary values were calculated for typical duration events at MCO. The primary difference in the results between ORD and MCO is caused by the difference in the number of aircraft affected by the delay. The results for the MCO monetary value analysis are presented in Table 11.

Again, following the analysis used for ORD, Table 11 estimates the potential savings of a shortening of the duration of each ramp closure event by 10 min. The potential savings from a 10-min improvement in delay time during peak hours at MCO is approximately $2.8 million, compared with the $6.2 million calculated for ORD.

Shorter Duration Events

Consideration was given to reducing the 60-min or less lightning delay interval in the cost analysis to a shorter time interval. In fact, as shown in Figure 18 and Figure 19, a majority of the duration delay events are for periods of less than 60 min. This would argue for a further stratification of the monetary value analysis for "short duration" delays to include an analysis for delays of less than 30 min or perhaps less than 15 min. Certainly, for an affected disgruntled passenger, any delay over 30 min would not be considered "short duration."

Notwithstanding this possible interpretation of delay time per lightning event, it is recognized that the focus of the research is on the economic impact to the airline and the air transportation system. The key point here is that airlines can choose to undertake certain mitigation actions, such as rescheduling flights and crews at other airports, to compensate for missed connecting flights attributable to lightning delays at an airport. However, because this takes time to analyze and implement, anticipated short-duration events are generally accepted and managed as best as possible. Furthermore, delays of less than 60 min produce comparatively minimal costs to the airline industry when compared with costs for delays of greater than 60 min. As indicated in Table 8 and Table 11, the per-minute cost of a short duration delay averages 21% of that for medium delay events and 14% of that for long delays.

Generating shorter duration delays would thus have the effect of reducing an already minimal cost contribution. Consequently, we have chosen to use the three delay event stratifications indicated above because they provide a clearer view of which events produce the major costs and therefore provide the focus for improvement.

Table 10. Typical monetary values for various duration events during the 7 a.m. to 8 p.m. core period at MCO.

Type of Event	Typical Duration (min)	No. of Aircraft Affected	Local Airport Cost ($)		Ripple Effect ($)		Total Cost ($)	Per Minute Cost ($)
			Direct	Opportunity	Direct	Opportunity		
Short	30	20	0	28,600	0	42,900	71,500	2,383
Medium	120	80	6,254	457,600	181,680	686,400	1,331,934	11,099
Long	210	140	28,371	1,401,400	317,940	2,102,100	3,849,811	18,332

Table 11. Estimate of potential savings from a 10-min improvement in lightning delays during the 7 a.m. to 8 p.m. core period at MCO.

Type of Event	Number of Events	Total Annual Minutes Delay	Potential Annual Minutes Saved	Per Minute Cost ($)	Total Annual Potential Savings ($)
Short	40	1,385	400	2,383	953,200
Medium	15	1,674	150	11,099	1,664,850
Long	1	184	10	18,332	183,322
All	**56**	**3,243**	**560**	**5,002***	**2,801,372**

*Weighted average, calculated with Total Annual Potential Savings divided by Potential Annual Minutes Saved.

30/15 Analysis

To evaluate the sensitivity of the predicted economic impact on the interval between the last lightning strike and a return to normal operations, we conducted an additional set of analyses reducing the all-clear time from 30 min to 15 min after the last reported lightning strike within 6 mi of the airport. Based on the surveys reported in Chapter 2, this time interval may be more common than the "standard" 30 min used for general outdoor activities. This "30/15" analysis was conducted for the summer months (June–August) when lightning activity is most frequent. The 30/15 summer 2006 delay data for ORD and MCO are included in Appendix A. A summary of these analyses are presented in Table 12.

The rule change from 30/30 to 30/15 results in a slight increase in the number of events because of a few cases where the airport would be opened and then quickly closed again under the 30/15 rule (causing two events instead of one to be recorded), while the airport would stay have stayed closed under the 30/30 rule. While this could represent an increased hazard for ramp personnel, it results in a significant reduction in delay time, totaling 354 min at ORD and 1,568 min at MCO.

The corresponding cost impact of the 30/15 summer (June–August) improvement for both ORD and MCO airports was calculated by analyzing the improvement in total delay time for each duration event during peak operating hours only and then multiplying the duration delay savings in minutes by the previously calculated per-minute delay costs. When events overlapped peak hours and nonpeak hours, the duration of the event was only taken as the duration that occurred during the peak hours. Note that in the ORD analysis, the single long duration event ended after the peak-hour period, resulting in no delay savings for that event.

The results for ORD, shown in Table 13, indicate a potential savings of approximately $3.4 million for the summer, based on hypothetical implementation of the 30/15 rule. The results for MCO are perhaps more intriguing. In this case, the change would hypothetically have increased the number of short-term events from 24 to 36, while reducing the number of medium-term events from 12 to 8. The shorter "all-clear" time provides limited openings in the ramp closures and reduces the number of longer and more costly delays. In our hypothetical analysis, this results in a potential savings of $6.3 million at MCO for the summer of 2006, as shown in Table 14.

Findings

This cost analysis indicates that delay cost impacts are complex. They are a function of several factors, including the activity levels and mix of aircraft operating at an airport, the number of lightning events, the timing of the lightning event, the type of lightning event (local convective or associated with broad-scale flow), the duration of the lightning event, and the rules the airline/airport operators use in issuing the "all clear" signal to resume ramp activity. The analysis also indicates that the annual value of new technologies or new procedures that could reduce ramp lightning delays, although varying by airport, could be substantial. The potential savings produced by a reduction of

Table 12. Impact of replacing the 30/30 rule with a 30/15 rule.

	Number of Events By Rule			Minutes of Total Delay By Rule		
Airport	30/30	30/15	Change	30/30	30/15	Change
Chicago (ORD)	26	28	2	1,922	1,568	-354
Orlando (MCO)	78	87	9	5,544	3,976	-1,568

Table 13. Potential savings with 30/15 rule, ORD June–August 2006.

	Delay By Rule			Savings With 30/15 Rule	
Delay Duration	**30/30**	**30/15**	**Change**	**Per Minute ($)**	**Total ($)**
< 60 min	421	284	137	5,362	734,594
60-180 min	514	408	106	25,032	2,653,392
> 180 min	184	184	0	33,845	0
Total	**1,120**	**876**	**243**	**13,942***	**3,387,986**

*Weighted average, calculated with Total Savings divided by Total Change.

Table 14. Potential savings with 30/15 rule, MCO June–August 2006.

	Delay By Rule			Savings With 30/15 Rule	
Delay Duration	**30/30**	**30/15**	**Change**	**Per Minute ($)**	**Total ($)**
< 60 min	819	810	9	2,383	21,477
60-180 min	1,415	847	568	11,099	6,304,322
> 180 min	0	0	0	18,332	0
Total	**2,234**	**1,657**	**577**	**10,963***	**6,325,799**

*Weighted average, calculated with Total Savings divided by Total Change.

even a few minutes would likely be sufficient to more than cover the cost of introducing improved technology or practices.

As a general guideline, the costs of direct lightning duration delays at any given airport may be approximated by the following equation:

$$TALAC = NPAD * NRPP * ORRW * TAD + VPT * NOPID * TAD$$

where

$TALAC$ = total annual local airport cost,
$NPAD$ = number of planes affected during a delay,
$NRPP$ = number of ramp workers per plane,
$ORRW$ = overtime rate of ramp work,
TAD = total annual delay minutes for delays over 60 min (medium- and long-term delays),
VPT = value of passenger time, and
$NOPID$ = number of passengers per plane incurring delay.

When compared against the potential cost of implementing improved lightning monitoring and forecasting systems, the analysis indicates that the annual value of new technologies or procedures for reducing ramp lightning delays, although varying by airport, could be substantial. The potential savings produced by a reduction of even a few minutes would likely be sufficient to more than cover the cost of introducing the improved technology or procedures.

Because safety of the ramp workers is the paramount concern, it appears the airlines will likely err on the side of caution in closing ramp operations. This suggests that the most likely path to improved operational efficiency is in being able to sound an “all clear” as quickly as possible after the initial event, so long as it can be done without compromising safety.

CHAPTER 4

Conclusions

Current Systems

From a safety point of view, the existing lightning warning systems for airports seem to be doing a very good job. Because airports and airlines are safety conscious and closely monitor the weather, lightning injuries to ramp and other outdoor workers have been infrequent and fatalities rare. At the same time, however, there appears to be no systematic attempt to collect or maintain lightning-related ramp injury records for the cases that do occur, and the information that is available is mostly in the form of anecdotal stories or in the corporate memory of long-term employees. On the federal side, no statistics on aviation-related lightning injuries are collected by the Occupational Safety and Health Administration, the National Transportation Safety Board, or the FAA.

With increasing pressure for on-time operations and efficiency, ramp closures resulting from nearby lightning can have a serious impact on local airport operations and reduce the efficiency of the national air transportation system. Although lightning frequently halts ramp operations at many airports, it is difficult to analyze the true scope and magnitude of the problem because neither airlines nor airports routinely record the frequency or duration of ramp closures. The serious impact of lightning on ramp safety and operational efficiency, and the potential impact on the national air transportation system, need to be reflected in better efforts to collect and maintain records.

On the industry side, lightning safety studies emphasize techniques designed to improve lightning detection capabilities and predictions. Researchers examine “gaps” in warning detection systems and try to eliminate potential “failures to warn” of imminent lightning strikes. At the same time, however, it is important to examine proposed system improvements for their potential to increase the number or duration of ramp closures without any increase in worker safety, and to focus on identifying the earliest time at which the “all clear” can be announced and ramp operations resumed.

What is needed is a balanced system that preserves or improves ramp safety, while better defining the hazard area and duration for maximum efficiency. A system that is too conservative and generates prolonged shutdowns will eventually be ignored or disregarded.

Lightning warning systems in the United States are generally based on lightning observations from the national lightning detection networks, primarily the NLDN. These systems are a national resource and provide high-accuracy location of cloud-to-ground lightning strokes from Seattle to Miami and from Maine to San Diego. With real-time access to lightning data, an airport monitoring system can track the development of lightning storms and their movement toward the airport. Warnings and ramp closures are then generated on the basis of the distance of flashes from the airport and the time since the most recent nearby stroke. This is an efficient system since it is based on directly detecting and monitoring the cloud-to-ground lightning strokes that pose the hazard.

Appropriate Systems for Airports of All Sizes

Ramp safety is essential for all airports. All commercial airports with scheduled operations in lightning-prone areas should have lightning detection and warning systems to alert managers and ramp personnel of approaching hazards. While our study has concentrated on the higher-end lightning warning systems designed for large airports, there are also less sophisticated and less expensive lightning warning systems appropriate for smaller airports.

Smaller airports may be well served by Internet-based lightning monitoring systems that provide real-time access to lightning information from the NLDN, but without the dedicated high-speed communication lines, sophisticated display workstations, or automatic sirens and alarms typically used at larger airports. Smaller airports with fewer operations have more flexibility and can more easily absorb delays caused by ramp closures than can large airports. This means that when lightning is near, they may be able to shut down earlier and wait a bit longer to declare an "all clear" than major airports with higher traffic volumes and tighter schedules. Safety issues become more critical and require closer, more expensive, monitoring of the situation when airport users are trying to push the envelope and keep operations going as long as possible without interruption.

Warnings based on NLDN monitoring the approach of active thunderstorms can identify perhaps 90% of the lightning events that affect an airport, with the remainder coming from new storms that develop in the immediate vicinity of the airport (*28*). To respond to this developing storms hazard, high-end lightning detection systems typically augment the NLDN observations with locally installed EFMs, which can detect the buildup of the local electric field that normally precedes lightning.

EFMs do, however, add significantly to the cost of a warning system. An EFM can cost as much as $16,000, and they would need to be installed at several locations around the airport to provide a useful indication of the developing potential for lightning strikes. Each EFM would require its own set of communication cables and regular maintenance to ensure reliable performance. While EFMs are routinely used at lightning-sensitive locations, such as the Kennedy Space Center in Florida and weapons testing sites, because they can provide early warning of developing storms, they are subject to false alarms since not all developing storms actually produce lightning. In most cases, the buildup of the electric field should be considered a necessary, but not sufficient, criterion for lightning activity (*29*).

From an airport operational perspective, the most important improvements that could be made in current lightning detection and warning systems would be to develop more precise and better defined warnings that still give operators time to effectively clear the ramp and suspend operations, and then get back to work as quickly as possible with less downtime, but without compromising safety.

There are a number of promising ways to refine and improve lightning detection and warning systems for airports by making better use of all the currently available weather observations, through the development of smarter software and analysis algorithms, and by incorporating new technologies. These options are highlighted in the following sections.

Smart Algorithms and Software

The performance of any lightning warning system is critically dependent on the specific warning criteria that are used to stop work and clear the ramp, as well as the guidelines that are subsequently used to decide when to resume work. These criteria affect both safety and efficiency. Conservative criteria may enhance safety, but at the cost of excessive downtime. On the other hand, standards designed to minimize disruptions may put airport workers at risk. System providers will normally recommend an initial set of warning criteria, but allow users to set their own criteria for alerts and warnings based on their collective experience with typical weather patterns at their airport. As a practical matter, this means that the specific warning criteria used at different airports can vary greatly.

One approach to improving this situation and helping individual airports and airlines refine their warning criteria would be to make use of intelligent, self-monitoring warning systems. A lightning detection and warning system with this sort of capability would be able to monitor its own performance and evaluate the adequacy of the specific warning criteria being used. Any unanticipated lightning strikes in the immediate vicinity of the airport, or strikes that follow the declaration of an alert too closely for the ramp to be cleared, would be evaluated to see if reasonable changes to the warning criteria would have provided a better warning. Such a system could also keep track of excessive warnings or lengthy ramp closures and evaluate to what extent safety would have been compromised with slightly more relaxed criteria. The system would be, in effect, self-training and would provide an objective approach for making gradual adjustments to the specific warning criteria used at an airport in response to the actual lightning events it experiences over time. This approach could also be used to refine warning criteria to reflect the local storm climatology, and permit seasonable adjustments to optimize performance.

For example, consider an airport with a lightning warning system that recommends that outdoor operations be stopped whenever a lightning strike is detected within 6 mi of the airport and declares an "all clear" when there have been no additional lightning strikes within this distance for 15 min. As a routine matter, the lightning system could be designed to keep track of the number of recommended alerts and alarms, the duration of the work stoppages, the number of lightning strikes over the immediate airport area (or other designated "area of concern"), and related statistics. Lightning strikes in the area of concern without adequate prior warning would be of particular importance and would be identified and recorded. In parallel with the statistics for the operational set of warning criteria, system software could also generate comparable statistics for other possible combinations of warning criteria. For example, there could be separate statistics generated for all distance thresholds from 3 mi to 10 mi, and for "all clear" times from 5 min to 30 min. These statistics would be collected and reviewed, perhaps once a year, identifying possible changes to the warning criteria that could improve airport efficiency, while preserving safety. Any changes of this sort would need to be done gradually and incrementally, but would eventually move the airport to an optimum balance of safety and efficiency.

With this sort of capability, the system operator could also be provided with periodic summaries of system performance and daily reporting of all lightning events. With an additional option for manual entry of actual ramp closure times and durations, the system could provide a permanent record of lightning activity and ramp closures.

These same capabilities, perhaps including a 24-hr temporary archive of nearby lightning strikes, would also be useful for airport and airline accident/incident investigations, hard landings, or lightning-related injuries and damage. While much of this information could be recovered or reconstructed from the national NLDN permanent data archive, the full set of local information should also be available at airports that operate lightning detection and warning systems. This capability would be particularly valuable in providing airport authorities, airlines, and other tenants with rapid access to recent lightning information and local statistics in response to emergencies.

Integrating Technologies for Improved Performance

Perhaps the most obvious way to improve the performance of existing lightning warning systems is to incorporate additional weather information into the warning algorithms. Meteorological radars have traditionally been the observing system of choice for monitoring thunderstorms. The current national U.S. network of high-quality Doppler radars (NexRad) is a uniquely valuable resource for tracking the development and movement of lightning-producing storms and should be able to be used in conjunction with standard NLDN observations to produce a new set of comprehensive warning products.

Radar Echo Properties and Tracking

Radar studies of storm structure have led to radar-based predictions of the likelihood of lightning (*30, 31*). Although such second-order products are of little direct use when NLDN observations are available, they indicate that radar echo patterns and properties may be useful in helping to identify specific meteorological situations that may be particularly problematic or require additional safeguards. Studies of this sort are currently underway and may lead to improved lightning warning products (*32*). From an airport operational perspective, the most important potential contribution of radar data may be to provide a better estimate of the end of the lightning hazard as storms move away from the airport area.

Radar observations can also be used to track the movement of storm cells. Thunderstorm cells generally have great spatial and time continuity and are relatively easy to track by radar. While it is also possible to identify and track areas of lightning activity, lightning "cells" are composed of individual, discrete lightning strokes and are more difficult to define and harder to track. While radar and lightning cells are clearly linked, it is important to remember that the radar echo boundaries do not always coincide with the limits for lightning strikes, as exemplified by the "bolt from the blue" phenomena discussed in Chapter 1. Nevertheless, a blended product identifying the boundaries of the most active lightning-producing areas through a combination of radar echoes and direct lightning observations should provide a good estimate of the expected movement of active lightning areas. A better delineation of the boundaries of the active lightning strike areas should in turn allow a better estimate of the onset and termination of the lightning threat.

Knowledge of the advection direction of the lightning-producing cells can also provide additional direct benefits. One of the most interesting results of our study generating synthetic airport closure statistics based on archived NLDN observations (discussed in Chapter 3) was the relatively high number of closures that resulted from a single lightning strike, or from an extremely short burst of lightning activity extending less than 1 min. While this phenomena needs additional study, it is likely the result of lightning-producing storms drifting past the airport, just barely within the distance criteria used for shutting down ramp operations. These storms would presumably be producing lightning as they approach and move on past the airport area, but are only within the warning range for a short time. In this case, it may be possible to significantly reduce the total number of ramp closures by adjusting the warning area boundaries based on storm motion vectors. Adjustments of this sort are essentially equivalent to modifying the current distance-based lightning proximity warning criteria to also consider the time before an approaching storm is likely to reach the airport.

Warning boundaries in the direction of storms moving rapidly directly towards the airport, for example, may need to be extended to provide adequate time to shut down operations before the storm reaches the airport. Shrinking the dimensions of the warning area in the directions perpendicular to the motion of the lightning cells, on the other hand, would reduce the number of storms that just brush along the side of the normal warning area and then move on without becoming a real hazard. Once fast-moving storms have passed the airport, knowledge of the storm speed and direction of movement may also permit an earlier declaration of an "all clear" without compromising safety.

Total Lightning Systems

The NLDN has been designed to provide high-quality, high-collection-efficiency observations of CG lightning strikes. While these ground strikes are the specific hazard that endangers airport workers, they only represent a small fraction of the total lightning in a storm. The majority of the lightning discharges stay within the cloud or strike adjacent clouds and are generally described as IC strikes. Measurement systems that can detect and locate both CG and IC lightning are termed *total lightning systems*.

CG lightning strikes are predominantly vertically orientated and can be associated with a single geographical position, essentially their impact point. IC lightning, on the other hand, often extends in complicated patterns over long horizontal distances. The most sophisticated total lightning detection systems can track the full path of an IC stroke and, by combining the tracks of several successive strokes, can produce two-dimensional coverage plots. Because there are many more IC lightning strokes than CG strokes, and since their positions can be mapped in a two-dimensional grid, they provide a valuable description of the overall extent of active lightning in a cloud system. Total lightning patterns can be monitored and tracked with more precision than can be done with CG strokes alone, and since IC strokes are generally observed several minutes before the first CG strokes they may be able to be used to identify potential hazards in storms that are developing overhead before the first CG stroke is observed.

Total lightning systems require special VHF sensors to track the IC strokes and are currently only available over a few regional areas where they are being tested. Because the IC lightning patterns identify areas that have already developed active charge separation processes and are actively producing lightning strikes, they represent a uniquely valuable enhancement to operational lightning warning systems. Integrated systems based on total lightning detection networks may be able to provide significantly improved lightning warnings, in terms of a better delineated hazard area and a reduction in total downtime for airport operations.

While it is not yet clear to what extent total lightning systems will become available, or who will install, operate, and fund their operation, they may eventually provide significant improvements for lightning detection and warning systems, as well as enhancing short-term weather forecasts for the entire terminal area.

Predicting Lightning Hazards

Mesoscale "nowcasting" systems are quite effective at identifying the growth and motion of developing convective systems and are used by the FAA for both terminal and en route air traffic management. These forecasting systems can also be used to identify developing storms that are likely to produce lightning.

Airline operations are time-sensitive and have a very low tolerance for false alarms. Most lightning prediction products should therefore only be used to generate "advisory" products that call attention to the potential for storm development. Such an advisory would serve as a "heads-up" and not in itself call for a "stand down." Predictive systems may be valuable for operational planning, but are not likely to replace or eliminate the need for lightning-specific detection and warning systems.

Making Use of Existing Data Integration Systems

Integrating multiple data sets into a decision support system can be a difficult and expensive process. Data access and latency are particularly critical issues. One way to minimize these efforts and costs is to make use of existing data integration systems instead of developing new systems that process much the same information.

Potentially valuable additions to airport lightning detection and warning systems include meteorological radar data, cell identification and tracking algorithms, and observations from regional total lighting detection systems.

Radar data and associated cell identification and tracking algorithms are fundamental to both the FAA-sponsored ITWS developed by Raytheon (*33*) and Vaisala's WSDDM system that was developed at NCAR (*34*). Because both systems already include access to real-time NLDN lightning reports, it should be relatively straightforward to transfer specific lightning warning algorithms to these existing operational systems for easy access to their extended data sets and processing algorithms. The expanded weather systems, however, would need to support additional communication links, lightning user displays, and integration of electric field mill data, as well as be able to trigger the needed alarms and notification systems. An ITWS-based integration would also extend the government's use of lightning data beyond the limits of the current U.S. contract with Vaisala and directly compete with Vaisala's commercial lightning warning products. The terms and conditions of the NLDN contract, however, could be renegotiated when the contract comes up for renewal in 2010.

On the other hand, customized products or output fields could be generated by ITWS, WSDDM, or other data integration platforms for export to existing lightning warning systems, with the final integration being done there.

In both cases, the technical challenges for these types of integration should not be too difficult, but the issues of data rights and the generation of customized products for use by other, separately funded systems could become a major impediment. Integrating aviation-related weather decision support systems into unified systems, however, should be the most efficient and cost-effective way to ensure a higher level of operational safety.

Additional Issues

In reviewing the current state of airport lightning detection and warning systems, it was immediately evident that there are no common system standards, no certification or testing procedures for lightning detectors, and no general agreement as to who should provide these warning services at U.S. airports. While we are not in a position to make recommendations in these areas, they are important issues that limit our options for enhanced systems.

Who Should Provide Lightning Warning Services?

At present, there is no general agreement as to who should provide lightning warning services for airports. This is a difficult issue that hinges on the relative roles of the government and private industry and that is complicated by potential liability issues and the very significant cost of system installation and maintenance.

In some cases, the largest or dominant airline at an airport will purchase a system or contract for lightning warning services, with the other carriers following their lead in deciding when to clear the ramp, but occasionally making a contrary decision on their own. In other cases, airports may maintain warning systems for their own use, but not share their information with tenant airlines and other users. FAA and other government agencies often have access to NLDN lightning data, sometimes on systems operated at the airport, but are prohibited by the terms of the government contract with the NLDN's commercial operator to make the data available for nongovernment use. The result is an often inefficient delivery of lightning warnings, with hit-or-miss application of safety measures and great potential for duplication of services.

Standardization

With different organizations providing lightning warning services at different airports, it is not surprising that there is little or no standardization of procedures or of shut down and restart criteria. Individual operators make their own decisions, sometimes following their own established standards, and other times responding to a supervisor's individual decision.

Standardization is generally the result of regulations and mandatory procedures passed down from above or promulgated by the agency providing the services. With no agreement as to who should provide these services, it is natural that there is no standardization to how the warnings are determined and what warning criteria are applied. A lack of standardization, however, permits individual operators to respond to their own needs and is often welcome.

Certification

While there are a large number of commercial lightning detection systems available, it is difficult to evaluate them since there is no certification process to assess their performance.

For relatively low cost systems that only signal when lightning is near, comparison with lightning detection and position information from the NLDN should be adequate to evaluate and document each system's performance and limitations. Because these products are sold and advertised for the general consumer market, nonprofit organizations such as the Consumers Union might be willing to perform such tests.

Performing an end-to-end evaluation of higher-end products with sophisticated warning algorithms and workstation displays would be more difficult. Unfortunately, these are the systems that are typically used at large airports. There has not been a comprehensive comparison of the relative accuracy and detection efficiency of the two competing national lightning detection networks. Performing such a test would require an independent detection capability to serve as ground-truth. In practice, validation studies have made use of photographic or video imagery from multiple viewing angles and by rocket triggered lightning strikes. This means that validation testing is a time-consuming, expensive effort, with each study concentrating on a single geographical area. A number of such validation tests have been published in the refereed literature for the NLDN (*17, 18*), but not for the USPLN.

Government laboratories such as the FAA's William J. Hughes Technical Center, NOAA Laboratories, and NOAA's university-based Cooperative Institutes could perform such tests, but these organizations are not general testing laboratories. They are government-funded organizations that do applied research in response to the needs of their sponsors. From a government perspective, there has not been a reason to provide certification or testing since the government has not purchased these systems to provide lightning detection and warning services.

Looking Toward the Future

Next Generation Air Transportation System (NextGen)

Planning is currently underway to modernize and upgrade the U.S. air transportation systems to meet the needs of the 21st century. The demand for air traffic services is expected to double or triple by 2025. Planning for the Next Generation Air Transportation System (NextGen) is the responsibility of the Joint Planning and Development Office (JPDO), composed of representatives from the FAA, NASA, Department of Transportation, Department of Commerce, Department of Defense (DoD), Department of Homeland Security, and the White House Office of Science and Technology Policy.

NextGen will require a systemwide transformation, which is expected to be completed in 2025, with initial system enhancements beginning to come on line by 2012. Weather information and weather observations are crucial to NextGen, and the required upgrades will impact all elements of our aviation weather system (*35*).

To achieve NextGen goals, all aspects of the aviation system, including airport and ramp operations, will be tightly integrated to provide a shared awareness of all aspects of the system for joint planning and system management (*36*). Weather information will be fully integrated in the NextGen environment, with observational data and forecast products available from a single authoritative source and distributed through a network-enabled weather information sharing system. At the core of this capability will be a virtual four-dimensional database formed by expert system fusion of various gridded fields, model output, statistical systems, climate information, observations, and human forecaster input (*37*).

These anticipated changes may well become a vehicle for more standardization of weather products, including lightning detection and warning systems. JPDO planning, however, is still in its early stages, and the specific details of the new procedures and policies, and how they will be implemented, will take time to be resolved. The concept of a "single authoritative source" for weather information suggests increased centralization of weather observations and dissemination of weather information. The "four-dimensional weather information database," will, however, be a virtual database and not necessarily mean a single information provider. The database concept also includes provisions for restricted or classified information for DoD users, as well as ways to include proprietary commercial products. This will take time to sort out, but NextGen clearly has a potential to change the way ramp operations are managed and the way lightning detection and warning services are provided to all users of the air transportation system.

GOES-R Geostationary Lightning Mapper

Sometime after 2014, the United States will launch the first of its new generation of geostationary meteorological satellites—the GOES-R series of spacecraft. These new satellite systems will, for the first time, include a GLM. The GLM is an optical *total lightning* detector that can detect and locate lightning strokes over most of the visible earth disk with very high efficiency (*38*).

The GLM will provide real-time lightning information to ground users. While the details of the dissemination system are still being developed, it is likely that the GLM will provide information on the location and extent of lightning discharges, including two-dimensional flash density products. From geostationary orbit, the instrument is expected to provide gridded data sets with a grid size of about 8 km. This is significantly coarser than the density mappings that can be provided by surface-based total lightning detection systems, but will be provided at no cost to the user and with relatively uniform resolution coverage over CONUS lightning activity areas. Prior to launch, there will be a number of efforts to use currently available regional ground-based total lightning networks to test the potential application of this new satellite-based data source at airports.

Summary and Recommendations

From the safety perspective, currently available lightning detection and warning systems seem to be meeting airport and aviation industry needs. There are, however, a number of potential options for enhancing and improving the current systems to reduce the number and duration of ramp closures and to improve operational efficiency, including the following:

- Refining the warning algorithms and criteria through the use of self-monitoring software. While this approach is not necessarily guaranteed to shorten ramp closures, it would provide an objective standard for selecting warning criteria to balance safety and efficiency.
- Additional meteorological data sets, primarily meteorological radar data, can be used to better define the spatial and temporal limits of the lightning hazard. Using integrated data sets to define the geometrical extent of the lightning cells and then tracking their evolution and movement should be particularly valuable.
- Most specifically, lightning cell tracking and echo movement vectors may also be used to adjust the warning criteria to minimize the number of short-duration ramp closures triggered by storms that are not likely to impact the airport area.
- Recent demonstrations and tests of total lightning systems are showing great promise for enhancing and refining lightning warnings. Limited regional total lightning networks are currently available for experimentation, but routine availability of these systems for operational use is still years away.
- Given the economic pressure on the aviation industry to reduce costs, enhancements in lightning detection and warning systems will need to be critically reviewed to determine their cost effectiveness. Software enhancements and optimization of warning criteria should be a relatively low cost system enhancement, but would have to be implemented by lightning warning system vendors. The costs of integrating radar and other meteorological observations may be able to be minimized by making use of existing data integration platforms, such as ITWS and WSDDM, or by moving the processing to regional or national analysis

> centers (either governmental or commercial), and then transmitting only the information needed for the local airport display systems and warning decisions to each individual airport system. Another way to realize significant cost savings would be to develop new technologies and new algorithms to detect and monitor thunderstorms that develop over the airport, and then minimize or eliminate the use of EFMs as an essential component in airport lighting warning systems.

NextGen and, to a lesser extent, lightning observations from the next generation of geostationary weather satellites may eventually provide enhanced capabilities or increased federal support, but they cannot be counted on in the near future. Those developments are too far off to influence near-term operational decisions, but should be monitored for future potential. For current planning purposes, airports and airlines will need to depend on commercial vendors and current technology.

We recommend that industry trade groups such as the American Association of Airport Executives, Airports Council International–North America, and Air Transport Association encourage, on a voluntary basis, the routine collection and reporting of ramp closure statistics and associated lightning-related injuries and material damage.

There are a number of important follow-on studies that will be needed to further the advancement of improved lightning warning systems for airports. Of particular importance is the consideration and evaluation of remote sensing observations, most likely meteorological radars and total lightning systems, as replacements for EFMs in operational lightning detection and warning systems. Warning systems based exclusively on routine surface observations, numerical models, and remote sensing may be able to remove any need for lightning-specific detection hardware to be installed or maintained at individual airports. If successful, this transformation should result in lower costs to airports and airlines, while preserving or improving lightning hazard identification. Airport-specific studies should also be directed at evaluating the performance of currently available lightning systems, optimizing the warning criteria for these systems, and quantifying the potential tradeoff between safety and efficiency.

Another topic for additional research and evaluation can address ramp lightning facility mitigation strategies. For example, it may be possible to design a facilities mitigation concept, where ramp workers could safely unload baggage during a lightning event. A program could be developed where a set of ramp mitigation ideas would be collected via survey and analyzed. A cost/benefit analysis could then be developed so each airport could calculate the potential utility of introducing various ramp mitigation strategies based on their individual circumstances.

To the extent possible, we urge airports and airlines that operate lightning detection and warning systems to collaborate with research efforts designed to test or enhance warning products by granting researchers access to monitor the performance of their installed operational systems and observe ramp operations.

Lightning is but one of many weather factors causing economic loss for the airlines. It would seem appropriate to conduct a follow-on study to analyze all weather factors affecting airline delays, such as, high winds, heavy rains, snow, ice, and fog. This analysis would employ a different economic approach than used for lightning-caused delays and enable a focus on air traffic flow delays, with ramp closings as a secondary impact.

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Abbreviations

CG—cloud to ground lightning
CONUS—continental United States
DoD—Department of Defense
EFIDS—electronic flight information display
EFM—electric field mill
FAA—Federal Aviation Administration
GLM—geostationary lightning mapper
GPS—global positioning system
IC—inter- and intra-cloud
IR—infrared
ITWS—integrated terminal weather system
JDPO—Joint Planning and Development Office
LDSS—lightning decision support system
LF—low frequency
LIS—lightning imaging sensor
MADS—master alarm distribution system
MDF—magnetic direction finding
MF—medium frequency
NASA—National Aeronautics and Space Administration
NCAR—National Center for Atmospheric Research
NLDN—National Lightning Detection Network
NOAA—National Oceanic and Atmospheric Administration
NTSB—National Transportation Safety Board
OCC—operations control center
OSHA—Occupational Safety and Health Administration
OTD—optical transient detector
PLWS—Precision Lightning Weather System
RAD—remote alarm display
RF—radio frequency
TDWR—Terminal Doppler Weather Radar
TOA—time of arrival
TRACON—terminal radar control center
USPLN—U.S. Precision Lightning Network
VHF—very high frequency
VLF—very low frequency
WSSDM—Weather Support for Deicing Decision Making

APPENDIX A

Lightning Events Data

Appendix A presents the data obtained from the NLDN and used to produce a synthetic lightning duration scenario for the two case study airports—Chicago-O'Hare International (ORD) and Orlando International (MCO), as described more fully in Chapter 3. The data depict the start and end times of lightning events during a full-year period based on the "30/30" rule (Table A-1 and Table A-2), and for the summer months when considering a "30/15" adaptation (Table A-3 and Table A-4). These data were then evaluated to generate per-minute cost savings that can potentially be achieved by reducing the time interval between stopping and resuming aircraft ramp activities.

Table A-1. ORD 2006 30/30 lightning events.

Date	Start	End	Duration (min)
1/2/2006	11:02 AM	11:47 AM	45
1/2/2006	12:45 PM	1:15 PM	30
1/2/2006	2:14 PM	2:44 PM	30
2/16/2006	10:34 AM	12:45 PM	131
2/16/2006	1:48 PM	3:10 PM	82
3/8/2006-3/9/2006	11:26 PM	12:30 AM	64
3/12/2006	6:40 PM	7:55 PM	75
3/12/06 - 3/13/06	11:50 PM	1:11 AM	81
3/13/2006	1:50 AM	2:10 AM	30
4/2/2006	7:58 PM	9:00 PM	62
4/2/2006	9:19 PM	10:02 PM	43
4/13/2006	10:41 PM	11:11 PM	30
4/14/2006	9:59 AM	10:29 AM	30
4/16/2006	1:27 PM	1:57 PM	30
5/17/2006	5:07 PM	6:17 PM	70
5/24/2006	9:10 AM	9:40 AM	30
5/24/2006	9:33 PM	10:22 PM	49
5/25/2006	8:26 AM	8:56 AM	30
5/29/2006	4:40 PM	6:26 PM	106
5/30/2006	3:43 PM	4:20 PM	37
5/30/2006	4:58 PM	5:20 PM	30
5/30/2006	7:31 PM	9:15 PM	94
6/21/2006	5:35 PM	6:05 PM	30
6/22/2006	9:08 AM	10:19 AM	71
6/25/2006	3:27 PM	3:57 PM	30
6/25/06-6/26/06	11:17 PM	2:53 AM	206
6/26/2006	11:54 AM	12:31 PM	42
6/26/2006	12:51 PM	1:36 PM	45
6/28/2006	6:24 AM	8:32 AM	128
6/28/2006	9:00 PM	9:51 PM	51
7/3/2006	4:50 AM	5:26 AM	36
7/3/2006	7:09 AM	7:41 AM	32
7/14/2006	3:34 AM	4:14 AM	40
7/17/06 - 7/18-06	10:33 PM	12:38 AM	125
7/20/2006	4:03 AM	5:44 AM	101
7/20/2006	6:20 AM	6:50 AM	30
7/20/2006	7:35 AM	10:03 AM	148
7/20/2006	10:35 AM	12:28 PM	113
7/22/2006	6:38 PM	7:08 PM	30
7/27/2006	4:50 PM	5:20 PM	30
7/30/2006	12:21 PM	1:02 PM	41
8/2/2006	6:16 PM	6:46 PM	30
8/2/06 - 8/3/06	6:56 PM	12:00 AM	304
8/3/2006	5:18 AM	6:05 AM	47
8/10/2006	9:34 AM	10:04 AM	30
8/24/2006	5:04 AM	7:05 AM	121
8/24/2006	7:11 AM	8:41 AM	90
8/24/2006	9:03 AM	9:33 AM	30
9/11/2006	4:40 AM	5:10 AM	30
9/11/2006	8:27 AM	9:33 AM	54
9/12/2006	2:50 AM	3:20 AM	30
9/12/2006	4:46 PM	5:26 PM	40
9/13/2006	3:56 AM	4:26 AM	30
9/17/2006	5:26 PM	6:10 PM	44
9/22/2006	4:48 PM	6:50 PM	122
9/30/2006	1:31 PM	2:12 PM	41
9/30/2006	7:00 PM	7:30 PM	30
10/2/2006	1:04 PM	2:17 PM	73
10/2/2006	2:22 PM	2:52 PM	30
10/2/2006	4:01 PM	4:31 PM	30

Table A-1. (Continued).

Date	Start	End	Duration (min)
10/2/2006	7:42 PM	11:45 PM	243
10/3/2006	12:13 AM	1:02 AM	49
10/4/2006	5:25 AM	5:55 AM	30
10/21/2006	6:45 PM	7:15 PM	30
11/10/2006	4:41 PM	6:24 PM	103
11/10/2006	6:51 PM	7:21 PM	30
11/29/2006	9:42 AM	10:33 AM	49
11/29/2006	10:41 AM	11:11 AM	30
Total Delay			**4,308**

Table A-2. MCO 2006 30/30 lightning events.

Date	Start	End	Duration (min)
1/13/2006	9:50pm	10:48pm	58
2/3/2006	11:42AM	12:12pM	30
2/3/2006	12:47pm	1:19pm	32
2/3/2006	3:35pm	4:05pm	30
2/3/2006	6:39pm	7:09pm	30
2/3/2006	9:27pm	10:05pm	38
2/3/2006	10:22pm	10:52pm	30
2/4/2006	5:23am	6:22am	59
2/4/2006	10:39am	12:02pm	83
2/4/2006	2:04pm	2:34pm	30
4/9/2006	4:23am	5:13am	50
4/9/2006	6:27am	10:04am	217
4/21/2006	8:57pm	10:19pm	82
4/22/2006	7:37pm	8:18pm	41
4/22 - 4/23/06	11:52pm	12:24am	42
5/9/2006	12:10pm	12:40pm	30
5/11/2006	5:49pm	6:35pm	46
5/12/2006	2:46am	4:41am	115
5/25/2006	9:27pm	9:57pm	30
5/26/2006	9:12pm	9:42pm	30
5/26 - 5/27/06	10:03pm	12:19am	136
5/28/2006	8:54pm	11:00pm	126
6/1/2006	5:06pm	6:29pm	83
6/2/2006	10:27pm	10:57pm	30
6/4/2006	7:38pm	8:27pm	49
6/04 - 05/06	10:32pm	12:12am	100
6/6/2006	2:38am	3:08am	30
6/11/2006	5:54pm	6:24pm	30
6/12/2006	4:02pm	4:32pm	30
6/12/2006	4:40pm	5:29pm	49
6/13/2006	9:29am	9:59am	30
6/16/2006	8:51pm	9:28pm	37
6/20/2006	9:30pm	10:19pm	49
6/24/2006	5:38pm	7:36pm	118
6/24/2006	8:16pm	9:12pm	56
6/25/2006	7:18pm	10:12pm	174
6/26/2006	7:56pm	9:15pm	79
6/26/2006	10:14pm	11:12pm	58
6/27/2006	4:08pm	6:54pm	166
6/27/2006	9:03pm	10:35pm	92
6/27/2006	11:24pm	11:54pm	30
6/28/2006	7:03pm	7:33pm	30
6/28/2006	8:10pm	8:40pm	30
6/28-6/29/06	9:58pm	12:21am	143
6/29/2006	7:34pm	8:04pm	30
6/29/2006	8:17pm	9:07pm	50
7/1/2006	7:02pm	7:32pm	30
7/1/2006	7:46pm	8:28pm	42
7/2/2006	4:37pm	5:50pm	73
7/2/2006	6:41pm	7:23pm	42
7/3/2006	5:47pm	6:24pm	37
7/6/2006	10:10pm	11:30pm	80
7/7/2006	12:03am	12:47am	44
7/7/2006	5:13pm	7:49pm	156
7/11/2006	3:34pm	4:04pm	30
7/11/2006	7:12pm	7:42pm	30
7/12/2006	4:49pm	5:19pm	30
7/12/2006	6:18pm	6:53pm	35
7/16/2006	10:04pm	11:36pm	92
7/17/2006	5:46pm	9:34pm	228

Table A-2. (Continued).

Date	Start	End	Duration (min)
7/18/2006	5:01pm	5:34pm	33
7/18/2006	6:17pm	7:58pm	101
7/19/2006	2:28am	4:48am	160
7/19/2006	5:22am	5:52am	30
7/20/2006	5:32pm	7:36pm	124
7/23/2006	6:58pm	9:17pm	139
7/24/2006	6:26pm	8:14pm	108
7/26/2006	8:16pm	10:18pm	128
7/27/2006	6:45pm	7:44pm	59
7/28/2006	4:48pm	5:28pm	30
7/28/2006	7:08pm	7:38pm	30
7/29/2006	8:25pm	10:02pm	97
7/30 - 7/31/06	11:07pm	12:59am	112
7/31/2006	2:12am	3:18am	66
7/31/2006	10:25pm	11:53pm	88
8/3/2006	9:39pm	11:49pm	130
8/4/2006	6:38pm	7:08pm	30
8/4/2006	7:25pm	8:07pm	42
8/4/2006	8:20pm	8:50pm	30
8/5/2006	7:54pm	8:30pm	36
8/13/2006	5:56pm	7:21pm	85
8/13/2006	8:01pm	9:50pm	109
8/15/2006	7:53pm	8:54pm	61
8/16/2006	8:23pm	8:53pm	30
8/17/2006	5:02pm	7:03pm	121
8/19/2006	2:28am	2:58am	30
8/19/2006	9:51pm	10:35pm	44
8/21/2006	7:18pm	8:55pm	97
8/21/2006	9:21pm	10:41pm	100
8/23/2006	8:16pm	9:03pm	47
8/23/2006	9:20pm	11:00pm	100
8/24/2006	5:10pm	7:30pm	160
8/25/2006	3:56pm	4:226pm	30
8/25/2006	6:06pm	6:43pm	37
8/26/2006	5:45pm	6:24pm	39
8/26/2006	9:47pm	11:58pm	131
8/27/2006	8:17pm	9:56pm	99
8/30/2006	1:39pm	2:09pm	30
8/30/2006	10:43pm	11:45pm	62
8/31/2006	5:11pm	5:48pm	37
9/1/2006	4:21pm	6:03pm	102
9/2/2006	8:17pm	9:28pm	71
9/2/2006	11:00pm	11:33pm	33
9/3/2006	7:12pm	8:00pm	48
9/4/2006	7:11pm	7:50pm	39
9/4/2006	10:17pm	10:54pm	37
9/06 - 9/07/06	10:24pm	1:08am	164
9/7/2006	7:14pm	9:17pm	123
9/8/2006	8:20pm	11:26pm	186
9/10/2006	6:52pm	7:30pm	38
9/14/2006	7:12pm	8:33pm	81
9/14/2006	9:09pm	9:42pm	33
9/14 - 9/15/06	11:36pm	1:02am	86
9/15 - 9/16/06	11:51pm	12:21am	30
9/19/2006	7:25pm	8:47pm	82
9/19/2006	9:25pm	9:55pm	30
9/19/2006	10:10pm	10:43pm	33
9/19/2006	11:07pm	11:40pm	33
9/26/2006	7:38pm	8:08pm	30
9/26/2006	8:12pm	9:10pm	58

(continued on next page)

Table A-2. (Continued).

Date	Start	End	Duration (min)
10/07 – 10/08/06	11:55pm	2:00am	125
11/7/2006	10:43pm	11:19pm	36
11/16/2006	7:32am	8:02am	30
11/16/2006	10:51am	11:21am	30
12/23/2006	12:52am	1:28am	36
12/25/2006	6:15pm	7:29pm	74
Total Delay			**8,577**

Table A-3. ORD 2006 30/15 summer lightning events.

Date	Start	End	Duration (min)
6/21/2006	5:35 PM	5:50 PM	15
6/22/2006	9:09 AM	10:04 AM	55
6/25/2006	3:27 PM	3:42 PM	15
6/25/2006 - 6/26/2006	11:17 PM	2:38 AM	201
6/26/2006	11:54 AM	12:22 PM	28
6/26/2006	12:51 PM	1:21 PM	30
6/28/2006	6:24 AM	6:39 AM	15
6/28/2006	6:57 AM	8:17 AM	80
7/3/2006	4:50 AM	5:11 AM	21
7/3/2006	7:09 AM	7:24 AM	15
7/14/2006	3:34 AM	3:58 AM	24
7/17/2006	10:33 PM	11:56 PM	81
7/18/2006	12:08 AM	12:23 AM	15
7/20/2006	4:03 AM	4:19 AM	16
7/20/2006	4:45 AM	5:19 AM	34
7/20/2006	6:20 AM	9:49 AM	209
7/20/2006	10:39 AM	12:13 PM	98
7/20/2006	4:50 PM	5:05 PM	15
7/20/2006	6:38 PM	6:53 PM	15
7/28/2006	9:01 PM	9:36 PM	35
7/30/2006	12:21 PM	12:37 PM	16
8/2/2006	6:16 PM	6:31 PM	15
8/2/2006	6:56 PM	11:45 PM	289
8/3/2006	5:18 AM	5:50 AM	32
8/10/2006	9:34 AM	9:49 AM	15
8/24/2006	5:05 AM	6:50 AM	105
8/24/2006	7:12 AM	8:16 AM	64
8/24/2006	9:03 AM	9:18 AM	15
Total Delay			**1,568**

Table A-4. MCO 2006 30/15 summer lightning events.

Date	Start	End	Duration (min)
6/1/2006	5:09p	6:04p	55
6/2/2006	10:27p	10:42p	15
6/4/2006	7:39p	8:12p	33
6/4/2006	10:32p	11:58p	86
6/6/2006	2:38a	2:53a	15
6/11/2006	5:54p	6:09p	15
6/12/2006	4:06p	4:18p	12
6/12/2006	4:40p	5:14p	34
6/13/2006	9:29a	9:44a	15
6/16/2006	8:51p	9:14p	23
6/20/2006	9:30p	9:54p	24
6/24/2006	5:38p	7:21p	33
6/24/2006	8:16p	8:58p	42
6/25/2006	7:19p	9:56p	157
6/26/2006	7:56p	9:00p	64
6/26/2006	10:13p	10:57p	44
6/27/2006	4:08p	6:39p	121
6/27/2006	9:03p	10:20p	77
6/27/2006	11:25p	11:40p	15
6/28/2006	7:03p	7:18p	15
6/28/2006	8:10p	8:25p	15
6/28 - 6/29/06	10:20p	12:06a	106
6/29/2006	7:34p	7:49p	15
6/29/2006	8:16p	8:52p	36
7/1/2006	7:02p	7:17p	15
7/1/2006	7:46p	8:03p	17
7/2/2006	4:37p	4:52p	15
7/2/2006	5:11p	5:35p	24
7/2/2006	6:41p	7:09p	28
7/3/2006	5:47p	6:09p	22
7/6/2007	10:10p	11:15p	75
7/7/2006	12:03a	12:32a	29
7/7/2006	5:13p	5:28p	15
7/7/2006	5:44p	6:15p	39
7/7/2006	7:08p	7:34p	26
7/11/2006	3:35p	3:50p	15
7/11/2006	7:13p	7:28p	15
7/12/2006	4:50p	5:05p	15
7/12/2006	6:18p	6:38p	20
7/16/2006	10:04p	11:21p	77
7/17/2006	5:46p	9:20p	214
7/18/2006	5:01p	5:20p	19
7/18/2006	6:17p	6:32p	15
7/18/2006	6:50p	7:43p	53
7/19/2006	2:28a	3:38a	70
7/19/2006	4:03a	4:33a	30
7/19/2006	5:22p	5:37p	15
7/20/2006	5:32p	7:21p	109
7/23/2006	6:58p	9:02p	124
7/24/2006	6:26p	7:59p	93
7/26/2006	8:17p	10:03p	106
7/27/2006	6:45p	7:19p	34
7/28/2006	4:57p	5:14p	17
7/28/2006	7:08p	7:23p	15
7/29/2006	8:25p	9:47p	82
7/30 - 7/31/06	11:07p	12:44a	97
7/31/2006	2:13a	3:03a	50
7/31/2006	9:43p	9:58p	15
7/31/2006	10:25p	11:38p	73
8/3/2006	9:40p	10:18p	38

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Table A-4. (Continued).

Date	Start	End	Duration (min)
8/3/2006	11:05p	11:35p	20
8/4/2006	6:38p	6:53p	15
8/4/2006	7:24p	7:52p	28
8/4/2006	8:20p	8:35p	15
8/5/2006	7:54p	8:15p	21
8/13/2006	5:56p	7:06p	70
8/13/2006	8:01p	8:25p	24
8/13/2006	8:42p	9:35p	53
8/15/2006	7:54p	8:09p	15
8/15/2006	8:24p	8:39p	15
8/17/2006	5:02p	6:49p	93
8/19/2006	2:28a	2:47a	19
8/19/2006	9:51p	10:21p	30
8/21/2006	7:18p	8:41p	83
8/21/2006	9:01p	10:34p	93
8/23/2006	8:17p	8:58p	41
8/23/2006	9:20p	10:45p	85
8/24/2006	5:10p	7:15p	125
8/25/2006	3:56p	4:11p	15
8/25/2006	6:06p	6:29p	23
8/26/2006	5:45p	6:09p	24
8/26/2006	9:47p	11:43p	116
8/27/2006	8:17p	9:42p	85
8/30/2006	1:39p	1:54p	15
8/30/2006	10:43p	11:30p	47
8/31/2006	5:11p	5:34p	23
Total Delay			**3,976**

APPENDIX B

Glossary of Lightning Terms

The text presented in this research study includes a wide range of often unfamiliar words and specialized terminology. For the convenience of the reader, the glossary of lightning terms is presented on the following pages. This glossary is extracted from the *American Society of Meteorology Glossary of Meteorology, 2nd ed.*, and is used with permission (*1*).

Air–earth current—The transfer of electric charge from the positively charged atmosphere to the negatively charged earth.

> This current is made up of the air-earth conduction current, a point-discharge current, a precipitation current, a convection current, and miscellaneous smaller contributions. Of these, the air–earth conduction current is by far the largest. This is not just true locally, but throughout the world where there are no thunderstorms occurring, which is estimated to be 80%–90% percent of the earth. The existence of this quasi-steady current in fair weather and the observed maintenance of the earth's net negative charge are both better established than the nature of the supply current, which must replenish the positive charge in the upper atmosphere and the negative charge on the earth.
>
> –Gish, O. H., 1951: *Compendium of Meteorology*, p. 113.

Atmospheric electric field—A quantitative term denoting the electric field strength of the atmosphere at any specified point in space and time.

In areas of fair weather, the atmospheric electric field near the earth's surface typically is about 100 volts (V) m^{-1} and is directed vertically in such a sense as to drive positive charges downward to the earth. In areas of fair weather this field decreases in magnitude with increasing altitude, falling, for example, to only about 5 V m^{-1} at an altitude of about 10 km. Near thunderstorms, and under clouds of vertical development, the surface electric field (the electric field measured at the surface of the earth) varies widely in magnitude and direction, usually reversing its direction immediately beneath active thunderstorms. In areas of minimal local disturbance, a characteristic diurnal variation of electric field strength is observed. This variation is characterized by a maximum that occurs at about 1900 UTC for all points on the earth and is now believed to be produced by thunderstorms that, for geographic regions, are more numerous for the world as a whole at that universal time than at any other. It is now believed that thunderstorms, by replenishing the negative charge to the earth's surface, provide the supply current to maintain the fair-weather electric field in spite of the continued flow of the air–earth current that tends to neutralize that field. The range of the electric field in fair weather varies considerably with geographical area, from one part of the globe to another. If, however, there are no local sources of pollution, the surface electric field has its maximum amplitude around 1900 UTC.

Atmospherics—(Also called atmospheric interference, strays, sferics) The radio frequency electromagnetic radiation originating, principally, in the irregular surges of charge in thunderstorm lightning discharges.

Atmospherics are heard as a quasi-steady background of crackling noise (static) on certain radio frequencies, such as those used to broadcast AM radio signals. Since any acceleration of electric charge leads to emission of electromagnetic radiation, and since the several processes involved in propagation of lightning lead to very large charge accelerations, the lightning channel acts like a huge transmitter, sending out radiation with frequencies of the order of 10 kHz. Atmospherics may occasionally be detected at distances in excess of 3500 km (2000 mi) from their source. Advantage has been taken of this characteristic by using radio direction-finding equipment to plot cloud-to-ground lightning locations, and to locate active thunderstorm areas in remote regions and in-between weather reporting stations.

Ball lightning—(Also called globe lightning) A rare and randomly occurring bright ball of light observed floating or moving through the atmosphere close to the ground.

Observations have widely varying identifying characteristics for ball lightning, but the most common description is that of a sphere having a radius of 15–50 cm, orange or reddish in color, and lasting for only a few seconds before disappearing, sometimes with a loud noise. Most often ball lightning is seen in the vicinity of thunderstorms or a recent lightning strike, which may suggest that ball lightning is electrical in composition or origin. Considered controversial due to the lack of unambiguous physical evidence for its existence, ball lightning is becoming more accepted due to recent laboratory recreations resembling ball lightning. Despite the observations and models of these fire balls, the exact mechanism(s) for naturally occurring ball lightning is unknown.

Beaded lightning—(Also called chain lightning, pearl lightning) A particular aspect of a normal lightning flash occasionally seen when the observer happens to view end-on a number of segments of the irregular channel (zigzag lightning) and hence receives an impression of higher luminosity at a series of locations along the channel.

Blue jets—Weakly luminous upward propagating discharges, blue in color, emanating from the tops of thunderstorms.

Following their emergence from the top of the thundercloud, they typically propagate upward in narrow cones of about 15° full width at vertical speeds of roughly 100 km s^{-1} (Mach 300), fanning out and disappearing at heights of about 40–50 km. Their intensities are on the order of 800 kR near the base, decreasing to about 10 kR near the upper terminus. These correspond to an estimated optical energy of about 4 kJ, a total energy of about 30 MJ, and an energy density on the order of a few millijoules per cubic meter. Blue jets are not aligned with the local magnetic field.

Cloud flash—(Also called intracloud flash, cloud-to-cloud flash) A lightning discharge occurring between a positively charged region and a negatively charged region, both of which may lie in the same cloud.

The most frequent type of cloud discharge is one between a main positively charged region and a main negatively charged region. Cloud flashes tend to outnumber cloud-to-ground flashes. In general, the channel of a cloud flash will be wholly surrounded by cloud. Hence, the channel's luminosity typically produces a diffuse glow when seen from outside the cloud and this widespread glow is called sheet lightning.

Cloud-to-ground flash—A lightning flash occurring between a charge center in the cloud and the ground.

On an annual basis, negative charge is lowered to the ground in about 95% of the flashes. The remaining flashes lower positive charge to the ground. This type of lightning flash, which can be contrasted with an intracloud flash or cloud flash, consists of one or more return strokes. The first stroke begins with a stepped leader followed by an intense return stroke that is the principal source of luminosity and charge transfer. Subsequent strokes begin with a dart leader followed by another return stroke. Most of the strokes use the same channel to ground. The time interval between strokes is typically 40 μs.

Dart leader—(Also called continuous leader) The leader which, after the first stroke, typically initiates each succeeding stroke of a multiple-stroke flash lightning. (The first stroke is initiated by a stepped leader.)

The dart leader derives its name from its appearance on photographs taken with streak cameras. The dart leader's brightest luminosity is at its tip which is tens of meters in length, propagating downward at about 10^7 m s^{-1}. In contrast to stepped leaders, dart leaders do not typically exhibit branching because the previously established channel's low gas density and residual ionization provide a more favorable path for this leader than do any alternative ones.

–Chalmers, J. A., 1957: *Atmospheric Electricity*, p. 239.

Direction finder—An instrument consisting of two orthogonal magnetic loop antennas and associated electronics for the purpose of detecting the azimuth to a cloud-to-ground lightning stroke.

Electrical breakdown—The sudden decrease of resistivity of a substance when the applied electric field strength rises above a certain threshold value (the substance's dielectric strength).

For air at normal pressures and temperatures, experiment has shown that the breakdown process occurs at a field strength of about 3×10^6 V m^{-1}. This value decreases approximately linearly with pressure, and is dependent upon humidity and traces of foreign gases. In the region of high field strength just ahead of an actively growing leader in a lightning stroke, breakdown occurs in the form of a rapidly moving wave of sudden ionization (electron avalanche). The dielectric strength in a cloud of water drops is less than that in cloud-free humid air.

Electric field mill—see field mill.

Elve—Transient laterally extensive illumination of the airglow layer, at about 90 km, over thunderstorms, and associated with the electromagnetic pulse from the return stroke of a lightning flash to ground.

Field mill—An instrument that obtains a continuous measurement of the sign and magnitude of the local electric potential gradient by alternately shielding and exposing a conductor that is grounded through a resistance to develop an alternating potential that is proportional to the field.

Forked lightning—The common form of cloud-to-ground discharge always visually present to a greater or lesser degree that exhibits downward-directed branches from the main lightning channel.

In general, of the many branches of the stepped leader, only one is connected to the ground, defining the primary, bright return stroke path; the other incomplete channels decay after the ascent of the first return stroke. *Compare* streak lightning, zigzag lightning.

Ground flash—Same as cloud-to-ground flash or cloud-to-ground discharge.

Ground-to-cloud discharge—A lightning discharge in which the original leader process starts upward from some object on the ground; the opposite of the more common cloud-to-ground discharge.

Ground-to-cloud discharges most frequently emanate from very tall structures that, being at the same potential as the earth, can exhibit the strong field intensities near their upper extremities necessary to initiate leaders.

Heat lightning—Nontechnically, the luminosity observed from ordinary lightning too far away for its thunder to be heard.

Since such observations have often been made with clear skies overhead, and since hot summer evenings particularly favor this type of observation, there has arisen a popular misconception that the presence of diffuse flashes in the apparent absence of thunderclouds implies that lightning is somehow occurring in the atmosphere merely as a result of excessive heat.

Intracloud flash—A lightning discharge occurring between a positive charge center and a negative charge center, both of which lie in the same cloud; starts most frequently in the region of the strong electric field between the upper positive and lower negative space charge regions.

In summer thunderstorms, intracloud flashes precede the occurrence of cloud-to-ground flashes; they also outnumber cloud-to-ground flashes. Intracloud lightning develops bidirectionally like a two-ended tree: one end of the tree is a branching negative leader, the other is a branching positive leader. Later in the flash, fast negative leaders similar to dart leaders (also called K changes) appear in the positive end region and propagate toward the flash origin. In weather observing, this type of discharge is often mistaken for a cloud-to-cloud flash, but the latter term should be restricted to true intercloud discharges, which are far less common than intracloud discharges. Cloud discharges tend to outnumber cloud-to-ground discharges in semiarid regions where the bases of thunderclouds may be several kilometers above the earth's surface. In general, the channel of a cloud flash will be wholly surrounded by cloud. Hence the channel's luminosity typically produces a diffuse glow when seen from outside the cloud, and this widespread glow is called sheet lightning.

K changes—The K process is generally viewed as a recoil streamer or small return stroke that occurs when a propagating discharge within the cloud encounters a pocket of charge opposite to its own.

In this view, the J process represents a slowly propagating discharge that initiates the K process. This is the case for K changes in cloud discharges. It is reasonable to expect that cloud discharge K changes are similar to the in-cloud portion of ground discharges.

Leader—(Or leader streamer) The electric discharge that initiates each return stroke in a cloud-to-ground lightning discharge.

It is a channel of high ionization that propagates through the air by virtue of the electric breakdown at its front produced by the charge it lowers. The stepped leader initiates the first stroke in a cloud-to-ground flash and establishes the channel for most subsequent strokes of a lightning discharge. The dart leader initiates most subsequent strokes. Dart-stepped leaders begin as dart leaders and end as stepped leaders. The initiating processes in cloud discharges are sometimes also called leaders but their properties are not well measured.

Lightning—Lightning is a transient, high-current electric discharge with path lengths measured in kilometers.

The most common source of lightning is the electric charge separated in ordinary thunderstorm clouds (cumulonimbus). Well over half of all lightning discharges occur within the thunderstorm cloud and are called intracloud discharges. The usual cloud-to-ground lightning (sometimes called streak lightning or forked lightning) has been studied more extensively than other lightning forms because of its practical interest (i.e., as a cause of injury and death, disturbances in power and communication systems, and ignition of forest fires) and because lightning channels below cloud level are more easily photographed and studied with optical instruments. Cloud-to-cloud and cloud-to-air discharges are less common than intracloud or cloud-to-ground lightning. All discharges other than cloud-to-ground are often lumped together and called cloud discharges. Lightning is a self-propagating and electrodeless atmospheric discharge that, through the induction process, transfers the electrical energy of an electrified cloud into electrical charges and current in its ionized and thus conducting channel. Positive and negative leaders are essential components of the lightning. Only when a leader reaches the ground does the ground potential wave (return stroke) affect the lightning process. Natural lightning starts as a bidirectional leader, although at different stages of the process unidirectional leader development can occur. Artificially triggered lightning starts on a tall structure or from a rocket with a trailing wire. Most of the lightning energy goes into heat, with smaller amounts transformed into sonic energy (thunder), radiation, and light. Lightning, in its various forms, is known by many common names, such as streak lightning, forked lightning, sheet lightning, and heat lightning, and by the less common air discharge; also, the rare and mysterious ball lightning and rocket lightning. An important effect of worldwide lightning activity is the net transfer of negative charge from the atmosphere to the earth. This fact is of great important in one problem of atmospheric electricity, the question of the source of the supply current. Existing evidence suggests that lightning discharges occurring sporadically at all times in various parts of the earth, perhaps 100 per second, may be the principal source of negative charge that maintains the earth–ionosphere potential difference of several hundred thousand volts in spite of the steady transfer of charge produced by the air–earth current. However, there also is evidence that point discharge currents may contribute to this more significantly than lightning. *See also* cloud-to-ground flash, intracloud flash, lightning discharge.

–Chalmers, J. A., 1957: *Atmospheric Electricity*, 235–255.
–Schonland, B. F. J., 1950: *The Flight of Thunderbolts*, 152 pp.
–Hagenguth, J. H., 1951: *Compendium of Meteorology*, 136–143.

Lightning channel—The irregular path through the air along which a lightning discharge occurs.

The lightning channel is established at the start of a discharge by the growth of a leader, which seeks out a path of least resistance between a charge source and the ground or between two charge centers of opposite sign in the thundercloud or between a cloud charge center and the surrounding air or between charge centers in adjacent clouds.

Lightning detection network—An integrated array of lightning direction finders that provide information for trigonometric location of cloud-to-ground lightning discharges.

Timing and direction information from individual receivers are combined to provide evolving maps of lightning occurrences across vast regions that sometimes reach beyond the range of storm surveillance radars. *See* sferics receiver.

Lightning direction finder—*See* sferics receiver.

Lightning discharge—The series of electrical processes taking place within 1 s by which charge is transferred along a discharge channel between electric charge centers of opposite sign within a thundercloud (intracloud flash), between a cloud charge center and the earth's surface (cloud-to-ground flash or ground-to-cloud discharge), between two different clouds (intercloud or cloud-to-cloud discharge), or between a cloud charge and the air (air discharge).

It is a very large-scale form of the common spark discharge. A single lightning discharge is called a lightning flash.

Lightning flash—The total observed lightning discharge, generally having a duration of less than 1 s.

A single flash is usually composed of many distinct luminous events that often occur in such rapid succession that the human eye cannot resolve them.

Lightning mapping system—A network of lightning detection equipment for locating the electromagnetic sources of a lightning flash.

The flash, both intracloud and cloud-to-ground, is mapped in three-dimensional space using equipment with a time resolution of less than 1 μs. Since cloud-to-cloud and cloud-to-air are rare lightning phenomena, mapping them has little or no importance.

Lightning stroke—In a cloud-to-ground discharge, a leader plus its subsequent return stroke.

In a typical case, a cloud-to-ground discharge is made up of three or four successive lightning strokes, most following the same lightning channel.

Negative cloud-to-ground lightning—A lightning flash or stroke between a cloud and the ground that lowers negative charge to the ground.

Negative ground flash—Same as negative cloud-to-ground lightning.

Peak current—Usually refers to the maximum current in a lightning return stroke.

Pearl lightning—Same as beaded lightning.

Point discharge current—The electrical current accompanying any specified source of point discharge.

In the electrical budget of the earth–atmosphere system, point discharge currents are of considerable significance as a major component of the supply current. Estimates made by Schonland (1928) of the point discharge current from trees in arid southwest Africa suggest that this process accounts for about 20 times as much delivery of negative charge to the earth during typical thunderstorms as do lightning discharges. Although the great height of thundercloud bases in arid regions, such as that referred to in Schonland's study, tends to favor point discharge over lightning charge transfer, point discharge still seems more significant than lightning even in England, where Wormell (1953) found for Cambridge a ratio of about 5:1 in favor of point discharge over lightning charge transfer.

–Chalmers, J. A., 1957: *Atmospheric Electricity*, 156–175.
–Wormell, T. W., 1953: Atmospheric electricity: some recent trends and problems. *Quart. J. Roy. Meteor. Soc.*, **79**, 3–50.
–Schonland, B. F. J., 1928: The polarity of thunderclouds. *Proc. Roy. Soc. A*, **118**, 233–251.

Positive cloud-to-ground lightning—A lightning flash or stroke between a cloud and the ground that lowers positive charge from the cloud to the ground.

Positive discharge—A positive discharge lowers positive charge to the ground via a lightning flash.

The flash may be initiated in the cloud or from the ground.

Positive ground flash—Same as positive cloud-to-ground lightning.

Return stroke—The intense luminosity that propagates upward from earth to cloud base in the last phase of each lightning stroke of a cloud-to-ground discharge.

In a typical flash, the first return stroke ascends as soon as the descending stepped leader makes electrical contact with the earth, often aided by short ascending ground streamers. The second and all subsequent return strokes differ only in that they are initiated by a dart leader and not a stepped leader. It is the return stroke that produces almost all of the luminosity and charge transfer in most cloud-to-ground strokes. Its great speed of ascent (about 1×10^8 m s^{-1}) is made possible by residual ionization of the lightning channel remaining from passage of the immediately preceding leader, and this speed is enhanced by the convergent nature of the electric field in which channel electrons are drawn down toward the ascending tip in the region of the streamer's electron avalanche. Current peaks as high as 3×10^5 A have been reported, and values of 3×10^4 A are fairly typical. The entire process of the return stroke is completed in a few tens of microseconds, and even most of this is spent in a long decay period following an early rapid rise to full current value in only a few microseconds. Both the current and propagation speed decrease with height. In negative cloud-to-ground flashes the return stroke deposits the positive charge of several coulombs on the preceding negative leader channel, thus charging earth negatively. In positive cloud-to-ground flashes, the return stroke deposits the negative charge of several tens of coulombs on the preceding positive leader channel, thus increasing positive charge on the ground. In negative cloud-to-ground flashes, multiple return strokes are common. Positive cloud-to-ground flashes, in contrast, typically have only one return stroke. The return streamer of cloud-to-ground discharges is so intense because of the high electrical conductivity of the ground, and hence this type of streamer is not to be found in air discharges, cloud discharges, or cloud-to-cloud discharges.

–Hagenguth, J. H., 1951: *Compendium of Meteorology*, 137–141.

Ribbon lightning—Ordinary cloud-to-ground lightning that appears to be spread horizontally into a ribbon of parallel luminous streaks when a very strong wind is blowing at right angles to the observer's line of sight.

Successive strokes of the lightning flash are then displaced by small angular amounts and may appear to the eye or camera as distinct paths. The same effect is readily created artificially by rapid transverse movement of a camera during film exposure.

Rocket-triggered lightning—A form of artificial lightning discharge initiated with a rocket trailing wire that may or may not be connected to the ground.

The first phase of the discharge is a unidirectional leader starting from the tip of the wire. When the low end of the wire is not connected to ground, bidirectional leader development occurs from both ends of the wire, similar to lightning initiation from aircraft. In the case of negative space charge overhead (usual summer thunderstorm condition), a triggered lightning may only be a positive leader or may become a sequence of dart leader–return stroke processes following the initial positive leader. The latter is analogous to the subsequent return stroke process in a negative cloud-to-ground flash with the initial positive leader being analogous to the first return stroke. In the case of positive space charge overhead (usual winter storm condition), the triggered lightning is a single negative leader.

Sferics fix—The determination of the bearing to the lightning source usually based on the measurement of the horizontal magnetic field with orthogonal coils or loop antennas.

Sferics observation—The detection of electromagnetic radiation from lightning generally in the frequency range 10–30 kHz.

The physical measurement can include the electric field, the magnetic field, or both. Sferics are generally attributed to the high current phases of source, that is, return strokes and K changes.

Sferics receiver—(Also called lightning direction finder.) An instrument that measures, electronically, the direction of arrival, intensity, and rate of occurrence of atmospherics; a type of radio direction finder, it is most commonly used to detect and locate cloud-to-ground lightning discharges from distant thunderstorms.

In its simplest form the instrument consists of two orthogonally crossed antennas that measure the electromagnetic field changes produced by a lightning discharge and determine the direction from which the changes arrived. Negative and positive polarity cloud-to-ground discharges can be distinguished. Cloud-to-cloud discharges can be distinguished based on characteristics of the received signal, and the geometry of nearby discharge channels may be determined. *See also* lightning detection network.

Sferics source—That portion of a lightning discharge that radiates strongly in the frequency interval 10–30 kHz.

The physical source is generally identified with the return stroke in flashes to ground and the K change in the case of intracloud flashes.

Sheet lightning—(Also called luminous cloud.) A diffuse, but sometimes fairly bright, illumination of those parts of a thundercloud that surround the path of a lightning flash, particularly a cloud discharge or cloud-to-cloud discharge.

Thus, sheet lightning is no unique form of lightning but only one manifestation of ordinary lightning types in the presence of obscuring clouds. *Compare* heat lightning.

Spark discharge—That type of gaseous electrical discharge in which the charge transfer occurs transiently along a relatively constricted path of high ion density, resulting in high luminosity.

It is of short duration and to be contrasted with the nonluminous point discharge, the corona discharge, and the continuous arc discharge. The exact meaning to be attached to the term "spark discharge" varies somewhat in the literature. It is frequently applied to just the transient phase of the establishment of any arc discharge. A lightning discharge can be considered a large-scale spark discharge.

Spider lightning—Lightning with extraordinary lateral extent near a cloud base where its dendritic structure is clearly visible.

This lightning type is prevalent beneath the stratiform anvil of mesoscale convective systems and is often associated with positive ground flashes. This discharge form is also referred to as sheet lightning.

Sprite—Weak luminous emissions that appear directly above an active thunderstorm and are coincident with cloud-to-ground or intracloud lightning flashes.

Their spatial structures range from small single or multiple vertically elongated spots, to spots with faint extrusions above and below, to bright groupings that extend from the cloud tops to altitudes up to about 95 km. Sprites are predominantly red. The brightest region lies in the altitude range 65–75 km, above which there is often a faint red glow or wispy structure that extends to about 90 km. Below the bright red region, blue tendril-like filamentary structures often extend downward to as low as 40 km. High-speed photometer measurements show that the duration of sprites is only a few milliseconds. Current evidence strongly suggests that sprites preferentially occur in decaying portions of thunderstorms and are correlated with large positive cloud-to-ground flashes. The optical intensity of sprite clusters, estimated by comparison with tabulated stellar intensities, is comparable to a moderately bright auroral arc. The optical energy is roughly 10–50 kJ per event, with a corresponding optical power of 5–25 MW. Assuming that optical energy constitutes 10^{-3} of the total for the event, the energy and power are on the order of 10–100 MJ and 5–50 GW, respectively. Early research reports for these events referred to them by a variety of names, including upward lightning, upward discharges, cloud-to-stratosphere discharges, and cloud-to-ionosphere discharges. Now they are simply referred to as sprites, a whimsical term that evokes a sense of their fleeting nature, while at the same time remaining nonjudgmental about physical processes that have yet to be determined. *Compare* blue jets.

Stepped leader—The initial leader of a lightning discharge; an intermittently advancing column of high ionization and charge that establishes the channel for a first return stroke.

The peculiar characteristic of this type of leader is its stepwise growth at intervals of about 50–100 μs. The velocity of growth during the brief intervals of advance, each only about 1 μs in duration, is quite high (about 5×10^7 m s^{-1}), but the long stationary phases reduce its effective speed to only about 5×10^5 m s^{-1}.

Streak lightning—Ordinary lightning, of a cloud-to-ground discharge, that appears to be entirely concentrated in a single, relatively straight lightning channel.

Compare forked lightning, zigzag lightning

Streamer—A sinuous channel of very high ion density that propagates itself though a gas by continual establishment of an electron avalanche just ahead of its advancing tip.

In lightning discharges, the stepped leader, dart leader, and return stroke all constitute special types of streamers.

Stroke—*See* lightning stroke.

Stroke density—The areal density of lightning discharges over a given region during some specified period of time, as number per square mile or per square kilometer.

Supply current—The electrical current in the atmosphere that is required to balance the observed air–earth current of fair-weather regions by transporting positive charge upward or negative charge downward.

Accounting for the supply current has been for many years a key problem of the field of atmospheric electricity and has received much attention. A quasi-steady current of about 1800 A for the earth as a whole is estimated to be required to balance the air–earth current. Wilson (1920) suggested that the thunderstorms present in widely scattered regions of the earth at any one time might be responsible for the supply current. Although this suggestion has not been fully confirmed, there is growing conviction that this is correct. When one considers an average over many storms, thunderstorm lightning transports negative charge downward to earth, as does point discharge in the regions below thunderstorms. Also, positive ions flow upward above active thunderstorms. *See* air–earth current, point discharge current.

–Gish, O. H., 1951: *Compendium of Meteorology*, 113–118.
–Wilson, C. T. R., 1920: Investigations on lightning discharges and on the electric field of thunderstorms. *Phil. Trans. A*, **221**, 73–115.

Thunder—The sound emitted by rapidly expanding gases along the channel of a lightning discharge.

Some three-fourths of the electrical energy of a lightning discharge is expended, via ion–molecule collisions, in heating the atmospheric gases in and immediately around the luminous channel. In a few tens of microseconds, the channel rises to a local temperature of the order of 10,000 °C, with the result that a violent quasi-cylindrical pressure wave is sent out, followed by a succession of rarefactions and compressions induced by the inherent elasticity of the air. These compressions are heard as thunder. Most of the sonic energy results from the return streamers of each individual lightning stroke, but an initial tearing sound is produced by the stepped leader; and the sharp click or crack heard at very close range, just prior to the main crash of thunder, is caused by the ground streamer ascending to meet the stepped leader of the first stroke. Thunder is seldom heard at points farther than 15 miles from the lightning discharge, with 25 miles an approximate upper limit, and 10 miles a fairly typical value of the range of audibility. At such distances, thunder has the characteristic rumbling sound of very low pitch. The pitch is low when heard at large distances only because of the strong attenuation of the high-frequency components of the original sound. The rumbling results chiefly from the varying arrival times of the sound waves emitted by the portions of the sinuous lightning channel that are located at varying distances from the observer, and secondarily from echoing and from the multiplicity of the strokes of a composite flash.

Thunderstorm cell—The convective cell of a cumulonimbus cloud having lightning and thunder.

Thunderstorm—(Sometimes called electrical storm.) In general, a local storm, invariably produced by a cumulonimbus cloud and always accompanied by lightning and thunder, usually with strong gusts of wind, heavy rain, and sometimes with hail.

It is usually of short duration, seldom over two hours for any one storm. A thunderstorm is a consequence of atmospheric instability and constitutes, loosely, an overturning of air layers in order to achieve a more stable density stratification. A strong convective updraft is a distinguishing feature of this storm in its early phases. A strong downdraft in a column of precipitation marks its dissipating stages. Thunderstorms often build to altitudes of 40,000–50,000 ft in midlatitudes and to even greater heights in the Tropics; only the great stability of the lower stratosphere limits their upward growth. A unique quality of thunderstorms is their striking electrical activity. The study of thunderstorm electricity includes not only lightning phenomena per se but all of the complexities of thunderstorm charge separation and all charge distribution within the realm of thunderstorm influence. In U.S. weather observing procedure, a thunderstorm is reported whenever thunder is heard at the station; it is reported on regularly scheduled observations if thunder is heard within 15 minutes preceding the observation. Thunderstorms are reported as light, medium, or heavy according to 1) the nature of the lightning and thunder; 2) the type and intensity of the precipitation, if any; 3) the speed and gustiness of the wind; 4) the appearance of the clouds; and 5) the effect upon surface temperature. From the viewpoint of the synoptic meteorologist, thunderstorms may be classified by the nature of the overall weather situation, such as airmass thunderstorm, frontal thunderstorm, and squall-line thunderstorm.

–Byers, H. R., and R. R. Braham Jr., 1949: *The Thunderstorm*, U.S. Government Printing Office, 287 pp.
–Byers, H. R., 1951: *Compendium of Meteorology*, p. 681.

Time-of-arrival technique—The time-of-arrival technique refers to locating the source of an emitted signal from a precise recording of the time that a signal is observed.

For example, the time interval between an observed lightning flash and the arrival of the thunder can be used to estimate the distance to the lightning flash. On the average, a time arrival difference of five seconds indicates that a lightning flash occurred one mile away from the observer, since the speed of sound in air is approximately 1000 ft s^{-1}.

Whistler—A type of VLF electromagnetic signal generated by some lightning discharges.

Whistlers propagate along geomagnetic field lines and can travel back and forth several times between the Northern and Southern Hemispheres. So named from the sound they produce in radio receivers.

Zigzag lightning—Ordinary lightning of a cloud-to-ground discharge that appears to have a single, but very irregular, lightning channel.

Compare streak lightning, forked lightning.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation