The Los Alamos Sferic Array: A research tool for lightning investigations

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[1] Since 1998 the Los Alamos Sferic Array (LASA) has recorded electric field change signals from lightning in support of radio frequency (RF) and optical observations by the Fast On-orbit Recording of Transient Events (FORTE) satellite. By “sferic” (a colloquial abbreviation for “atmospheric”), we refer to a remote measurement of the transient electric field produced by a lightning flash. LASA consisted of five stations in New Mexico in 1998 and was expanded to 11 stations in New Mexico, Texas, Florida, and Nebraska in 1999. During the 2 years of operation described in this paper, the remote stations acquired triggered 8- or 16-ms duration, 12-bit waveforms and GPS-based sferic time tags 24 hours per day year-round. Source locations were determined daily using differential time of arrival techniques, and the waveforms from all geolocated events were transferred to Los Alamos National Laboratory (LANL), where they have been archived for further analysis, including event classification and characterization. We evaluated LASA location accuracy by comparing temporally coincident (occurring within 100 μs) LASA and National Lightning Detection Network (NLDN) event locations. Approximately one half of the locations agreed to within 2 km, with better agreement for events that occurred within the confines of LASA subarrays in New Mexico and Florida. Of the ~900,000 events located by the sferic array in 1998 and 1999, nearly 13,000 produced distinctive narrow bipolar field change pulses resembling those previously identified as intracloud discharges. INDEX TERMS: 3324 Meteorology and Atmospheric Dynamics: Lightning; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 6934 Radio Science: Ionospheric propagation (2487); 6904 Radio Science: Atmospheric propagation; KEYWORDS: lightning, RF, sferic array, FORTE

1. Introduction

[2] The Los Alamos Sferic Array (LASA) was developed to perform lightning research in support of the Fast On-orbit Recording of Transient Events (FORTE) satellite. The purpose of FORTE, which was launched into a 69° inclination, 800-km orbit in August of 1997, has been to study transient VHF radio and optical emissions from the Earth for the purpose of nuclear weapon monitoring research. FORTE’s primary research payloads include two 22-MHz bandwidth RF receivers, one 85-MHz bandwidth RF receiver, a broadband optical CCD imager, and a narrowly filtered optical photodiode detector. These instruments regularly record the radio and optical emissions from terrestrial lightning discharges. FORTE RF payloads and observations have previously been described by Massey et al. [1998a], Jacobson et al. [1999, 2000], and Susczynsky et al. [2000]. Optical payloads, observations, and modeling have been described by Kirkland et al. [1998], Susczynsky et al. [1999], Light et al. [2001], and Susczynsky et al. [2000, 2001].

[3] A significant fraction of the FORTE science effort has focused on merging FORTE RF and optical observations with those from other satellite- and ground-based resources. This data fusion has enhanced the value of FORTE observations in at least three respects: (1) Sensors with the ability to accurately geolocate sources have provided locations for events that FORTE has recorded but been unable to locate (FORTE’s limited geolocation capabilities have been described by Jacobson et al. [1999], Susczynsky et al. [2001], Jacobson and Shao [2000], and Shao and Jacobson [2001]); (2) multiple characterizations of the same stroke, flash, or storm using different sensor types have provided insight into thunderstorm electrification and discharge processes that no single sensor has been able to provide; and (3) sensors capable of continuously observing storms have provided a context for FORTE data collection, which is limited to the observation of a single location on the ground for only 15 min (at most) per 100-min orbit, with no guarantee of observing the same location on the subsequent orbit.
[4] An example of a resource that has been used to supplement FORTE data analysis is the National Lightning Detection Network (NLDN) [Cummins et al., 1998a], which has played a role in the processing of FORTE data acquired over the contiguous United States (CONUS). The NLDN provided locations, event identifications, and peak current estimates for nearly 15,000 FORTE-coincident events in 1998 [Jacobson et al., 2000] and over 10,000 in 1999 (A. R. Jacobson, private communication, 2000). Other resources that have been utilized for FORTE comparative analyses include the Kennedy Space Center (KSC) Lightning Detection and Ranging (LDAR) system [Lennon and Maier, 1991], New Mexico Tech Lightning Mapping Array (LMA) [Rison et al., 1999b], optical imagers on board the NASA MicroLab-1 and Tropical Rain Forest Measuring Mission (TRMM) satellites, the Brazilian Lightning Detection Network (BLDN) [Pinto et al., 1999], space-based visible and IR imagers (e.g., GOES), and the Next Generation Weather Radar (NEXRAD) surveillance network.

[5] The Los Alamos Sferic Array was developed as a resource for locating, classifying, and characterizing lightning discharges in support of FORTE. One advantage of operating our own ground-based array has been our ability to tailor operations for coordination with FORTE in order to maximize the likelihood of making coincident observations. A second advantage has been our ability to retain all waveform data from all located events to permit detailed reanalysis of data. This brute-force approach to data archiving has allowed us to evolve and optimize our processing techniques and to apply them back to a large collection of ground-based sferic and satellite-based RF waveforms. As we have advanced our understanding of the lightning data and developed new questions, the ability to reprocess these waveform data has been of greater value than if we had retained only waveform parameters.

[6] Conceptually, LASA is an expansion of the three-station array utilized by Smith et al. [1999a] [see also Smith, 1998] to make observations of compact intracloud discharges (CIDs) and other lightning electrical discharges in New Mexico and west Texas during the summer of 1996. The success of both the previous array and the current array have been made possible by the marriage of a well-established sensor technology, the electric field change meter [Krehbiel et al., 1979], with the modern-day capability to derive accurate, absolute time tags at multiple, distant locations using GPS (Global Positioning System) receivers. The Los Alamos National Laboratory (LANL) sferic array has additionally made extensive use of the Internet to cost-effectively manage multiple, unattended sensors and to retrieve hundreds to thousands of megabytes of waveform data on a daily basis.

[7] The purpose of this paper is three-fold: (1) to describe the implementation and operation of the Los Alamos Sferic Array during its first two years in service; (2) to present an evaluation of its geolocation accuracy through comparison with the NLDN; and (3) to introduce initial results on the topic of automatic classification of narrow bipolar pulses (NBPs) in the LASA database. By NBPs we refer to the distinct class of electric field change waveforms described by Le Vine [1980], Willett et al. [1989], and Smith et al. [1999a] that are accompanied by very powerful HF and VHF radiation and that have been associated with CIDs [Smith, 1998].

2. Instrumentation

2.1. Array Overview

[8] We began operation of the Los Alamos Sferic Array with five stations (only four of which were independently located) in New Mexico in 1998. The stations were located in Los Alamos (two stations), Socorro, Roswell, and Tucumcari. In 1999 the array was expanded to 11 stations (all independently located), with four stations in New Mexico (in the previously mentioned locations); one in Omaha, Nebraska; one in Lubbock, Texas; and five in Florida in the following locations: Kennedy Space Center, Tampa, Fort Myers, Boca Raton, and Gainesville. Table 1 lists the field change station locations, the two-letter station identifiers used throughout this paper, the host facilities, and the starting dates of operation. Figure 1 is a map of the 1998 and 1999 LASA station locations.

[9] As shown in Figure 1, the 1998 array stations (represented as squares) approximately formed a square with ~200 km separating the stations along the perimeter. The configuration was excellent for lightning studies in and near the state of New Mexico.

[10] The 1999 array consisted of two five-sensor station clusters, one in New Mexico/Texas (referred to as the NM subarray) and one in Florida (the FL subarray), with one additional, outlying station in Nebraska (NE) for a total of

Table 1. Los Alamos Sferic Array Stations, Locations, and Dates of Operation

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Initial Date of Operation</th>
<th>Location</th>
<th>Host Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA</td>
<td>Apr. 6, 1998</td>
<td>Los Alamos, NM</td>
<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>SO</td>
<td>May 1, 1998</td>
<td>Socorro, NM</td>
<td>New Mexico Tech</td>
</tr>
<tr>
<td>RO</td>
<td>May 12, 1998</td>
<td>Roswell, NM</td>
<td>Eastern New Mexico University</td>
</tr>
<tr>
<td>TU</td>
<td>May 27, 1998</td>
<td>Tucumcari, NM</td>
<td>Mesa Technical College</td>
</tr>
<tr>
<td>LO</td>
<td>July 1, 1998</td>
<td>Los Alamos, NM</td>
<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>CR</td>
<td>Feb. 9, 1999</td>
<td>Omaha, NE</td>
<td>Creighton University</td>
</tr>
<tr>
<td>KC</td>
<td>April 5, 1999</td>
<td>Cape Canaveral, FL</td>
<td>Kennedy Space Center</td>
</tr>
<tr>
<td>TA</td>
<td>April 6, 1999</td>
<td>Tampa, FL</td>
<td>University of South Florida</td>
</tr>
<tr>
<td>FM</td>
<td>April 8, 1999</td>
<td>Fort Myers, FL</td>
<td>Cyberstreet ISP</td>
</tr>
<tr>
<td>BR</td>
<td>April 8, 1999</td>
<td>Boca Raton, FL</td>
<td>Florida Atlantic University</td>
</tr>
<tr>
<td>GV</td>
<td>April 9, 1999</td>
<td>Gainesville, FL</td>
<td>University of Florida</td>
</tr>
<tr>
<td>LB</td>
<td>April 27, 1999</td>
<td>Lubbock, TX</td>
<td>Texas Tech University</td>
</tr>
</tbody>
</table>

a LO station was second of two in Los Alamos during 1998. It was decommissioned on August 11, 1998.
11 stations. The baselines for the NM and FL subarrays were between 160 and 240 km. Utilizing the two subarrays plus the additional station in NE, we were able to perform high-sensitivity, high-location-accuracy studies within and near each subarray and were simultaneously able to detect and locate (with less accuracy) large-amplitude events that occurred over a large portion of the southern and central United States.

[11] Except where footnoted in Table 1 and during temporary computer or network outages, LASA stations were operated 24 hours per day from their starting dates through the end of 1999 (and beyond, but this paper addresses only the 1998/1999 data).

[12] The primary goals for 1998 were to support FORTE and to gain experience in the remote operation of an array by establishing field change stations close to Los Alamos. The nearby locations simplified the deployment and servicing of the stations and also allowed us to make comparative observations with the New Mexico Tech LMA, which was operated in the vicinity of Socorro during the latter part of the 1998 thunderstorm season (and also in 1999). Rison et al. [1999a, 1999b] have described joint LASA/LMA observations of NBPs that were made during this campaign.

[13] The expansion to Florida in 1999 was motivated by the following factors: (1) The Florida peninsula features the highest flash density in the United States [Cummings et al., 1998b]; (2) the location provided us with the opportunity to make thunderstorm observations in a maritime environment; (3) for operational reasons related to the locations of the FORTE ground stations (in Albuquerque, New Mexico, and Fairbanks, Alaska), the FORTE satellite was capable of spending more time acquiring data over Florida than over New Mexico, increasing the likelihood of achieving LASA/FORTE coincidental detections; and (4) the LDAR system at KSC, which produces accurate, highly resolved, three-dimensional (3-D) maps of lightning RF sources within ~100 km of Cape Canaveral [Boccippio et al., 2001], is located on the perimeter of the Florida sferic subarray and is available for joint lightning studies.

[14] The Nebraska station was installed and made operational in 1998, but was not incorporated into daily LASA processing until 1999. It was originally deployed to support sprite research in the Great Plains region of the United States, but has since proven to be useful for long-range studies of lightning discharges in general.

2.2. Station Description

[15] The requirements for LASA site locations include a relatively quiet noise environment at VLF/LF radio frequencies, access to AC power and a high-speed Internet connection in close proximity to an outdoor rooftop location, and the existence of a cooperative host institution and/or individual. Of these, the requirement for an Internet connection generally presented the most serious restriction on potential sites.

[16] Figure 2 is a block diagram of a LASA electric field change installation. All stations were identical in configuration except for the low-pass and high-pass signal filters, which were added in 1999 and were not the same for all stations. Figure 3 is a photograph of the array station at the University of Florida in Gainesville. The “inverted salad bowl” or “hairdryer” design was adapted from a design by M. Brook of New Mexico Tech and was previously described by Smith et al. [1999a]. The stainless steel dome
suspended from the "neck" of the field change meter in Figure 3 shields a 38-cm-diameter sensing plate from precipitation. Without the dome the sensor would be susceptible to spurious signals produced by the impact of charged raindrops on the sensing plate. A charge amplification circuit inside the dome was fed from the sensing plate and configured with a 1-ms decay time constant. A 50-Ω line driver sent the field change output signal through 30 m (typically) of coaxial cable to the interior of the building. Rising from the neck of the field change meter in Figure 3 is the GPS antenna/receiver for the station. It interfaces with the computer inside the building to provide absolute (UTC) event time tagging with a maximum error of 2 μs.

As mentioned earlier, the low-pass and high-pass signal filters were added in 1999. The low-pass filters had a cutoff frequency of 500 kHz and were inserted to prevent aliasing by the 1-megahertz waveform digitizer. We had previously concluded that the antialiasing filters were not necessary due to a roll-off in the field change meter frequency response above the Nyquist sampling frequency. However, at two of the stations the roll-offs were not steep enough to prevent transmissions from powerful local AM radio stations (with center frequencies near 1 MHz) from aliasing into the digitized sferic waveforms. The low-pass filters greatly reduced the interference problem. The single-pole high-pass filters were added in 1999 to eliminate DC offsets in the outputs at some of the Florida stations (possibly caused by leakage current due to high humidity) and also to mitigate a 60-Hz noise problem at the Fort Myers station. The 3-dB cutoff frequencies at all stations except Fort Myers (FM) were 34 Hz. The FM cutoff was 340 Hz. The difference has been noticeable in waveforms or waveform segments dominated by low-frequency signal components, which are more severely attenuated in the FM data. Note that the external high-pass filters act in addition to the ~1-kHz high-pass effect resulting from the 1-ms decay time constant of the field change meter electronics.

The filtered field change signal (refer again to Figure 2) was split between a 12-bit analog-to-digital converter (A/D) card in the computer and an external trigger module, which was used to implement trigger criteria. The trigger module accepted positive and negative DC thresholds from a digital-to-analog converter (D/A) card in the computer. The two thresholds were separately and remotely adjustable and were used to define the thresholds at which the bipolar trigger circuit would trigger data acquisition. During 1998 the thresholds were adjusted infrequently and simply set to levels that produced comfortable trigger rates. During 1999, a "campaign mode" of operation was implemented to maximize the likelihood of making coincident observations of FORTE-detected events and also to study long-distance sferic propagation. In campaign mode, monthly schedules of threshold changes were sent to the remote stations where resident scheduling programs raised and lowered station thresholds in conjunction with FORTE passes and at other regular time intervals when increased sensitivities were desired. Typical thresholds during campaign mode and noncampaign mode were ±1.5 V/m and ±6 V/m, respectively. Campaign mode increased the likelihood of a given array event being detected by FORTE by a factor of 4 from 0.074% in 1998 to 0.30% in 1999. The total number of FORTE/LASA coincidences for 1998 and 1999 was 2422, where we have defined a coincidence as an event time agreement within ±300 μs after correction for the propagation delay to FORTE.

Figure 2. Block diagram of a Los Alamos Sferic Array station.

Figure 3. Photograph of the sferic array station at the University of Florida in Gainesville.
found to be a function of the fullness of the data directory at
ranged from 30 to over 100 ms, depending on the time
to-ground (CG) lightning stroke signatures. The dead time
features in waveforms immediately following positive cloud-
LO station configuration was to search for sprite signa-
records with 25% pretrigger. The motivation behind the
and 25%, respectively. The LO station was operated in
fractions for non-LO stations in 1998 and 1999 were 50%
1 megasample/s during 1998 and 1999. The pretrigger
station, all stations acquired 8-ms waveforms sampled at
for each detected event. With the exception of the LO
station, all stations acquired 8-ms waveforms sampled at
1 megasample/s during 1998 and 1999. The pretrigger
fractions for non-LO stations in 1998 and 1999 were 50%
and 25%, respectively. The LO station was operated in
1998 only and acquired 1 megasample/s, 16-ms duration
records with 25% pretrigger. The motivation behind the
LO station configuration was to search for sprite signa-
tures in waveforms immediately following positive cloud-
to-ground (CG) lightning stroke signatures. The dead time
between triggers for the individual stations during 1998
ranged from 30 to over 100 ms, depending on the time
required to write each waveform to disk. This time was
found to be a function of the fullness of the data directory at
each station. In 1999, file handling improvements reduced
the dead time between triggers, so that the retriger time
was consistently <40 ms. Reducing the dead time
increased the likelihood of detecting subsequent CG return
strokes.

Each time a trigger was received by a remote station
the corresponding sferic waveform was written to a data file
and the UTC time tag (from the GPS receiver) was written
to a separate header file, which was used to log daily station
time tags. Data acquisition proceeded in this fashion until
the UTC day rollover, when data acquisition was automati-
cally stopped and restarted to allow transfer and processing
of the previous day’s data.

A trigger rate limiter was implemented in software at
each remote station to prevent the hard drive from filling up
in the event of an extremely high trigger rate resulting from
a close lightning storm or the appearance of a new or
intermittent noise source. During times when the rate limiter
was activated (typically corresponding to a trigger rate of
>10 events per second for at least 10 s), waveform acquis-
tion halted but time tag acquisition continued.

During 1998 and 1999 the field change hardware,
computers, operating systems, and software functioned
reliably. In part because of this reliability and in part
because of the cooperation of our colleagues at the remote
sites, it was not necessary for LANL personnel to visit the
stations at any time for troubleshooting following the
establishment of initial station operating capability.

2.3. Array Processing

Like the remote stations, the LANL array-process-
ing computer (APC) operated automatically (without oper-
ator intervention) on a daily cycle. The first task following
the UT day rollover was to transfer (via the Internet) the
previous day’s header files from the remote stations to
LANL, where temporal coincidences involving a minimum
of three stations were identified (three stations are required
to make a 2-D source location determination). The width
of the coincidence time window was determined by the
time required for a radio signal to transit (at the speed of
light) the longest chord of the array, since this time
represents the largest possible differential time of arrival
(DTOA) for a real event. A slightly longer window was
implemented in practice to allow for the possibility that
stations trigger on the same event, but not on the same
waveform feature. In 1998 the window was 2 ms, corre-
sponding to the delay between the RO and LA stations.
In 1999 the window for the complete 11-station array was
10 ms, corresponding to the delay between the BR and LA
stations.

Having identified the temporal coincidences between
array stations, the APC directed the remote computers to
compress the coincident waveforms for subsequent retrieval
and decompression. Following the retrieval of all data from
all stations for the day, waveforms were cross-correlated to
determine timing corrections between the events recorded
by different stations. In addition to making fine timing
corrections, this step was used to reject (on the basis of
poor cross-correlation coefficients) waveforms suspected to
originate from different sources, i.e., noise recorded by a
single sensor or independent, nearly simultaneous (occur-
ing within milliseconds of each other) lightning flashes.

![Figure 4. Plot of the trigger rate as a function of time (mountain daylight time) for the Los Alamos array station during 3 days of activity during the summer of 1999. Spikes in the trigger rate are indicative of lowered station thresholds in association with campaign mode.](image-url)
Figure 5 shows multiple waveforms recorded from a single positive CG flash that occurred in the Texas Panhandle on May 16, 1999 (the location is indicated by a numeral “1” in Figure 1). The waveforms were recorded by the LB, TU, RO, and SO stations from ranges of 101, 291, 344, and 554 km, respectively. The waveforms are presented in order from nearest to farthest distance between the sensor and event, as are all waveforms in this paper. The flash was characterized by NLDN as a positive CG with a peak current of 94 kA. The physics polarity convention (indicating current flow from overhead to below) is used throughout this paper. Note that the SO (Figure 5, bottom) waveform features an early/fast negative excursion at the expected single-hop ionospheric delay time (68 μs) given the source range (554 km) and an assumed ionospheric virtual reflection height of 70 km (typical for the late afternoon).

Cross correlations were not performed on the entire 8- or 16-ms sferic waveforms. This was found to be burdensome with regard to computational intensity and also resulted in an occasional missed correlation due to ionospheric reflections or noise. Because most sferic waveforms have a single, prominent feature that lasts less than 1 ms, correlations were performed on 512-point (512 μs) windows centered on the peak absolute waveform amplitudes.

The computed cross-correlation coefficients for the waveforms in Figure 5 were 0.95 (1 and 2), 1.00 (2 and 2),...
As indicated by the unity coefficient for the second waveform, the cross correlations were all performed with respect to the second waveform in time order of arrival. This has been the standard convention for LASA waveform correlation because it guarantees that the template waveform is dominated by the radiation component of the electric field and not by the intermediate or static components, which can seriously affect the field change waveshape within several tens of kilometers of a recording station.

Figure 6 shows waveforms recorded from a negative CG lightning return stroke that occurred 25 km southwest of Los Alamos (the location is indicated by a numeral “2” in Figure 1). The first waveform features an obvious static field component. The NLDN characterized the stroke as a negative CG with a peak current of 54 kA.

Figure 6. Electric field change waveforms from a negative CG lightning return stroke that occurred 24 km southwest of Los Alamos (the location is indicated by a numeral “2” in Figure 1). The first waveform features an obvious static field component. The NLDN characterized the stroke as a negative CG with a peak current of 54 kA.

0.97 (3 and 2), and 0.85 (4 and 2). As indicated by the unity coefficient for the second waveform, the cross correlations were all performed with respect to the second waveform in time order of arrival. This has been the standard convention for LASA waveform correlation because it guarantees that the template waveform is dominated by the radiation component of the electric field and not by the intermediate or static components, which can seriously affect the field change waveshape within several tens of kilometers of a recording station.

Figure 6 shows waveforms recorded from a negative CG (54 kA peak current as reported by the NLDN) that occurred 25 km southwest of Los Alamos on August 11, 1999, and was recorded by the LA, TU, and LB stations (the event location is indicated by a “2” in Figure 1). The Los Alamos (Figure 6, top) waveform features a large negative shift near time zero that decays to zero over a period of several milliseconds. The shift is from the static component of the electric field, which is superimposed on the radiation and induction field components. The exponential decay following the stroke is a characteristic of the field change meter electronics that allows subsequent strokes or flashes to utilize the same instrumental dynamic range by returning the trace to zero within a few milliseconds. By always performing the cross correlations with respect to the second waveform (except for 1998 events when the first two stations were the colocated LA and LO sensors, in which case we used the third waveform as the template), the
The location solution is determined using a multidimensional downhill simplex method \cite{Nelder1965} called Amoeba \cite{Press1986}. A similar sferic location method has been described and employed by Lee \cite{1989}. Prior to applying the location algorithm the software verifies that the interstation DTOAs are physically possible, i.e., less than the interstation speed-of-light propagation times. Stations with times that do not meet this criterion are rejected from the solution determination. Additionally, three-station events that include both LA and LO (the colocated sensors) are rejected from the database because there exists only one independent DTOA for these cases.

Following waveform cross correlation the events are located by the APC using the correlation-adjusted DTOAs. The location solution is determined using a multidimensional downhill simplex method \cite{Nelder1965} called Amoeba \cite{Press1986}. A similar sferic location method has been described and employed by Lee \cite{1989}. Prior to applying the location algorithm the software verifies that the interstation DTOAs are physically possible, i.e., less than the interstation speed-of-light propagation times. Stations with times that do not meet this criterion are rejected from the solution determination. Additionally, three-station events that include both LA and LO (the colocated sensors) are rejected from the database because there exists only one independent DTOA for these cases.

As stated earlier, correlation coefficients have been used to eliminate poor waveform matches. The minimum coefficient we accept for first waveform (in time order of arrival, cross-correlated with respect to the second waveform) is 0.20. The minimum we accept for third, fourth, etc., waveforms is 0.55. Waveforms with a significant static component are often rejected for their poor correlation coefficients. When a waveform is rejected and the total number of contributing stations is equal to three, only two waveforms remain after the rejection of the dissimilar waveform, so the event is rejected because three stations are required to locate an event. A final interesting note on Figure 6 is that both static and radiation (and/or intermediate) field terms are observable in the approaching leader prior to the attachment near time zero.

As stated earlier, correlation coefficients have been used to eliminate poor waveform matches. The minimum coefficient we accept for first waveform (in time order of arrival, cross-correlated with respect to the second waveform) is 0.20. The minimum we accept for third, fourth, etc., waveforms is 0.55. Waveforms with a significant static component are often rejected for their poor correlation coefficients. When a waveform is rejected and the total number of contributing stations is greater than three, the dissimilar waveform is discarded and the location solution is derived from the remaining stations. When the number of contributing stations is equal to three, only two waveforms remain after the rejection of the dissimilar waveform, so the event is rejected because three stations are required to locate an event. A final interesting note on Figure 6 is that both static and radiation (and/or intermediate) field terms are observable in the approaching leader prior to the attachment near time zero.
the offshore storms. Daily maps similar to those pictured in Figures 7 and 8 were generated automatically and made available via the Internet to assist in array state-of-health monitoring.

3. Array Geolocation Accuracy

3.1. Geolocation Data Analysis

[34] Time-of-arrival lightning location systems, using both low-frequency and high-frequency radio receivers, have been described and utilized by many researchers, including Proctor [1971], Lennon and Maier [1991], Cummins et al. [1998a], Smith et al. [1999a], and Rison et al. [1999b]. Limits on the location accuracy and precision of such systems depend on the quality of the timing source or sources used to time tag events at each station, the ability to correlate waveforms received by multiple stations, and the source viewing geometry.

[35] To evaluate the location accuracy of the sferic array, we compared LASA event locations to lightning locations determined by the NLDN during 6 months (April–September) in 1998 and 6 months (May–October) in 1999. The NLDN has been described in detail by Cummins et al. [1998a, 1998b]. NLDN data products include real time and archival (since 1989) times, locations, and current estimates for lightning return strokes. The network is an operational system that provides uniform coverage of CONUS with a high level of quality control. In contrast, LASA was conceived of as a research system to provide regional acquisition of waveforms for lightning (CG and intracloud) detection, location, and characterization, primarily in support of FORTE. LASA data are neither temporally nor spatially uniform, so statistical studies are difficult to perform. The array is more useful for single event or storm studies.

[36] The NLDN data sets used for the comparisons in this paper were not standard NLDN data products, but were reprocessed from raw data using relaxed event criteria in order to maximize the detection of both intracloud discharges and distant/weak CG discharges [Jacobson et al., 2000]. The standard NLDN data provide 80–90% detection efficiency of first CG strokes with currents of >5 kA within CONUS. These events are located with a median accuracy of 500 m [Cummins et al., 1998a]. The “loosened criteria” data used for comparison in this paper may not meet these quality-control criteria; their uncertainty has not been characterized.

[37] We began the comparison by identifying temporally coincident events in the LASA and NLDN data sets, the purpose being to select probably coincidences based on closeness in time and then to utilize those events for the location comparison. Figure 9 shows a histogram of all 1998/1999 LASA/NLDN time differences over a span of ±500 μs with a bin size of 5 μs. A significant peak is evident near zero lag, and the noise floor (indicative of random coincidences) is very low (indistinguishable from zero in Figure 9). The total number of events within ±500 μs is 566,946. The peak occurs at +2 μs, has a half-width of 7 μs (these numbers were determined separately with finer binning), and is slightly asymmetric with a bulge on the right side. The offset and asymmetry (indicative of LASA events that occurred a few to hundreds of microseconds after their corresponding NLDN events) are attributable to multiple factors. The first factor is that the NLDN utilizes a waveform extrapolation to zero amplitude to attempt to time tag the attachment process (or, presumably, the first detected current rise for an

Figure 8. Map of all array activity recorded on December 12–13, 1999. Color is indicative of local time of day (central standard time). The map demonstrates the long-range detection capability of the sferic array when the thresholds are low. See color version of this figure at back of this issue.

Figure 9. Histogram of LASA/NLDN time differences (1998/1999 data).
intracloud stroke in the loosened criteria database). The LASA convention is to time tag the peak recorded electric field amplitude, which physically corresponds to the time of peak current [Uman et al., 1975]. Peak current typically occurs a few microseconds after return stroke attachment. The second factor is that LASA more often (than NLDN) tags the ionospheric reflections of strokes. The reflection times of arrival are retarded from the groundwave sferics by tens to hundreds of microseconds. On the basis of Figure 9 the time coincidence window for the location analysis was selected to be ±100 μs. The number of events within this window was 497,288.

Figure 10 shows a cumulative log distribution of spatial separations between the LASA and NLDN event locations for events within the ±100 μs coincidence window in the 1998/1999 database. The bin size is 1.0 km. Figure 10 shows that for the entire database, 38% of the LASA/NLDN temporal coincidences agreed to within 1 km, 85% to within 10 km, 99% to within 40 km, and 99.9% to within 220 km.

To determine the extent to which poor LASA locations resulted from geometric dilution of precision, further analysis was performed only on the 1998 array data, since the 1998 NM array was small with a simple geometry (see Figure 1). This allowed us to easily evaluate the effect of event range on location accuracy.

Figure 11 illustrates LASA/NLDN location differences sorted as a function of range from the centroid of the 1998 NM array displayed on a log-log plot. Each 10-km-range bin value indicates the average location difference for all events occurring within the bin limits. Figure 11 shows that on average the event locations agreed to within 1.3 km out to a distance of 70 km from the center of the NM array. The locations agreed to within 2.0 km out to a distance of 130 km, a range that corresponds well to the edge of the NM array. Beyond the perimeter of the array the array location accuracy decayed steadily to 25 km at a range of 1000 km.

The conclusion with regard to LASA event location accuracy is that events occurring within the NM and FL subarrays were well located, with a mean location error of <2 km. The Florida result was not proven, but we make the argument based on the similar (or even shorter) FL baseline lengths and the better propagation conditions in Florida. Also, both arrays benefited from having five stations in 1999. Within an array diameter outside of the perimeter of each subarray, it is reasonable to expect location accuracy on the order of or better than 10 km. Beyond this distance, the accuracies degrade steadily with distance when the members of the subarray are the only participants in the location determination. Not addressed in this analysis are events detected by members of more than one subarray and/or by the satellite station in Nebraska. Having very distant stations participate in the geolocation solution can be useful in reducing errors, especially when the events to be located lie close to the line between the detecting stations. This is because the distant station constrains the radial component of the location uncertainty, and it is the radial component that grows fastest with distance from the event location.

3.2. Comments on Geolocation Accuracy

The LASA GPS receivers were evaluated prior to deployment and found to produce absolute time tags with a maximum error of <2 μs. On the basis of this measured uncertainty the theoretical achievable location accuracy is better than a kilometer (assuming that the ratio of the location accuracy to the timing accuracy is the speed of light). A number of considerations explain why this accu-
racy was apparently not achieved. The first is that LASA waveform cross correlations are not perfect. With identical waveforms at all stations it would be possible to determine the actual DTOAs to within 1 μs; however, propagation over the finitely conducting ground, ionospheric reflections, and static (near) and inductive (intermediate) field influences all affect the waveshapes. We hypothesized in the discussion of the Figure 6 waveforms that the 2.7-km difference between the LASA and NLDN locations resulted in part from the static contribution evident in the first waveform. Recent modeling and analysis by Willett et al. [2000] show that even when the previously mentioned factors are disregarded, channel tortuosity can cause radiation anisotropy as a result of nonvertical channel segments. This anisotropy also degrades waveform cross correlations. A second consideration is that NLDN lightning locations do not necessarily represent true source locations. The median accuracy for the standard NLDN data product is 0.5 km. The location uncertainty for the loosened criteria data (explained earlier) is not known. A third consideration is the potential for contamination from incidental coincidences. The events used for this comparative study were selected by finding ±100 μs LASA/NLDN coincidences. The 1998 and 1999 NLDN data sets often feature over one million events per day during the summer months. One million events per day corresponds to one every 80 ms. A random event occurring every 80 ms has a 1 in 400 chance of occurring in our ±100-μs window. Incidental NLDN events that occurred simultaneously (or nearly so) with LASA events but that occurred at great distances are included in Figure 11. As a result of geometry, these events are relatively less likely to contaminate the close event

**Figure 12.** Narrow positive bipolar field change waveforms from a discharge that occurred 32 km northwest of Tampa (the location is indicated by a numeral “3” in Figure 1).
range bins than the more distant ones, but the events certainly play a role in the Figure 11 plot beyond several hundred km in range.

4. Identification of Narrow Bipolar Pulses

Narrow bipolar pulses (NBPs) associated with very powerful RF radiation have previously been described by a number of researchers, including Le Vine [1980], Willett et al. [1989], Medelius et al. [1991], Smith [1998], Smith et al. [1999a], and Rison et al. [1999b]. Smith et al. [1999a] found that many of the discharges were intracloud events; that is, they occurred at heights above a few km as determined from reflections of field change signals from the Earth and ionosphere. The sources of these fast and isolated bipolar electric field change signatures were referred to as compact intracloud discharges (CIDs). As an extension of the previous work we attempted to identify waveform qualities that would allow NBPs to be automatically identified in the LASA database. CIDs are excellent targets for FORTE, which regularly records RF radiation from CIDs in the form of transionospheric pulse pairs (TIPPs) [Holden et al., 1995; Massey and Holden, 1995; Massey et al., 1998b].

Figures 12 and 13 show LASA examples of NBPs recorded by multiple stations. Figure 12 is a narrow positive bipolar pulse (NPBP) recorded by the Florida TA, GV, and BR stations on May 30, 1999, from distances of 32, 171, and 326 km, respectively. The event occurred northwest of Tampa (the event location is indicated by a “3” in Figure 1). The pulse is shown on a 500-µs timescale, expanded by a factor of 16 compared to the previous waveforms. The pulse is fast and isolated with little evidence of other electrical activity within the waveform (the same is true for the entire 8-ms record). Ionospheric reflections are barely visible in

![Figure 13. Narrow negative bipolar field change waveforms from a discharge that occurred east of the Texas Panhandle (the location is indicated by a numeral “4” in Figure 1).](image-url)
the BR (Figure 12, bottom) waveform in the neighborhood of 100 μs following the groundwave bipolar pulse. Figure 13 is a narrow negative bipolar pulse (NNBP) recorded by the New Mexico TU, RO, LA, and SO stations on July 8, 1998, from distances of 388, 544, 607, and 702 km, respectively. The event occurred in Oklahoma east of the Texas Panhandle (the event location is indicated by a “4” in Figure 1). Again the pulse is narrow, with a full width at half maximum on the order of 3 μs. Ionospheric reflections are visible in all four waveforms immediately following the groundwave signal. The two reflections correspond to the one-hop ionospheric reflection and the one-hop ionospheric reflection of the ground reflection. The delays are consistent with a source height of 18.6 km and an ionospheric virtual reflection height of 83.4 km. D. A. Smith et al. (Computation of intracloud lightning discharge heights using differential times of arrival of ionospheric and Earth reflections, manuscript in preparation, 2001) describe the methodology for this determination. The most likely explanation as to why the reflections in Figure 12 were weak or nonexistent and the ones in Figure 13 were obvious is that the Figure 12 waveforms were recorded from closer to the source, where the reflections tend to be weaker.

[45] Among the distinguishing characteristics of NBPs are their fast risetimes and fall times and their isolation within our 8-ms-duration electric field change records. It is not unusual to see indications of subsequent IC activity in NBP field change waveforms, but neither is it common. This topic has previously been addressed by Smith et al. [1999a, 1999b] and Rison et al. [1999a, 1999b]. Figure 14 is a scatterplot of event rise-plus-fall time versus waveform signal-to-noise ratio (SNR) for the entire 1998 LASA waveform database. The determination of risetime is made by extrapolating to zero the line determined by the peak absolute amplitude of the waveform and the first point prior to the peak that exceeds 10% of that amplitude. The risetime is defined as the time between the extrapolated zero crossing and the peak absolute amplitude. The fall time is the time between the extrapolated zero crossing and the peak absolute amplitude. The fall time is the time between the extrapolated zero crossing and the peak absolute amplitude. The fall time is the time between the extrapolated zero crossing and the peak absolute amplitude. The SNR for this study was computed by calculating the ratio of the average power within ±5 μs of the trigger point to the average power in the waveform from 6 μs after the trigger point to the end of the record. Once these parameters have been determined for each waveform that comprises an event, they are determined for the event itself. This was done by taking the average rise-plus-fall time and the minimum SNR. The minimum SNR was used rather than the average because local noise in waveforms at some stations significantly reduced NBP SNRs. The rise-plus-fall times in Figure 14 are in microseconds. The SNRs are in decibels. Two populations are evident in the scatterplot, providing a quantitative basis for identifying CID electric field change waveforms. The minor cluster in the upper left corner of Figure 14 represents NBPs, as verified by our observations of the waveforms. The large cluster of events on the lower right side of Figure 14 includes everything else and represents the vast majority (99.3%) of events recorded during 1998. The shaded line in Figure 14 was used to automatically classify events as NBPs or non-NBPs in the LASA database. Polarities of bipolar pulses were determined by assigning the polarity of the first point following the groundwave bipolar pulse. Figure 14. Scatterplot of rise-plus-fall time versus signal-to-noise ratio (in decibels) for all 1998 LASA events. The shaded line between the two populations indicates our criterion for classification of NBPs.

Table 2. Compilation of Statistics on Positive and Negative Narrow Bipolar Pulses (NPBPs and NNBPs) in 1998 and 1999

<table>
<thead>
<tr>
<th></th>
<th>1998</th>
<th>1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Events</td>
<td>135,835</td>
<td>765,208</td>
</tr>
<tr>
<td>NPBPs</td>
<td>728</td>
<td>8462</td>
</tr>
<tr>
<td>NNBPs</td>
<td>134</td>
<td>3568</td>
</tr>
</tbody>
</table>

5. Summary

[46] Motivation for the deployment of the Los Alamos Sferic Array was provided by the FORTE satellite project, which has a need for ground truth data that add value by providing the locations of events detected by FORTE, by further characterizing the events, and by providing background data when FORTE is not overhead. The sferic array now provides continuous coverage of lightning by providing event locations and limited event classifications. These data go back to May of 1998 when the array became operational. In the future the array will provide more comprehensive event classifications, as well as characterizations of event physical parameters. These expanded data sets will be applicable to the entire archive of sferic data, since all waveforms have been retained since array inception. This paper has described some of the initial event
location and identification capabilities and has provided a quantitative evaluation of its location accuracy.

References


J. Geophys. Res.


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Figure 7. Map of array activity recorded in the vicinity of the NM subarray on April 30, 1999. Color is indicative of local time of day (MDT).

Figure 8. Map of all array activity recorded on December 12–13, 1999. Color is indicative of local time of day (central standard time). The map demonstrates the long-range detection capability of the sferic array when the thresholds are low.