DEVELOPMENT OF THE NATIONAL LIGHTNING DETECTION NETWORK

BY RICHARD E. ORVILLE

Creative cooperation among private, federal, and university interests helped spread new lightning detection technology from isolated regional networks to nationwide coverage within only six years.

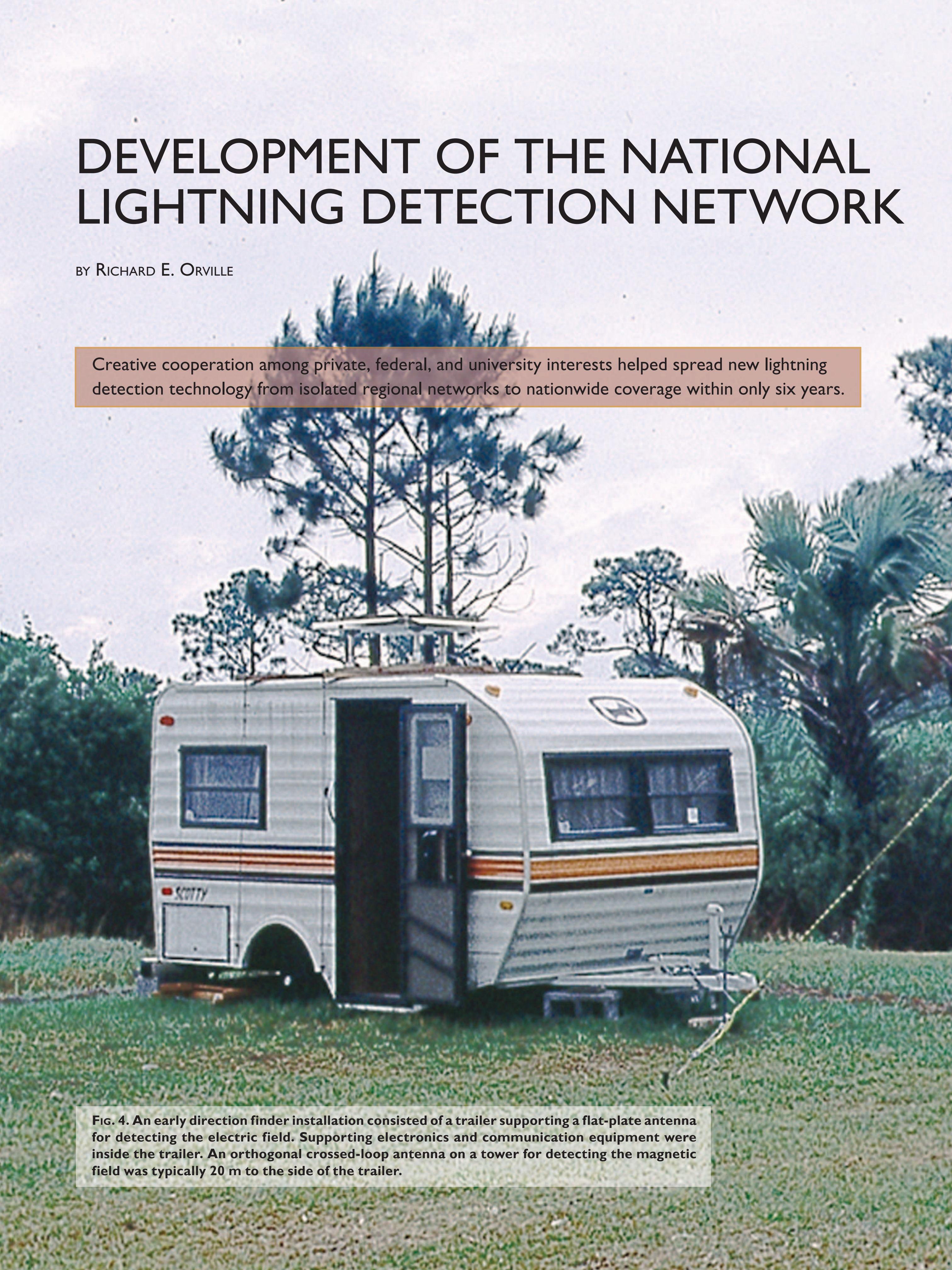
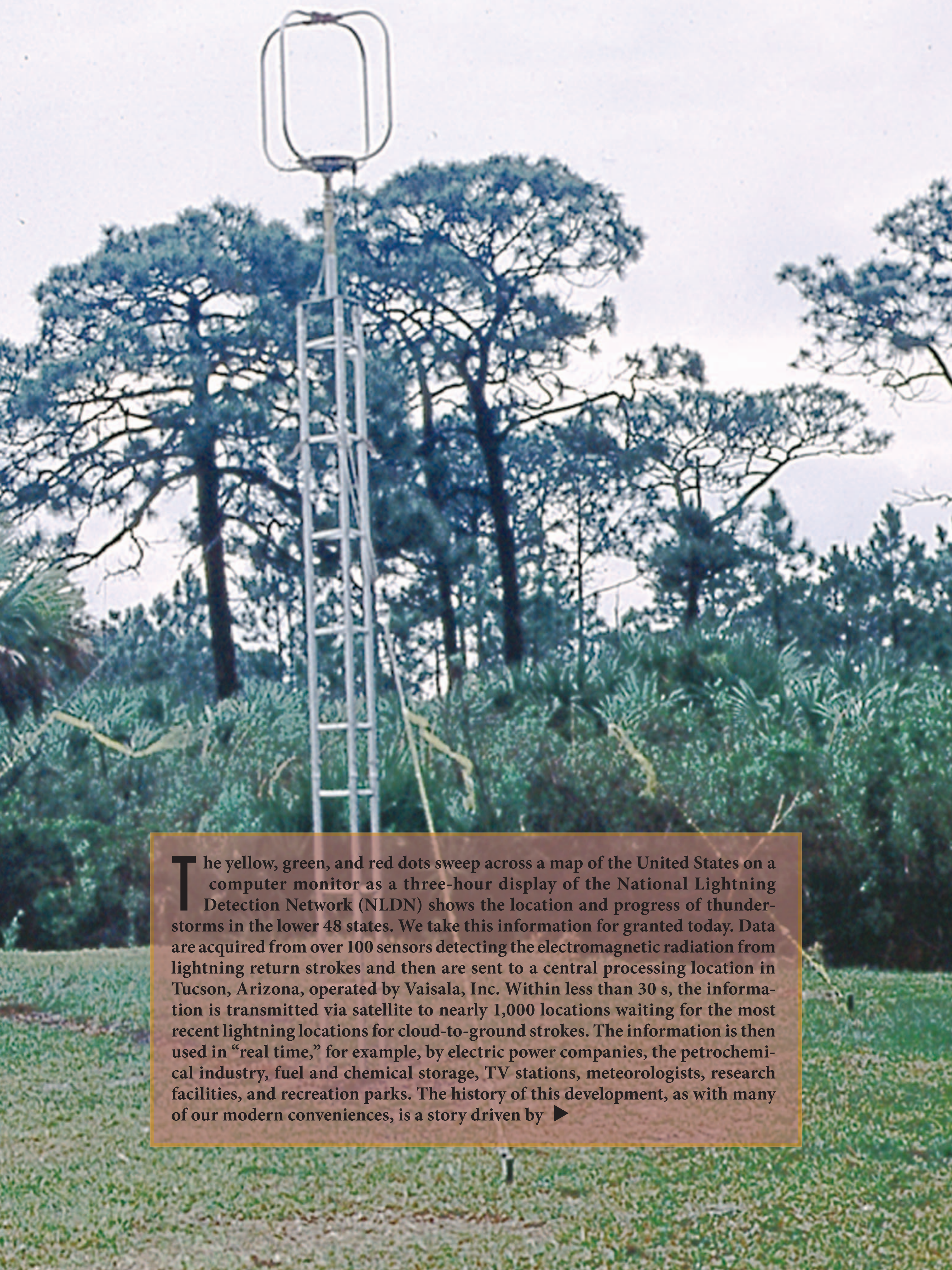


FIG. 4. An early direction finder installation consisted of a trailer supporting a flat-plate antenna for detecting the electric field. Supporting electronics and communication equipment were inside the trailer. An orthogonal crossed-loop antenna on a tower for detecting the magnetic field was typically 20 m to the side of the trailer.



The yellow, green, and red dots sweep across a map of the United States on a computer monitor as a three-hour display of the National Lightning Detection Network (NLDN) shows the location and progress of thunderstorms in the lower 48 states. We take this information for granted today. Data are acquired from over 100 sensors detecting the electromagnetic radiation from lightning return strokes and then are sent to a central processing location in Tucson, Arizona, operated by Vaisala, Inc. Within less than 30 s, the information is transmitted via satellite to nearly 1,000 locations waiting for the most recent lightning locations for cloud-to-ground strokes. The information is then used in "real time," for example, by electric power companies, the petrochemical industry, fuel and chemical storage, TV stations, meteorologists, research facilities, and recreation parks. The history of this development, as with many of our modern conveniences, is a story driven by ▶

technology with a beginning more than three decades ago.

PRE-1979. Success has many authors and the NLDN is a success that has several beginnings from which to choose. The electronic origins of the NLDN rest, I believe, on the invention of the modern-day direction finder (DF) by Krider et al. (1976). They developed a magnetic direction finder that used only the initial few microseconds of the wideband lightning return-stroke waveform to provide an accurate azimuth to the channel base of the lightning stroke to the ground. Their insight to use only the first few microseconds of rise time of a return-stroke waveform was a great advance. It is to their credit that they realized the source of the signal was then very close to the ground strike point, a location of great interest for those concerned with the lightning hazard. They also realized that direction-finding errors would be at their smallest at that point because that part of the lightning channel was predominantly vertical. Of equal importance was the set of waveform criteria that they developed to distinguish return-stroke waveforms from signals due to in-cloud processes. The random direction error in these first instruments was 1°–2° and the systematic error could be as much as 5°–10°. Much work was expended to remove these systematic errors, including the development of an analytical eigentechnique in 1985 (Orville, Jr. 1987).

Given the state of processing technology in the late 1970s it was an impressive engineering step to incorporate their scientific insight (Krider et al. 1980) into an automatic signal processor to compute the azimuth to the strike and then, a year or two later, to work out the communications and interfacing to bring the station data to a central processor (the position analyzer) and compute and plot a strike location within seconds. Combining the information from two or more direction finders led to the establishment of the Bureau of Land Management (BLM) lightning network in the western United States and in Alaska (Krider et al. 1980). Under the guidance of Dale Vance and later of Lonnie Brown, the BLM network coverage spread as it proved itself in range fire and forest fire applications. The BLM progressed from initially using pen plots of intersecting azimuths received from individual DFs to using a position analyzer to calculate the lightning locations and plot them. Eventually, they integrated these lightning data with surface meteorological and fuels data to provide an operational fire hazard index.

EARLY YEARS: 1979–83. The deployment of direction finders in the western United States did not go unnoticed in the research community. Michael Maier installed two direction finders in Oklahoma in March 1979 to record the lightning associated with the severe storms in the Severe Environmental Storm and Mesoscale Experiment (SESAME), based at the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma. Maier was successful in recording cloud-to-ground lightning in April and May 1979, a period during which the Wichita Falls tornado of 10 April 1979 occurred.

The University of Wisconsin, spring 1979. In the spring of 1979, I had the good fortune of spending a sabbatical at the Space Science and Engineering Center (SSEC) of the University of Wisconsin—Madison. Following a seminar in March on the subject of lightning, Fred Mosher, one of the SSEC key scientists, asked if it was possible to overlay lightning onto satellite data and what we might learn from this exercise. Mosher's question initiated our cooperation with Michael Maier, resulting in the first coordinated processing of lightning ground strike data, satellite data, and radar data. Figure 1, for 10 April 1979, shows the result.

In Fig. 1 we see the superposition of the visible image taken at 2330 UTC, the Weather Surveillance Radar 1957 (WSR-57) range image with two reflectivity levels of 20 (green) and 40 dBZ (blue), and the lightning ground strikes for the 30-min period (yellow). The red "W" marks the location of Wichita Falls, Texas; "L" marks Lawton, Oklahoma; "N" marks the location of one direction finder at Norman, Oklahoma; and "DF 2" marks the location of the second DF. Note that the yellowish lightning ground strike locations occur in a relatively small fraction of the area covered by a large cloud system oriented southwest to northeast, and that the lightning extends far to the northeast, but is sparse to the southwest, in the vicinity of Wichita

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-89-2-180

In final form 29 July 2007

Falls. Because this period covered the lifetime of the Wichita Falls tornado, we consider this one of the first indications of the lack of cloud-to-ground lightning in many strong tornadic storms, a tendency documented by MacGorman et al. (1989) in one case and found later in a large number of storms by Perez et al. (1997). Note, however, that there are exceptions, in which substantial cloud-to-ground flash rates occur in supercell storms during tornadoes, as reported, for example, by MacGorman and Nielsen (1991).

Following the above success, the NSSL Oklahoma lightning network was established beginning in late 1980 and early 1981, funded by Dave Rust's project at the NSSL and by the Nuclear Regulatory Commission. NCR's funding was to support a study led by Michael Maier to infer ground-strike density nationally from thunderstorm day and duration data by correlating LLP data from two locations—Florida and Oklahoma—with climatological thunderstorm records (MacGorman et al. 1984). Don MacGorman led the installation of three direction finders in Oklahoma during this time, establishing a network that would expand a few years later to seven sensors and become part of the NLDN. During the spring of 1981, the first modifications were made to DFs to allow the detection of positive ground flashes, which was promptly reported by Rust et al. (1981).

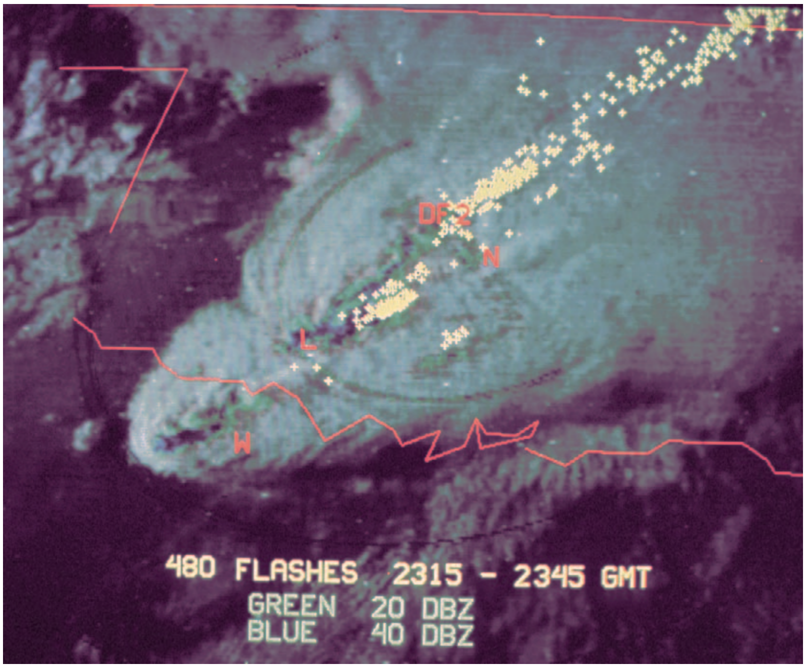

Fig. 1. Lightning ground flashes located by two direction finders during a 30-min period, superimposed on GOES cloud-top imagery for the 10 Apr 1979 storm over Oklahoma and north Texas. The two direction finders (N and DF2) formed a baseline perpendicular to the orientation of the tornadic storm, which produced the Wichita Falls tornado at W, southwest of Lawton (L). Green and blue shading depict regions having reflectivity of ≥20 and ≥40 dB*Z*, respectively, measured by a WSR-57 radar.

CCOPE (Montana field program, early NSF support, summer 1981). The early success in acquiring lightning data in the SESAME program led to the proposal and subsequent NSF funding of a four-DF lightning network in the 1981 summer Cooperative Convective Precipitation Experiment (CCOPE). Three DFs were deployed and a fourth from the Bureau of Land Management was integrated into a network to record lightning flashes to the ground in central Montana in the months of June and July. Approximately 67,000 ground flashes were recorded over these two months, and the locations were examined with respect to radar returns. No significant papers evolved from this field experiment, but lessons were learned that would enhance the installation of the DFs when they were moved from Montana to New York to begin the installation of a three-DF network in the spring of 1982.

State University of New York at Albany early installations. The first DFs in the northeast were installed at Little Falls, Cambridge, and Stuart Airport (all in New York) in the spring of 1982. A fourth DF was purchased and installed later in the year in Worcester, Massachusetts. In March 1982, the first lightning data were obtained at the State University of New York at Albany (SUNYA), and we observed a storm with predominately positive lightning. This reversal of polarity was unusual, and I accused my student at the time, Ron Henderson, of reversing the wires in the installation process. I was wrong. It was our first observation of a late-winter storm with mostly positive lightning.

In subsequent months, the network was extended with DFs at The Pennsylvania State University and Wilmington, Delaware. The National Aeronautic and Space Administration (NASA) added its own three-DF network to the configuration in 1983, extending our coverage to North Carolina. The direction

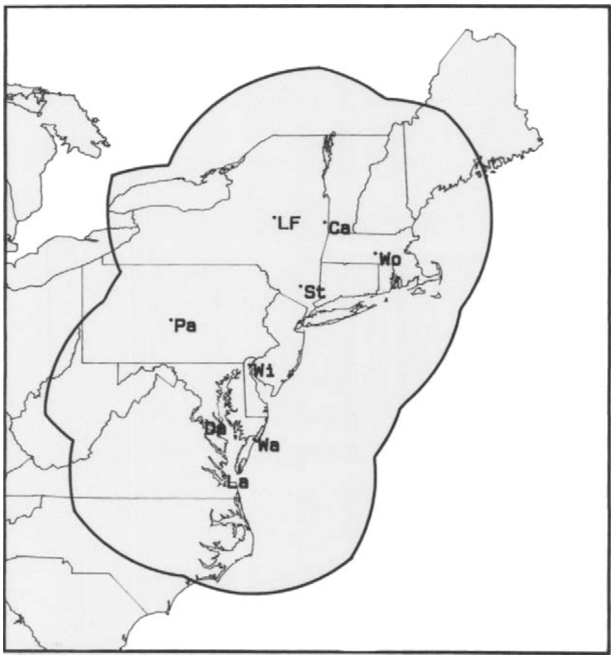

Fig. 2. The regional northeast lightning detection network was established in 1983 and was composed of nine direction finders funded by NSF and NASA. Nominal range of each sensor was 400 km, so the area within the dark line boundary is the region covered by two or more sensors.

finder installations represented a cooperative effort between SUNYA, funded by the National Science Foundation (NSF), and by NASA with installations located at Dahlgren, Wallops Island, and Langley, all in Virginia (Fig. 2). It was the early success of this extended network that led to the interest and support from the Electric Power Research Institute (EPRI) to develop a lightning network to serve the power industry. In June 1983, the EPRI support began and the network entered the expansion period that would not stop until the entire contiguous United States was covered.

EXPANSION PERIOD: 1983–87.

A major problem, however, hampered the expansion of the young lightning network. The Lightning Location and Protection (LLP), Inc., manufacturer of the DFs, delayed, postponed, and eventually refused to provide software for the operation of the expanding network. The LLP was intent on establishing multisensor DF networks, up to 10 sensors per network, throughout the United States that would ensure their continued income by requiring their servicing of the many networks. Putting the DFs together in one large network was never in the LLP plan.

Developing a large lightning network. From a scientific perspective, however, putting many DFs together in one network to cover a large area was the only way to obtain lightning information on storms whose coverage might extend to a thousand miles or more. Satellites monitored the propagation of storm systems across the United States, and we could do the same, we believed, with a network of direction finders. Our goal was to develop a network to provide lightning information over the continental United States. This was not easy. Software to process the DF information from 10 or more DFs did not exist. LLP did not wish to cooperative. So we began a software development program led by Rick Orville, Ron Henderson, and Rich Pyle and never looked back. The result was the THUNDER program that was used to display the lightning information on a personal computer, followed by programs to process the incoming DF information from many sensors that would provide the optimum location (Orville, Jr. 1987). All processing and displays were driven by IBM personal computers and were located in the operations room at SUNYA (Fig. 3).

I should say more about the THUNDER program. It was developed because in 1983 LLP, Inc. provided

Fig. 3. The network operations center was established in 1985 under the direction of Ron Henderson, shown in this photograph. Approximately 10 IBM PCs were used for data acquisition, processing, and display.

a hard-wired Remote Display Processor (RDP) over which the user had very limited control. We believed that a display system should provide the user with maximum control over the viewing options and use of the rapidly developing technology and easy availability and low cost of personal computers. The IBM PC was the answer. Rick Orville, Jr. wrote several display programs before completing THUNDER, a software display program based on the language FORTH. Note that Rick Orville, Jr. wrote his own FORTH compiler and completed THUNDER in the summer of 1985. THUNDER was the preferred display platform for many NLDN users and was marketed by the successor company to LLP, but it has now been supplanted by newer technologies.

Typical direction finder installation. The typical DF installation in the expansion period is shown in Fig. 4 (see title page). It consisted of a flat-plate electric field antenna on the roof of a trailer and a crossed-loop magnetic field antenna a few tens of meters away. The trailer housed the electronics and phone connection through which the data were transmitted via a landline to the operations center at SUNYA. Figure 5 shows the development of the network from 1984 to the end of 1988. Note that in 1985, the network had expanded along the East Coast and covered the area from Maine to Florida.

Early results. Early results from the expanding lightning detection network included a severe tornadic storm system on 31 May 1985 (Ferguson et al. 1987). This violent weather system struck Ohio and moved through western Pennsylvania, central New York, and Ontario, Canada. It was the worst tornado event in the written weather history of Pennsylvania. Eighty-eight people were killed in Ohio, Pennsylvania, and Canada. The tornadoes moved along 21 well-defined tracks in Ohio and Pennsylvania and another eight tracks in Canada and New York. In all, 71 tornadoes were reported. Total damage exceeded 200 million dollars. Significant amounts of cloud-to-ground lightning accompanied this storm. Figure 6 shows the total lightning distribution for 20 h beginning at 2000 UTC on 31 May and continuing until 1600 UTC on 1 June. Peak cloud-to-ground lightning flash rates exceeded 9,100 flashes per hour (fl h^{-1}), totaling over 60,000 flashes in the 20-h period. Ground flash densities from this storm exceeded 0.5 flashes per square kilometer (fl km^{-2}), or approximately 25% of the annual flash density for this region (Orville and Silver 1997).

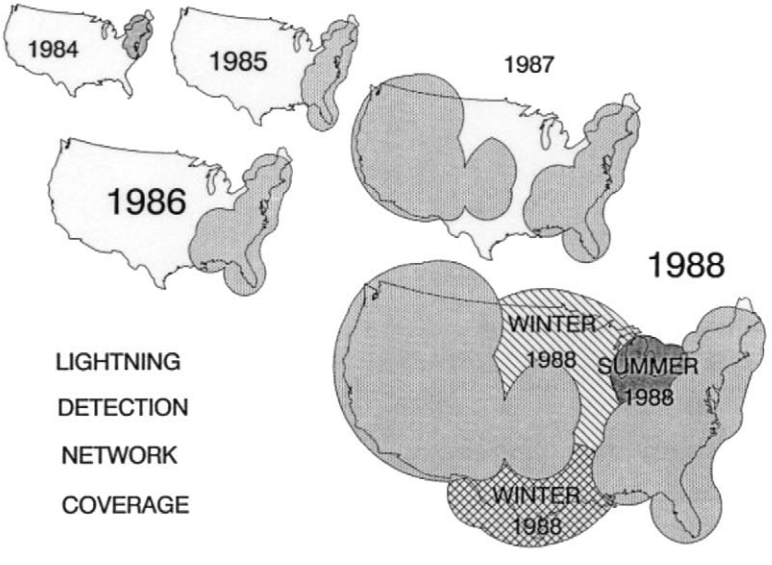

Fig. 5. The expanding coverage of the lightning detection network is shown from the beginning of 1984 to end of 1988. National lightning detection network data are available from Jan 1989 to today under the continuing operation by Vaisala, Inc.

Other significant lightning events occurred during the expansion of the lightning network along the East Coast. On 26 March 1987, a frontal system approached the NASA Kennedy Space Center, Florida, as an unmanned rocket was launched carrying an instrument package with a total value exceeding $190 million. Less than a minute into the flight the rocket was struck by or triggered a lightning flash causing the rocket to veer from the planned flight path (Christian et al. 1989). The rocket was destroyed. Figure 7 shows the cloud-to-ground lightning pattern at the time of the flash. Note that three hours of lightning data are coded in hourly values of red, green, and blue with the last flash plotted at 2123 UTC. The flash location of the lightning that struck the *Atlas Centaur* is shown at 2122:49 UTC.

FILLING IN 1987–89: "HOW CAN THE EXISTING NETWORKS BE COMBINED?"

By late 1986, we had made significant observations and established the feasibility of operating a large lightning detection network, but we still lacked the national coverage that the EPRI desired. At the January 1987 annual meeting of the American Meteorological Society in New Orleans, Louisiana,

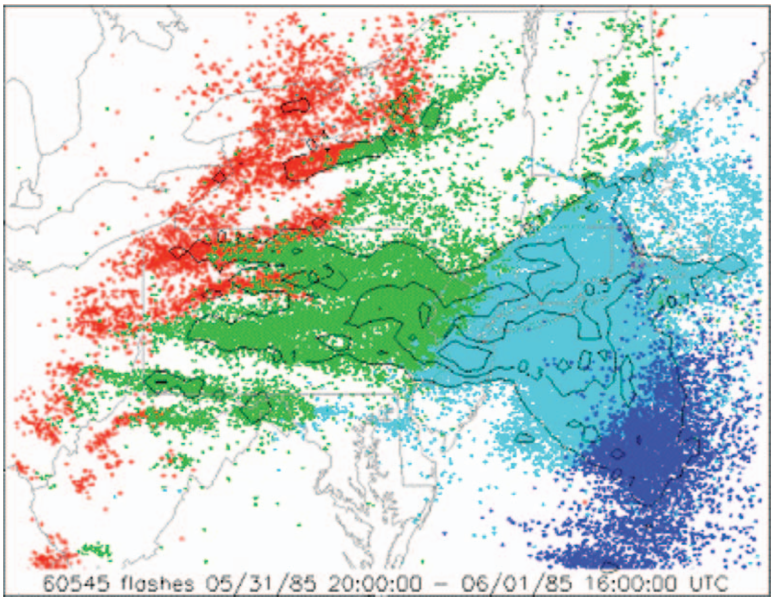

Fig. 6. On 31 May 1985, a severe tornadic storm swept through Pennsylvania and into the Atlantic Ocean. In a period of 20 h, over 60,000 flashes were recorded with a peak of 9,100 flashes in 1 h during the evening. Each color shows five hours of cloud-to-ground lightning with peak total flash densities exceeding 0.5 fl km^{-2}. The flash density is contoured at 0.1, 0.3, and 0.5 fl km^{-2}.

a chance meeting at the LLP commercial booth led to an agreement that would create the NLDN. In the presence of Ronald Henderson and Rick Orville from SUNYA and Ron Binford and Leon Byerly of LLP, Fred Mosher of the National Severe Storms Forecast Center asked if the western BLM network and the NSSL networks could be combined with the SUNYA network to cover the contiguous United States. The answer was “yes,” but we needed authorization. So we asked for and received permission for a 3-yr demonstration experiment from the Office of the Federal Coordinator for Meteorology (OFCM) in March 1987 to add the western region BLM lightning network and the NSSL network of the SUNYA network. (Unknown to us the OFCM had been watching the expanding EPRI network and was well aware of its potential, which explains their quick approval.) By July, just four months later, the joining of the three networks had been completed (Fig. 5; see 1987 map). This provided coverage of 75% of the continental United States. Only the areas in the upper Midwest and coastal areas of Texas and Gulf Coast needed coverage to complete what could become known as the “National Lightning Detection Network.”

Network communication. During the period of expansion, the cost of communication links increased dramatically as phone lines retrieved all data from the DF sites and two-way communication was maintained in real time. Relief from the increasing costs was only achieved by the development, under the direction of Rich Pyle, of satellite links to the remote DF sites. The satellite communication link brought data on the time, angle, multiplicity, polarity, and field strength to the operations center (Fig. 3). In the operations center, the data were processed and the solutions of the lightning location calculated. The results of the calculations, producing the location and time, were then transmitted via satellites to users, typically electric power companies that made up the membership of the EPRI.

Annual flash counts. As the area covered by the network increased as shown in Fig. 5, the recorded flash counts also increased. Figure 8 shows the monthly flash count from June 1983, the inception of the NLDN, to 1989, the first year of complete coverage. Patterns emerge that are consistent from year to year in spite of the growing and changing configuration of the network. Note that in all years there is a slow increase in the monthly flash rate from March–April to a maximum in July,

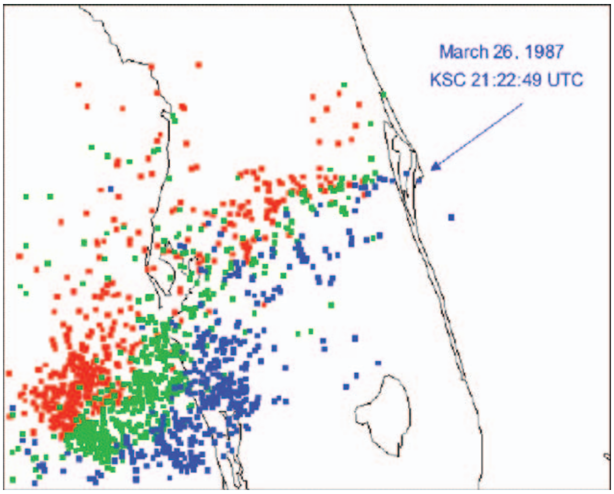

Fig. 7. Three hours (red, green, and blue) of cloud-to-ground lightning are plotted prior to the *Atlas Centaur-67* strike at 2122:49 UTC. Following this strike, the NASA Kennedy Space Center found the financial support to receive the ground strike data in real time.

followed by a relatively rapid decrease in recorded flashes to October. November through February are months characterized by few thunderstorms, but these storms can be significant and are of interest.

1989 AND BEYOND. At the end of 1989, the first full year of lightning data had been obtained from 100% coverage of the continental United States and the number of recorded flashes totaled 13.4 million (Orville 1991). See Fig. 9 for one day of lightning divided into 8-h segments of red, yellow, and green. Satellite communications had been established for sending information to and receiving data from the direction finders. The lightning information on location, polarity, multiplicity, and signal strength was sent to many tens of users.

Significant results included the detection of high flash densities along the Carolina coast (Orville 1990a; Orville et al. 2002), and an observation of a storm that produced a very large density of ground flashes, 0.5 fl km^{-2}, in northern New Jersey (Fig. 6), approximately equal to 25% of the average annual total at that location. Bipolar lightning patterns were identified in mesoscale storm systems (Orville et al. 1988). Rutledge and MacGorman (1988) documented the tendency for most of the ground flashes produced by the stratiform region of mesoscale convective systems (MCSs) to be positive flashes. Furthermore, Reap and MacGorman (1989) showed that positive flashes tend to be associated with severe storms, and this was followed by Curran and Rust (1992) and Branick and Doswell (1992), who reported on severe storms whose ground flash activity was dominated by positive flashes. Seasonal variations include the observation of a mean peak current increase in the first return stroke of approximately 25% from summer to winter and an increase of the percentage of positive flashes from 4% in the summer to 16% in the winter (Orville and Huffines 2001). We observed latitudinal variations of first-stroke peak currents of nearly a factor of 2 increasing from New York to Florida (Orville 1990b), and a similar latitudinal variation has been observed by more recent analysis of a decade of data (Orville and Huffines 2001). In addition, we reported an increase in the multiplicity of flashes as the latitude decreased from New York to Florida.

The NLDN has undergone a transition from the academic community to the commercial community and is now operated and maintained by Vaisala,

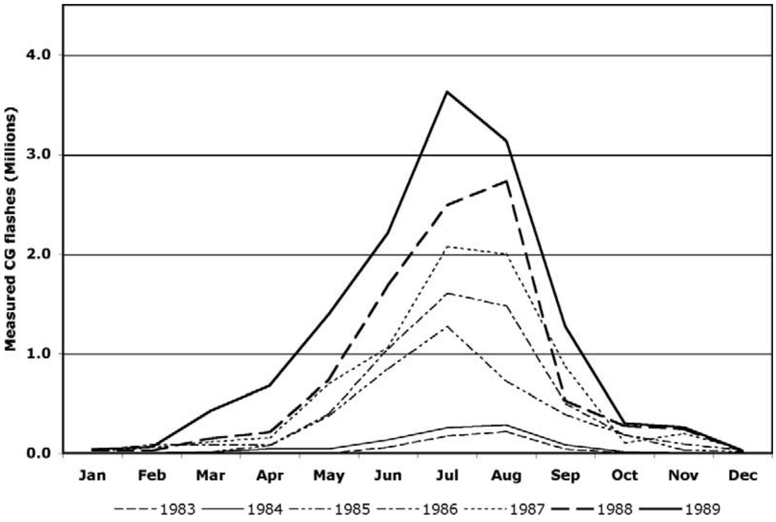

FIG. 8. Monthly distributions of the annual lightning through the development years are shown from 1983 to 1989.

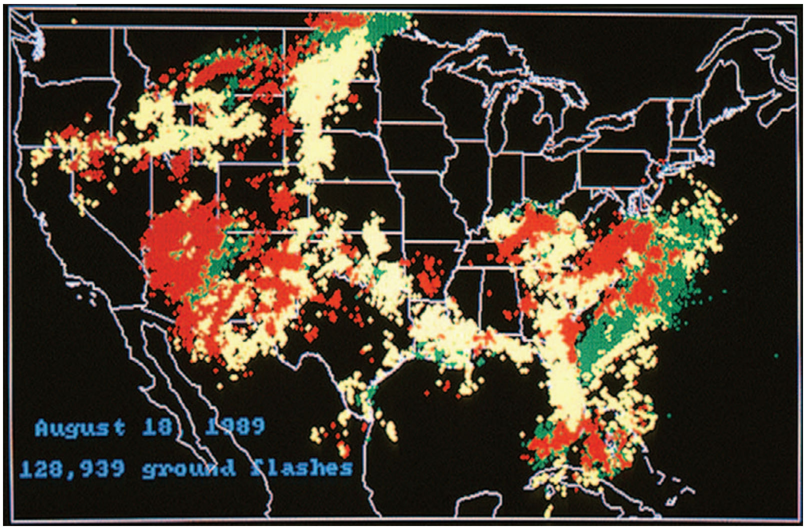

FIG. 9. Cloud-to-ground lightning flashes recorded for one summer day in 1989 in the United States from the National Lightning Detection Network. Each color, red, green, and yellow, in sequence, represents an 8-h segment of the day beginning at 0000 UTC. This was the first year of total coverage of the United States.

Inc. (formerly LLP, Inc.), in Tucson, Arizona. Since becoming a commercial facility in the 1990s, the NLDN has been completely redesigned twice, most recently in 2003–04 (Cummins et al. 2006). During this time, the IMPACT sensor was developed to combine the time of arrival (TOA) and direction finder technologies (Fig. 10). Coverage has been expanded into Canada, with pure time-of-arrival sensors at some installations and Improved Accuracy from Combined Technology (IMPACT) sensors at other installations, to form the current North American Lightning Network (NALDN; Fig. 11). A total of 187 sensors now provide continuous cloud-to-ground lightning detection throughout most of North America. Figure 12 is an average flash density for the first three years of the NALDN operation, 1998 through 2000 (Orville et al. 2002), based on the sensor distribution shown in Fig. 11.

Fig. 10. The IMPACT sensor was developed by a company successor to LLP in the 1990s and replaced the original sensors that required a trailer and tower (see Fig. 4) to hold the magnetic field crossed-loop antenna.

CONCLUSIONS. We have witnessed remarkable success brought about by the rare cooperation of government, the private sector, and the university sector over a period of several decades to bring about the largest continuously operating ground-based lightning network in the world. It is a demonstration that a few individuals with imagination and ingenuity can overcome obstacles and succeed with the support of a research administration, for example, EPRI in this case, that understands the importance of freedom and cooperation in the pursuit of an unselfish goal.

It is not too much to suggest that the establishment of the NLDN has laid the groundwork and demonstrated the need for a satellite capability that will be realized in the near future. The Geostationary Operational Environmental Satellites (GOES) R series spacecraft program is now planning a GEO Lightning Mapper capable of continuously mapping lightning flashes during both day and night from a geostationary orbit. Scheduled for launch in 2014, this satellite will be capable of detecting all forms of lightning with a high detection efficiency. The sensor will measure the total lightning activity over the United States and adjacent areas and provide a more complete dataset than previously possible. Specific objectives will include 1) measuring total lightning over a large area of the Americas, 2) developing a total lightning climatology for global change research, and 3) delivering, on a real-time basis, measurements that are of sufficient quality and quantity for operational storm monitoring and severe weather warnings. We will see total lightning data, in near–real time, related to other observable data, such as radar returns, cloud images, and other meteorological variables. Since these data will be distributed in real time, it will become an invaluable tool to aid weather forecasters in detecting severe storms in time to give advance warning to the public.

ACKNOWLEDGMENTS. Many colleagues made the development of the NLDN a reality; I will attempt

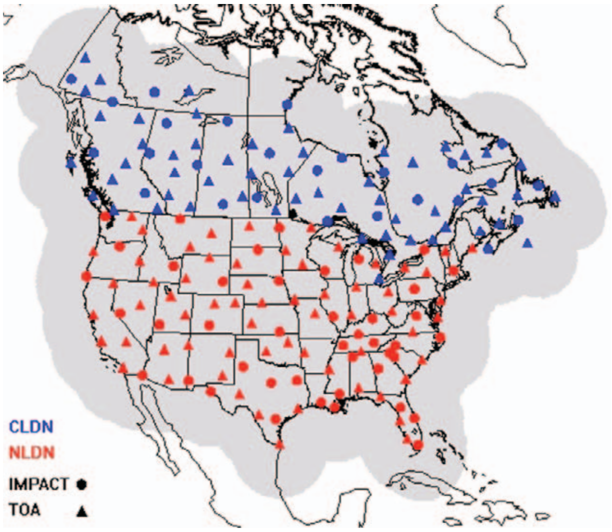

Fig. 11. The total area covered by the NALDN is shown in light gray. The blue symbols represent the Canadian Lightning Detection Network (CLDN), composed of 81 sensors, and the red symbols represent the NLDN, composed of 106 sensors. Each network is composed of IMPACT sensors and TOA sensors. Triangles mark the TOA sensor locations and circles mark the IMPACT sensor locations.

an incomplete list here. Ronald Henderson was involved in all phases of the development from day one; Richard Pyle developed software and was the first to see the potential of satellite communications to retrieve data in real time and he made it happen; the late Rick Orville's genius led to the development of software programs to make the NLDN a reality. Ron Henderson kept Rick's lightning display program, THUNDER, developed in 1985, up to date until recently. Martin Uman and E. Philip Krider provided insight and support throughout the development of the NLDN. The late Ron Taylor, NSF program manager, took a chance on the developing technology in 1981 and provided initial support, joined soon after by the willingness of James Dodge, NASA program manager, to expand the NASA network in 1982. Herbert Songster, followed by James Mitsche, EPRI program managers, initiated support in 1983, and it was their unbridled enthusiasm to support young researchers along an untested path that led to the development of the NLDN. Fred Mosher asked two critical questions, first, in 1979 that led to the first overlays of satellite, radar, and lightning data and second, in 1987 that led to the joining of the three existing regional networks, BLM, NSSL, and SUNYA, to form the NLDN. Michael Maier unselfishly provided his lightning data from the 10 April 1979 tornadic storm to allow the first lightning–satellite–radar overlays. Lance Bosart was among the first to see the meteorological potential of the lightning ground strike data and identified the bipolar pattern in a 1986 summer storm. Keith Orville provided insight into the eigenvalue solution to lightning analyses and assisted in early research. Walter Lyons and Rodney Bent provided friendly and inspired competition with the development of their commercial LDN for 15 months in the 1989–90 period. Pat Zumbusch and Ken Cummins provided management and engineering support through the commercialization of the NLDN in the 1990s and the transfer of the network operation to the Tucson, Arizona, office. Don MacGorman provided extensive comments through the review process and has significantly improved the resulting manuscript in addition to comments from two anonymous reviewers. Grants and contracts, too many to enumerate, from the EPRI, NSF, NASA, NOAA, and the NWS provided for the installation and support of the network, now owned and operated by Vaisala, Inc.

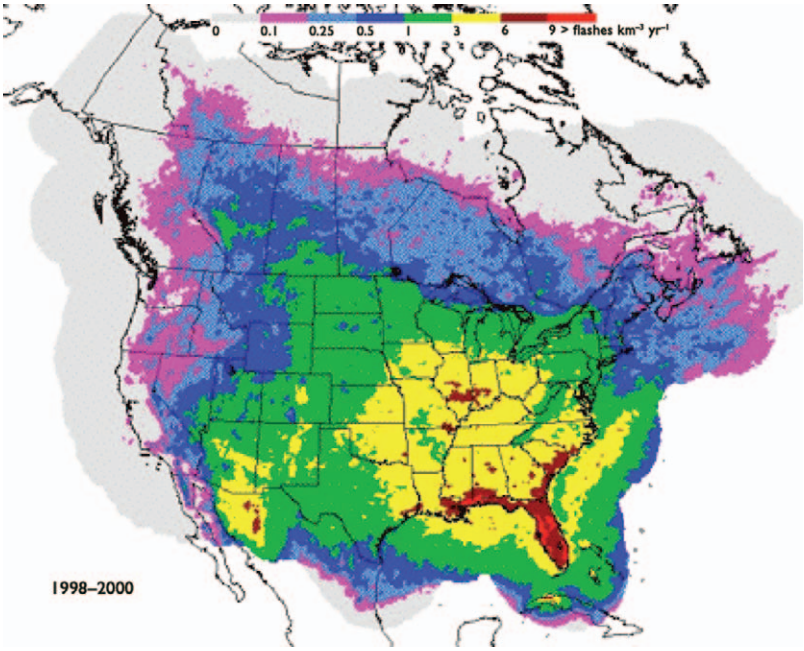

Fig. 12. The mean flash density for North America ranges from less than 0.1 (light gray) to greater than 9 fl km^{-2} (red) in Florida and along the Gulf Coast.

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