National Aeronautics
and Space Administration

FINAL REPORT

FOR

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(NRA-97-MTPE-03)

LIS Validation Studies Using Lightning at the KSC-ER

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Introduction

The Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) satellite provides time, location, and optical energy of lightning sources at regular orbital intervals over the tropics (see http://thunder.msfc.nasa.gov). Under NASA Grants NAG5-6461 and NAG5-9208 (NRA-97 MTPE-03), we have :

- Validated the performance of LIS (detection threshold and location accuracy) using intracloud (IC) and cloud-to-ground (CG) lightning detected at the NASA Kennedy Space Center (KSC) and USAF Eastern Range (ER);
- Investigated whether there are physical correlations between the total light output detected by LIS and the charge transfer in lightning and/or other lightning properties (current, multiplicity, VHF emission). [Such studies have been extended to include detailed comparisons between Optical Transient Detector (OTD) data and National Lightning Detection Network (NLDN) data. As an added benefit, we have also determined the retrieval errors associated with the new VHF Lightning Mapping Array (LMA) in Northern Alabama];
- Developed new and improved tools for analyzing lightning data obtained at the KSC-ER and for quantifying the response of the LIS sensor; and
- Examined if lightning can be used to provide convective rainfall estimates (intensity, amount) using data from the TRMM network of rain gauges that is operating at the KSC-ER.

Summary of Progress

1. LIS Performance

WJK and EPK have validated the performance of LIS using the ground-based lightning sensors at the NASA Kennedy Space Center (KSC) and the Cape Canaveral Air Force Station (CCAFS). The principal ground-truth sensors used were a Lightning Detection and Ranging (LDAR) system, a local Cloud-to-Ground (CG) Lightning Surveillance System (CGLSS), the U.S. National Lightning Detection Network© (NLDN), and an electric field mill (FM) network. The LDAR system maps the locations of VHF radio sources produced by both intracloud (IC) and CG flashes. The CGLSS sensors and the NLDN sensors locate the ground strike points of individual return strokes with an accuracy of a few hundred meters. The FM network can detect both IC and CG flashes within a range of 10 to 20 km, and the locations and magnitudes of lightning charges (ΔQs) can be inferred from the values of the field changes (ΔEs). It is rather rare to have a TRMM overpass of the KSC-CCAFS area at the same time a thunderstorm is in progress. An initial validation study was made of one LIS overpass of the KSC-ER, and the results were summarized at the 1999 Spring AGU meeting in Boston. An expanded analysis of 7 LIS overpasses of the KSC-ER were later completed and the results presented at the 2000 Fall AGU meeting in San Francisco. Further details of these two studies are provided below:

1.1 1999 spring AGU meeting presentation

On September 21, 1998 (Day 264), LIS reported 5 flashes over KSC during a 90 second interval; however, the KSC-ER ground-based sensors detected 6 flashes in the same interval. LIS actually detected optical emissions from all 6 flashes, but 2 of the 6 were separated by less than 1 second, and about 10 km in space. Because of this short interval, the 2 flashes were incorrectly combined into one by the LIS Data Processing Algorithm (LDPA). The locations of the 6 LIS events were generally consistent with both LDAR and CGLSS (field mill) locations, but 2 of the 6 appeared to be shifted about 8 km North of the corresponding LDAR and CGLSS locations. This study verified that KSC-ER lightning sensors can indeed be useful in examining LIS data, and in providing specific information as to how the LDPA should be improved.

1.2 2000 fall AGU meeting presentation

WJK, EPK, and Dr. Dennis Boccippio (NASA/MSFC) expanded on the above analyses. This time, a total of seven LIS overpasses of the KSC-ER were analyzed. Each overpass interval lasted from 2 to 3 minutes, for a total of about 15 minutes as indicated in **Table 1** below:

Date	Julian Day	Time (GMT)	# FM flashes	#Suitable	LM	NP
21 Sep 1998	Day 264	20:39-20:42	13	13	0	0
08 May 1999	Day 128	22:04-22:06	11	7	1	1
14 May 1999	Day 134	19:38-19:40	22	18	2	1
11 Jun 1999	Day 162	05:06-05:08	14	8	0	2
29 Jun 1999	Day 180	19:01-19:03	21	19	3	6
07 Aug 1999	Day 219	23:37-23:39	7	6	0	0
17 Aug 1999	Day 229	17:58-18:00.	6	6	0	1
		total:	94	77	6	11

Table 1. Summary of analyzed LIS overpasses of the KSC-ER during thunderstorm activity.

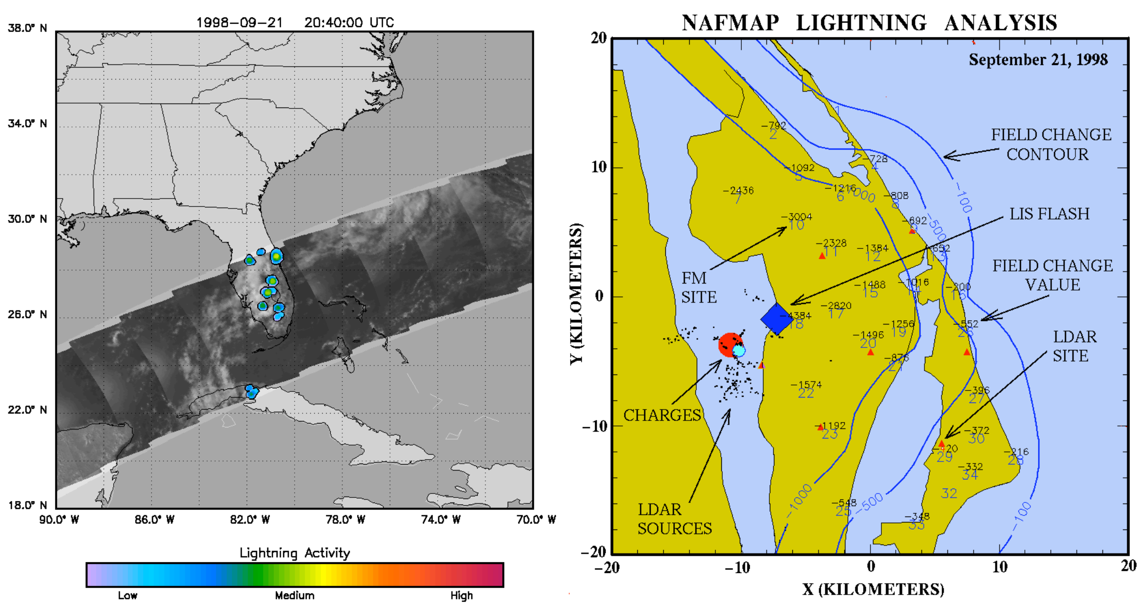


Figure 1. Sample LIS overpass of the KSC-ER adapted from the AGU presentation. The left hand figure is the LIS orbital pass, and the right hand figure is the NASA Field Mill Analysis Package (NAFMAP) analysis of one particular flash that occurred during the overpass [dots = VHF LDAR sources, circles = field mill network charge retrievals (red: $\Delta Q>0$, blue: $\Delta Q<0$), diamond = LIS optical flash location].

From these intervals the field mill network detected 94 discharges (each producing ΔE > 100 V/m at 2 or more field mill sites). The LDAR system detected each of these flashes. We compared the times and locations of the associated LIS optical events with the patterns of ΔE at the ground, the location/time of lightning ΔQs, the spatial-temporal development of the flashes as inferred from LDAR, and NLDN/CGLSS ground flash data.

Flashes not reported by LIS were divided into either a Legitimate Miss (LM) or a Not Processed (NP) type. For example, the LMs are due to: LIS data post-filtering, "pixel splitting" of radiance, and cloud attenuation. The NPs are due to: LIS buffer overflows, flashes (just) outside LIS field-of-view, and spacecraft incidences (e.g. telemetry bit errors, and spacecraft attitude maneuvers). In our case studies, LIS did not report 17 of the 94 flashes. Of the 17, six were LMs (mostly of the data post-filtering type), and eleven were NPs (mostly of the buffer overflow type and outside field-of-view type, but one flash was probably lost due to a spacecraft telemetry bit error).

Generally speaking, the location/time of LIS events were in good agreement with the ground-based measurements. This agreement was exemplified in a variety of spatial and temporal plots of the data. Some plots from one of the seven LIS overpasses are provided in **Figure 1** above; several other plots of this type (and vertical cross section plots) were presented at the 2000 AGU meeting. The NASA Field Mill Analysis Package (NAFMAP) plot on the right is unique in that it is the first-ever plot specifically showing lightning electric field change contours and LIS optical results.

2. Physical Correlations

2.1 LIS flash radiance and charge deposition

When a lightning flash occurs, high amperage currents deposit a large quantity of charge into the atmosphere. Multiple station ground-based measurements of the electric field can be used to determine both the quantity and location of the deposited charge. A lightning discharge is also associated with a very intense, but transient, optical emission along the breakdown channel. Our intent was to determine if there exists a notable correlation between the magnitude of *charge* deposited in the flash and the amplitude of

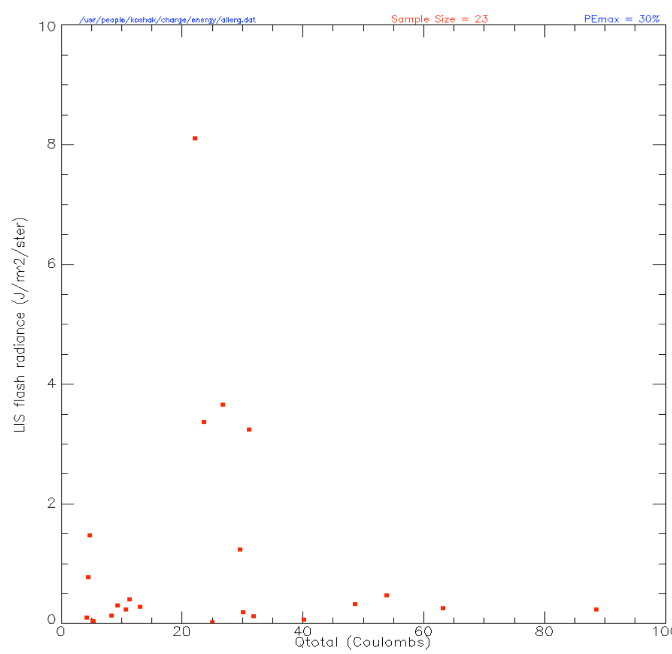


Figure 2. Sample plot of LIS flash radiance versus field mill derived flash charge. A low sample size, variable cloud attenuation, and differences in the spatial/temporal integration of the FM/LIS instrumentation make it difficult to correlate the variables.

optical energy (using LIS flash radiance) emitted from the channel. We were also interested in comparing flash radiance with other flash properties (peak current, multiplicity, number of LDAR sources).

Of the 94 discharges described in the previous section, 77 flashes were found suitable for a subsequent analysis that compared LIS optical amplitudes with the magnitude of ΔQ, the number of LDAR sources, the number of LIS events, and NLDN/CGLSS peak currents. Not all of the 77 flashes were reported by LIS and not all of the 77 flashes had acceptable charge fits using the field mill data. Hence, the sample size for comparing these data were further reduced. To date, only marginal correlation has been found. This is partly because of the limited sample size, but also because of other complications (e.g., variations in cloud optical thickness, differences in the spatial/temporal integration of the FM and LIS instrumentation). **Figure 2** above provides a sample of LIS flash radiance and field mill derived flash charge.

2.2 OTD/NLDN comparisons

In order to overcome the limited sample size, WJK has developed new widget-based Interactive Data Language (IDL) code called AMPS.PRO for inter-comparing NLDN-derived parameters (peak current, polarity, multiplicity) with OTD derived flash parameters (optical radiance, area, duration, # optical groups, # optical events) detected from space. Rather than use LIS (which is limited to the tropics), WJK has used the entire 5 year dataset from the LIS engineering model, called the Optical Transient Detector (OTD). Since the orbit inclination of OTD is 70 degrees, the entire US is covered. Because the NLDN detects a high percentage of all CGs nationwide, most CGs detected by OTD over the US can be inter-compared with NLDN results.

Since our last annual report, four additional years of OTD data have been compared with NLDN so that the entire 5 year OTD dataset has now been processed. We were able to match (on average) almost 10,000 NLDN-detected CGs per year with OTD flash data, for a total of 48,870 CGs over the US during the 5 year OTD period of operation. Specifically, **Figure 3** shows a plot of all NLDN CGs that were successfully matched with OTD data across the US.

We have reduced the large OTD/NLDN correlated dataset, and a variety of plots (e.g., OTD flash radiance versus NLDN peak current, OTD flash area versus NLDN current polarity) have been created and archived. We have also made similar plots for individual years (to look at annual variations), and for individual seasons (to look at seasonal variability).

Additionally, we generated a large number of frequency distributions of OTD/NLDN measurements for the entire/annual/seasonal datasets. For example, **Figure 4** shows individual frequency distributions for specific OTD measurements when the measurements are divided according to (NLDN-determined) peak current polarity. In **Figure 4a**, the OTD measurement is flash radiance. In **Figures 4b and 4c** the OTD measurements are flash area and flash duration, respectively. All of these plots show interesting features. *On average, it appears that positive polarity CGs have larger optical radiance, larger areal extent, and longer duration than do negative polarity CGs.* Hence, the statistical nature of OTD/LIS observations obviously contain some important information content about basic lightning physics. Such information content can potentially be exploited to further improve the remote sensing capability of space-based lightning detection systems.

In future analyses of our large correlated OTD/NLDN dataset, it will be possible to employ the empirical lightning current models of Bruce and Golde (*J. Inst. Electr. Eng*., vol. 88, 487-520, 1941) to convert NLDN current/multiplicity data into charge deposition estimates. The charge estimates can then be compared directly to the OTD measurements (i.e., in particular to the OTD flash radiance measurements for CGs). Consequently, we will be able to relate radiance to charge (a goal of section 2.1), but now for a far larger and statistically significant sample size and for a far larger geographical area (but for CGs only, not ICs). Of course, continued collection of data from LIS overpasses of KSC thunderstorms is important and should continue for the lifetime of the LIS. Ultimately, a juxtaposition of results obtained from both OTD/NLDN studies and LIS/KSC studies is optimum and complementary since they both aid in the understanding of lightning radiance/charge relationships.

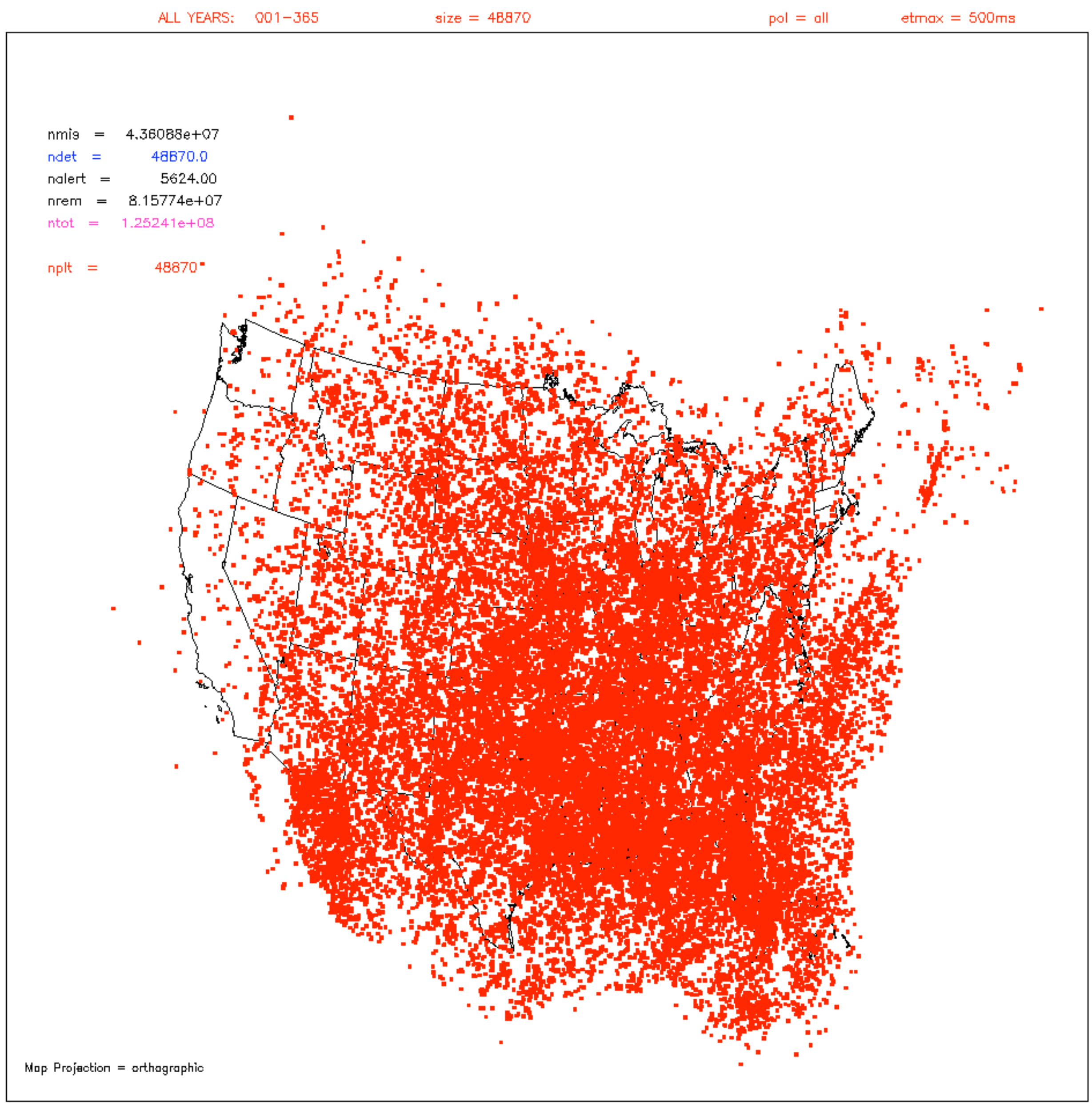


Figure 3. Plot of all CGs successfully paired between OTD and NLDN. The sample shown is for the entire 5 year lifetime of the OTD. This plot is one of several types of plots produced by the IDL program AMPS.PRO created for our research efforts.

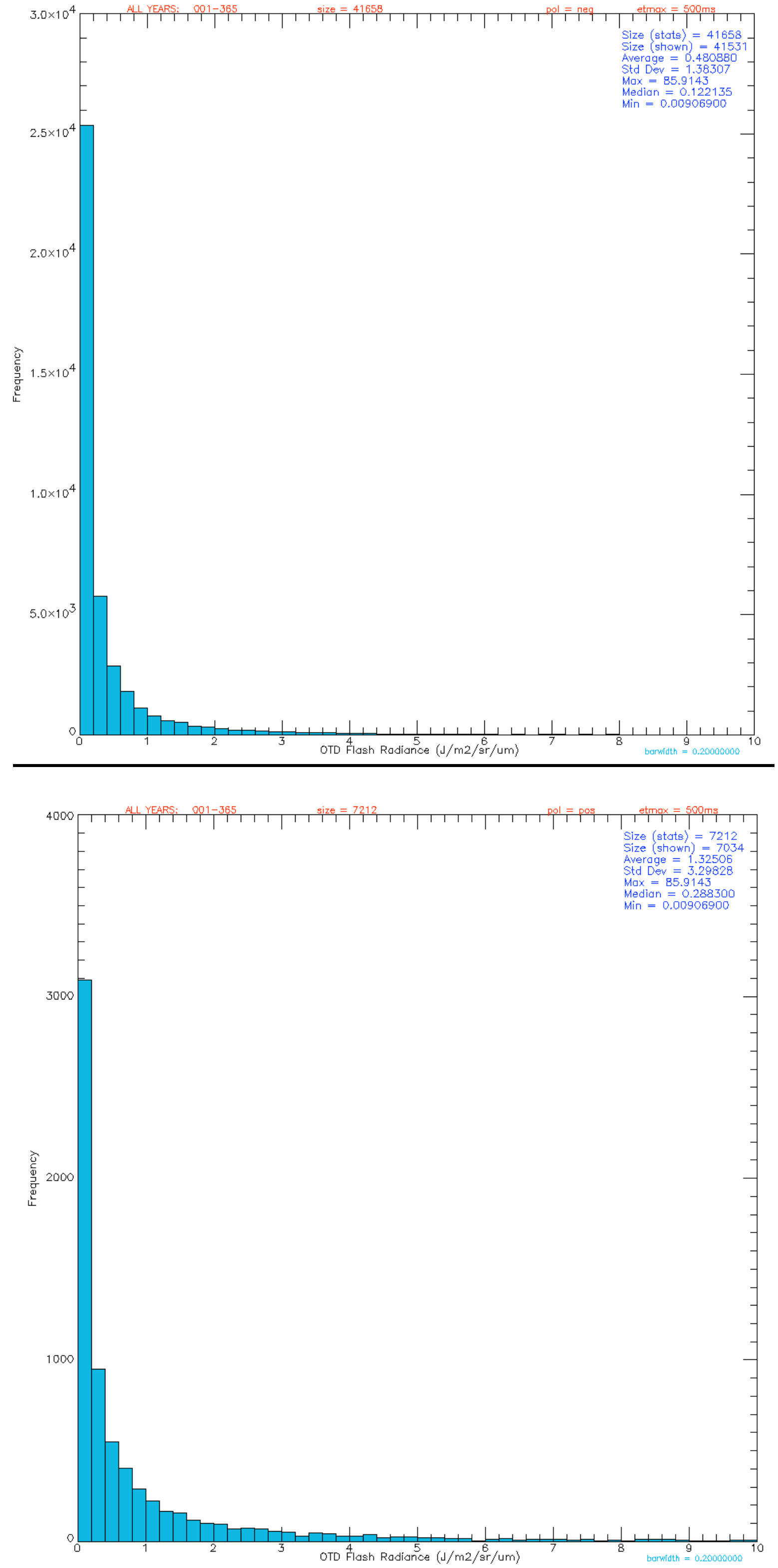
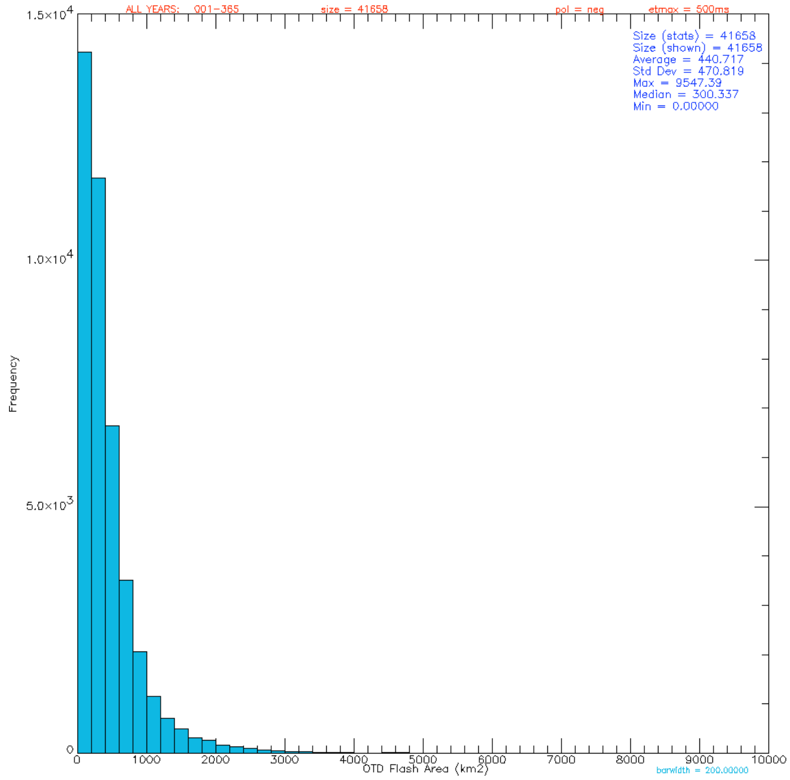


Figure 4a. Frequency distribution of OTD flash radiance for negative CGs (top plot) and positive CGs (bottom plot). CG polarity determined by NLDN.



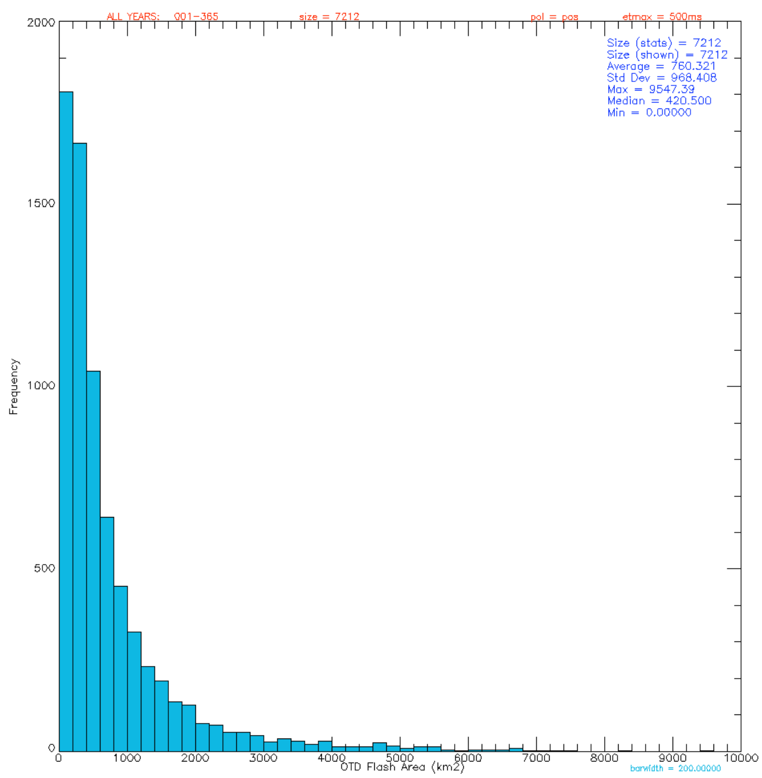


Figure 4b. Frequency distribution of OTD flash area for negative CGs (top plot) and positive CGs (bottom plot). CG polarity determined by NLDN.

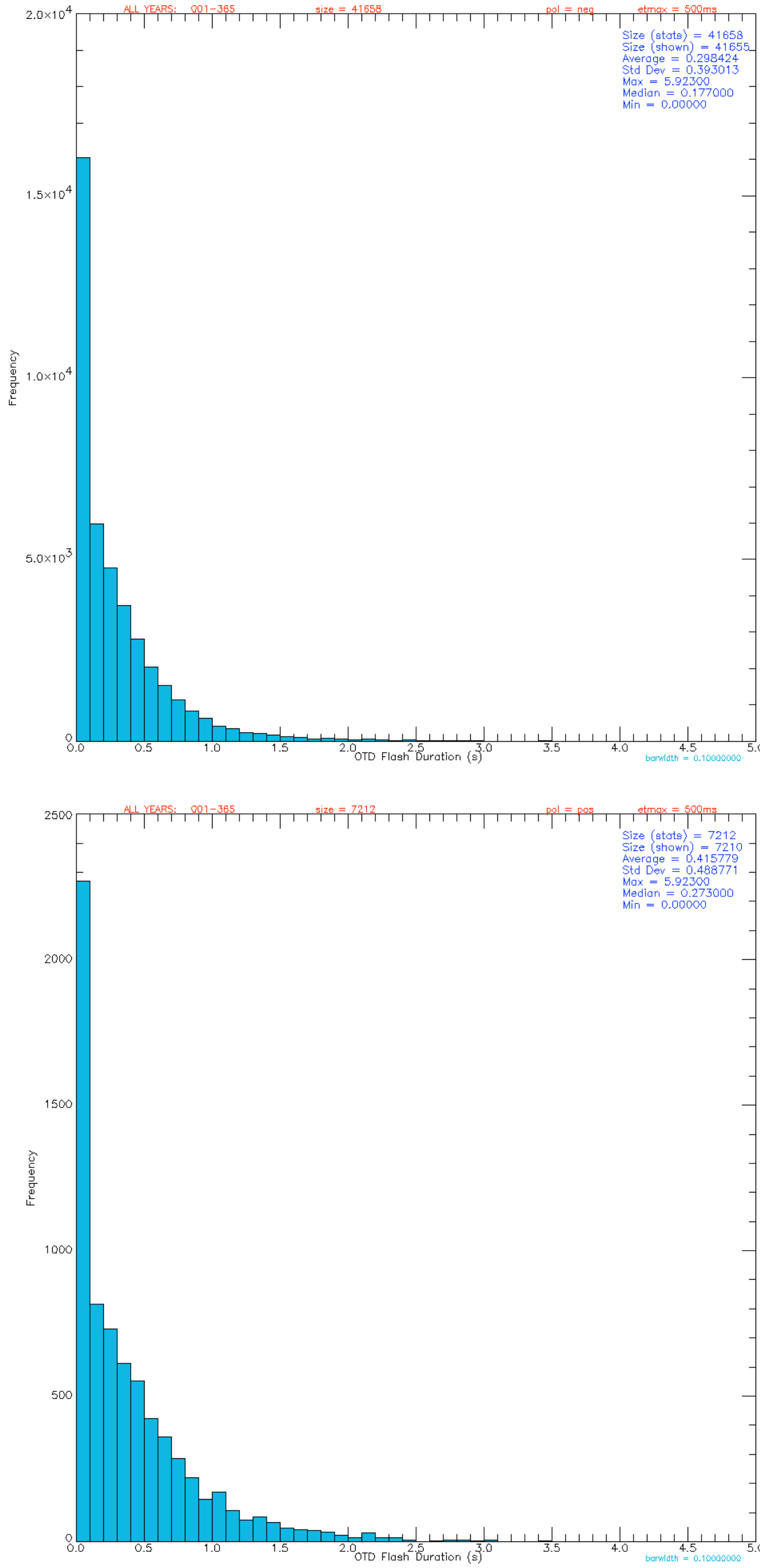


Figure 4c. Frequency distribution of OTD flash duration for negative CGs (top plot) and positive CGs (bottom plot). CG polarity determined by NLDN.

2.3 LMA algorithm development and error analyses

One facet of our work has been interested in making comparisons between LIS measurements and data derived from ground-based VHF lightning mapping systems. Because a new VHF network was recently installed in Northern Alabama [called the North Alabama Lightning Mapping Array (LMA)], we have put substantial effort into developing a robust lightning retrieval algorithm for this network, and for assessing retrieval errors. The formal results of our analyses have recently been presented in poster form at the 12th International Conference on Atmospheric Electricity (ICAE) in Versailles, France this past June. A four page paper for this conference was also published with the following reference citation:

Koshak, W.J., R. J. Solakiewicz, R. J. Blakeslee, S. J. Goodman, , H. J. Christian, J. M. Hall, J. C. Bailey, E. P. Krider, M. G. Bateman, D. J. Boccippio, D. M. Mach, E. W. McCaul, M. F. Stewart, D. E. Buechler, W. A. Petersen, Error analyses of the North Alabama Lightning Mapping Array (LMA), *12th International Conference on Atmospheric Electricity*, 613-616, 9-13 June, Versailles, France, 2003.

In addition, we have just submitted a full-length manuscript to the Journal of Atmospheric and Oceanic Technology (JTECH):

Koshak, W.J., R. J. Solakiewicz, R. J. Blakeslee, S. J. Goodman, , H. J. Christian, J. M. Hall, J. C. Bailey, E. P. Krider, M. G. Bateman, D. J. Boccippio, D. M. Mach, E. W. McCaul, M. F. Stewart, D. E. Buechler, W. A. Petersen, D. J. Cecil, North Alabama Lightning Mapping Array (LMA): VHF source retrieval algorithm and error analyses, submitted to *JTECH-A*, June, 2003.

and a copy of this paper is included as **Attachment 1**. Please note that.this “Monte Carlo” method of error estimation suggests that the LMA has remarkably good spatial resolution across the entire detection domain, and that error estimates made with the Curvature Matrix theory compare very favorably with the Monte Carlo results.

Some of the Monte Carlo error results are shown in **Figure 5,** and it is important to note that maps such as these are critical in helping to improve the algorithms that the LMA uses to derive the VHF source locations and to infer the *flash rates*, an important and fundamental LMA product. The grouping of VHF sources into flashes is particularly difficult if or when the VHF source retrieval errors are large or unknown. Consequently, there has been considerable interest in determining and understanding the characteristics of the source retrieval errors across the LMA detection domain. One such community with this interest is the National Space Science and Technology Center’s (NSSTC’s) Short-term Prediction Research and Transition (SPoRT) center. The SPoRT center seeks to accelerate the infusion of NASA Earth Science Enterprise (ESE) observations, data assimilation (including LMA data) and modeling research into NWS forecast operations and decision-making at the regional and local level. *Consequently, our efforts under NRA-97-MTPE-03 have directly helped progress in the SPoRT center.*

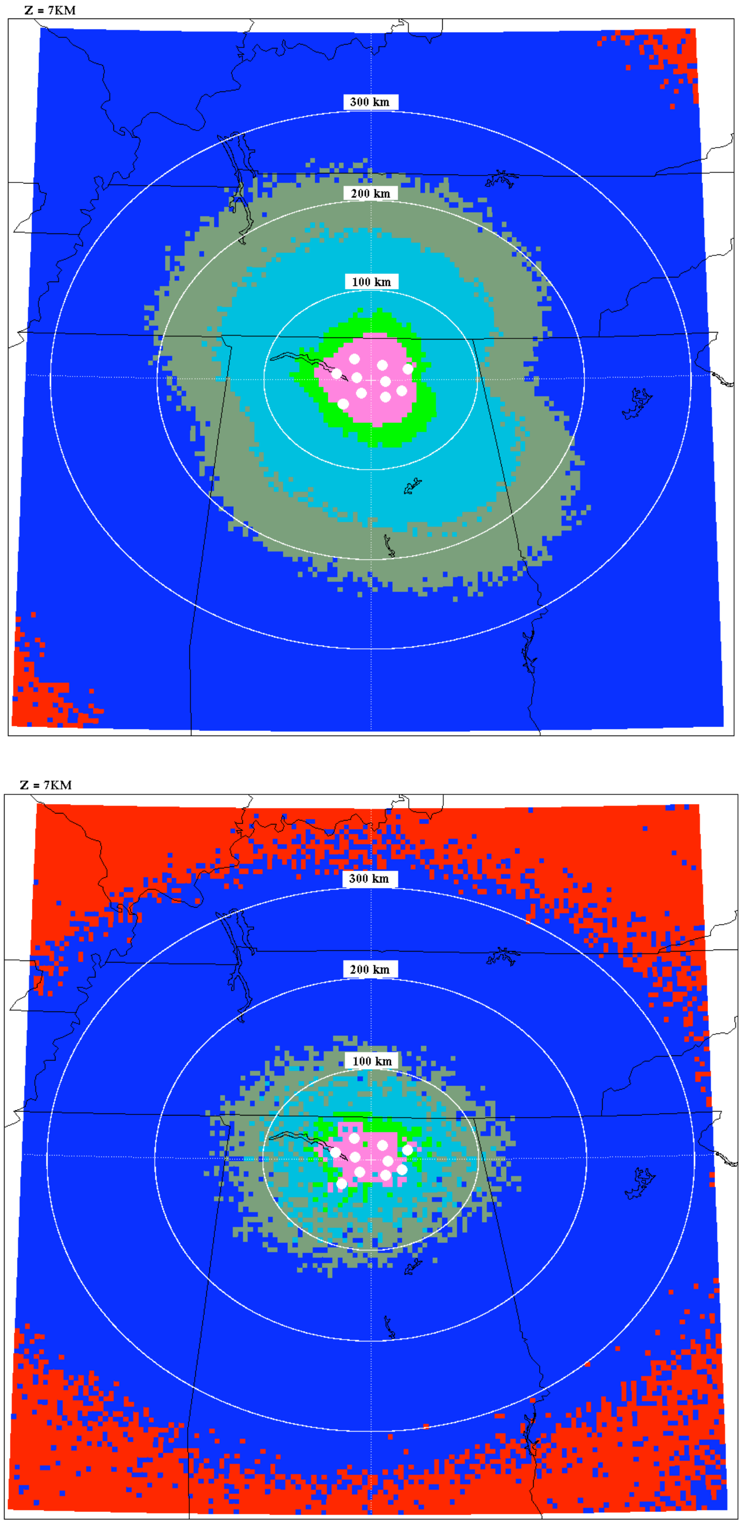


Figure 5. Spatial distribution of retrieval errors: geodesic distance error (top), altitude error (bottom). Known sources are at $z = 7$ km altitude, as indicated in the upper left portion of each plot. Color scale is as follows: 0 - 50 m (pink), 50 - 100 m (green), 100 - 500 m (turquoise) , 500 m - 1 km (grey), 1 - 5 km (blue), and >5 km (red).

3. New and Improved Tools

3.1 Software Tools

A great deal of effort has gone into creating/improving software analysis packages for analyzing lightning in these validation studies. The two main software packages developed in this study, and mentioned above, include the NAFMAP and AMPS.PRO. In addition, several ground-based RF lightning time-of-arrival (TOA) algorithms were developed, coded in IDL, applied to TOA data, and the results published in science journals.

The NAFMAP consists of a 30-file library written in IDL. It is a user interactive widget-based program; **Figure 6** below shows several different NAFMAP windows and associated widgets. The NAFMAP reads KSC field mill data, plots strip-chart type records of $E(t)$ for fast data quality checking (see **Figure 6a**), automatically detects flashes in the records with user adjustable flash detection criteria (see **Figure 6b**), computes the values of lightning ΔEs, plots ΔE contour maps (see **Figure 6c**), inverts the ΔEs, and plots the resulting charge solutions in space and in time (see **Figure 6d**). Multipole expansions, simulated annealing, and new "dimensional reduction" methods have been coded and tested for purposes of improving the accuracy of ΔE inversions (dimensional reduction techniques proved most useful). *Also, for the first time, the NAFMAP allows users to initialize charge source locations using LDAR data.* The NAFMAP also allows one to plot LDAR, CGLSS, NLDN, and LIS data for inter-comparisons (**Figure 6d**).

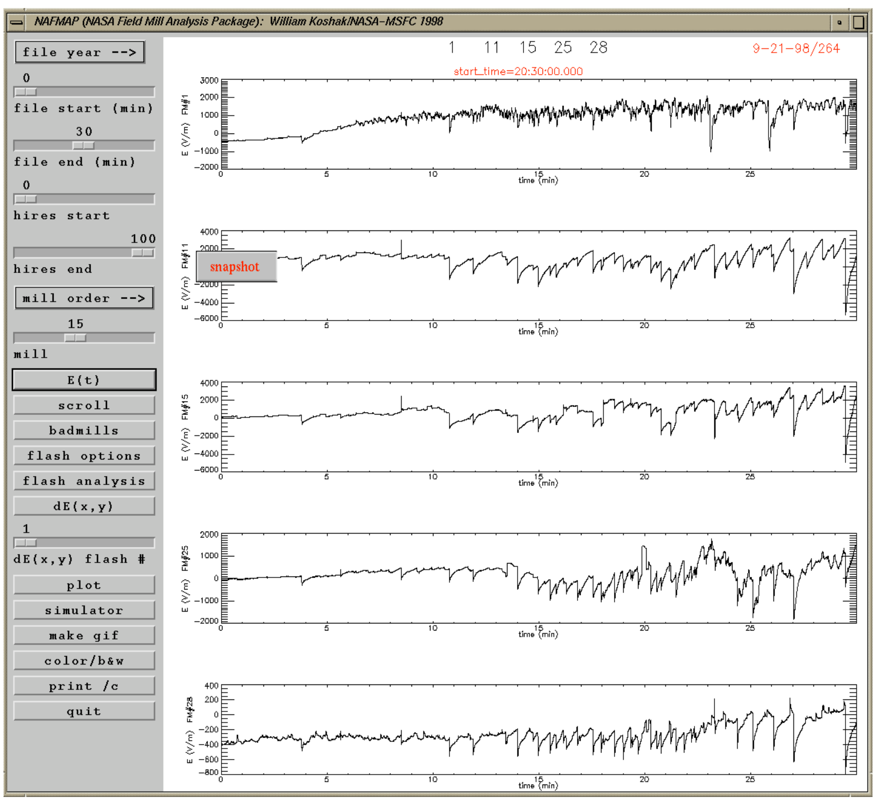


Figure 6a. Sample NAFMAP window showing KSC-ER field mill outputs. The user can quickly scan any field mill sensor in the network for arbitrary time intervals. This makes it easy to find poor data (one selects the "badmills" widget to remove certain mills from further analyses).

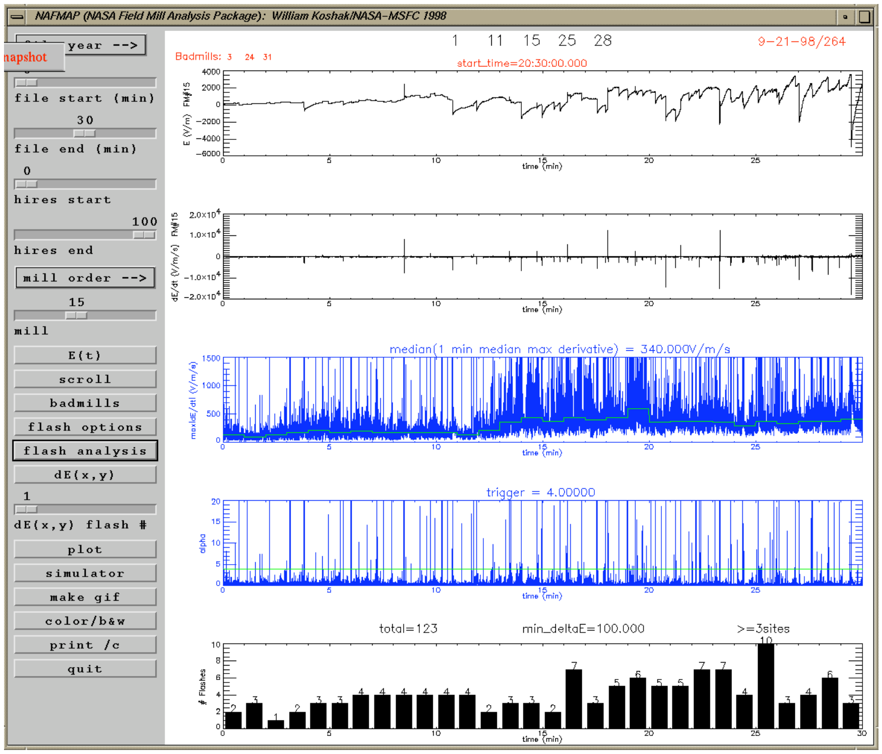


Figure 6b. This window is obtained by clicking the "flash analysis" widget which scans the interval to determine the flashes. A variety of flash detection criteria (e.g., threshold settings) are selectable using the "flash options" widget.

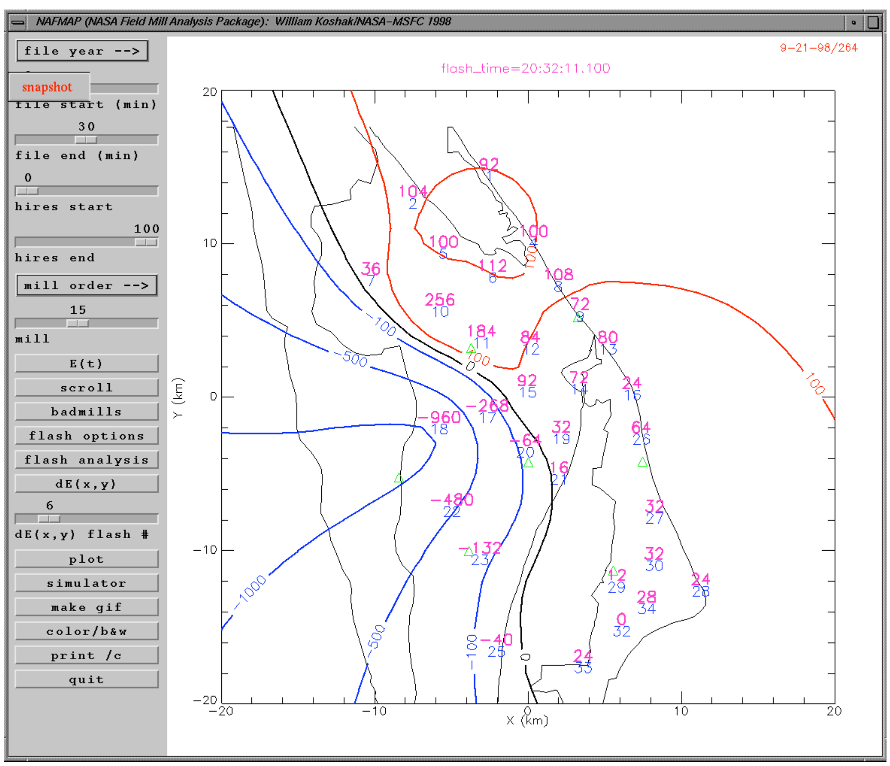


Figure 6c. By clicking the "dE(x,y)" widget, the pattern of lightning electric field changes (□Es) at the ground are obtained. An on-board "simulator" widget allows one to choose known charge sources, generate the associated field changes (with simulated errors), invert the field changes, and assess charge retrieval errors.

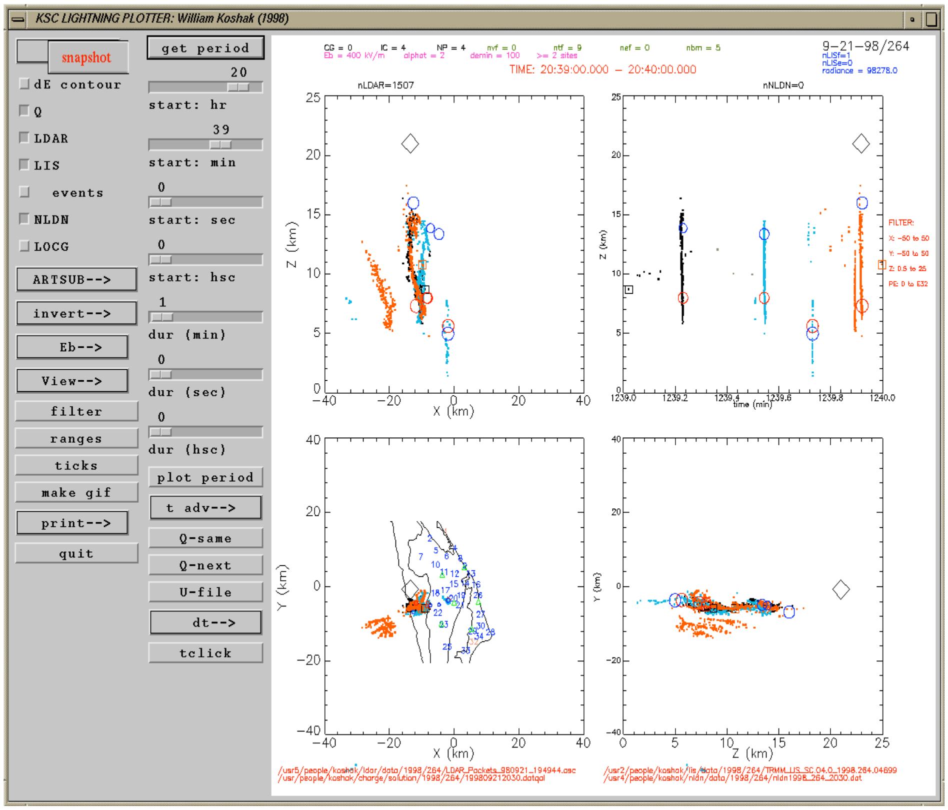


Figure 6d. By clicking the "plot" widget, one can plot a variety of data in plan view (lower left panel), cross section (upper left and lower right), or in time (upper right). The time-color-coded dots are LDAR VHF radio sources, the circles are FM charge retrievals, and the diamonds are LIS flash positions (LIS flash height is fictitious here). NLDN and CGLSS data can also be displayed.

In order to have LIS data satisfactorily processed, the NAFMAP was specifically written to be compatible with the standard NASA/MSFC LISAPPS software engine (this engine contains basic HDF data read and time conversion utilities fundamental to LIS data analyses). The NAFMAP is not suited for quickly scanning large (world tropical) LIS datasets for lightning activity in the relatively confined KSC-ER region. To do this, we aided Mr. Johnny Hall of the National Space Science & Technology Center (NSSTC) in Huntsville, AL in the development of a KSC-ER "quick-scan" software tool. It allows one to swiftly scan entire LIS datasets for lightning events that occur directly over the KSC-ER FM network. The tool is available at http://thunder.nsstc.nasa.gov/data/lisbrowse.html.

The AMPS.PRO program is geared toward specifically processing OTD and NLDN data. The entire OTD lightning dataset (5 years) and associated NLDN dataset reside on one Silicon Graphics 02 computer at NASA/MSFC NSSTC. The AMPS.PRO program meticulously scans each US OTD optical event (several OTD "events" compose a single OTD "flash") for an associated NLDN CG. Like the NAFMAP, it has several widget sliders/buttons to assist the user in easily selecting analysis periods. It also allows the user to make a variety of plot types. For example, one can swiftly plot any of the following variables against each other: OTD flash radiance, OTD # events, NLDN peak current, NLDN multiplicity, OTD flash duration, OTD flash area, OTD/NLDN distance error, OTD/NLDN timing error. Additionally, one can also plot the mean or standard deviation of any of these variables across the US; such a plot is shown in **Figure 7** for OTD optical radiance of CGs during August 1997.

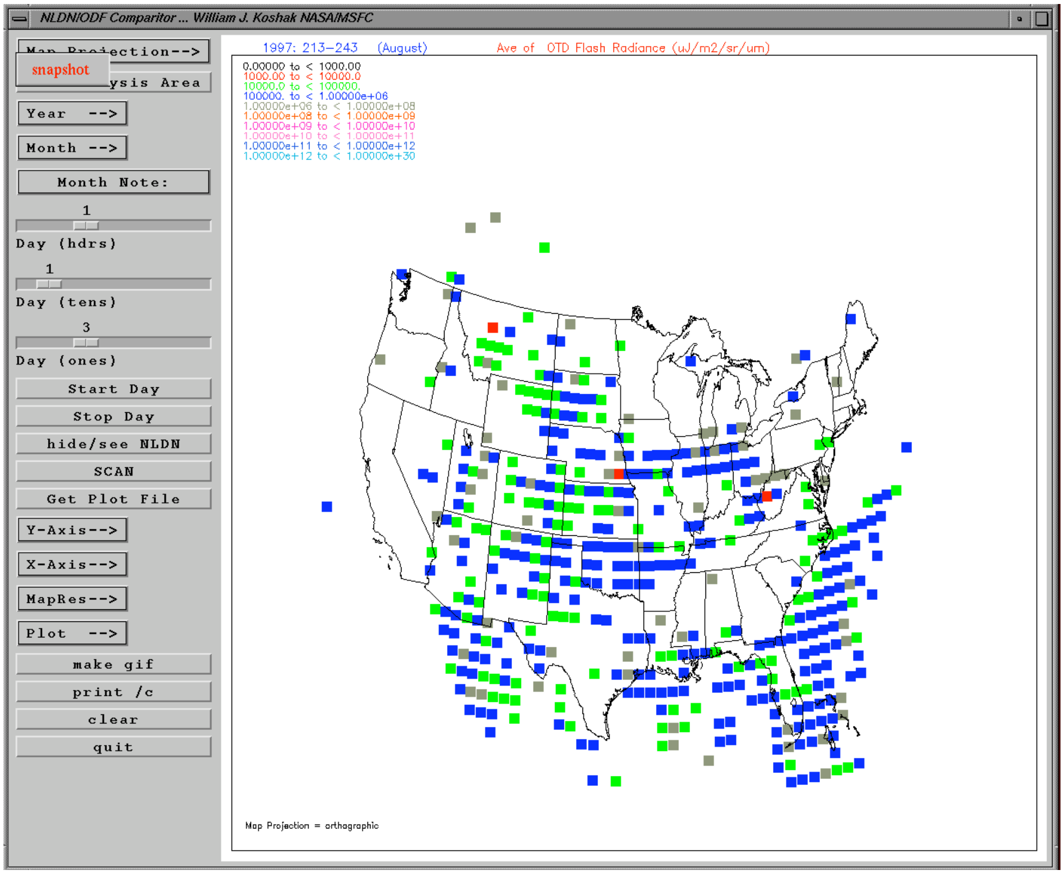


Figure 7. Sample window from the AMPS.PRO software tool for comparing OTD and NLDN characteristics. This plot shows the US spatial distribution of the average OTD CG flash radiance for August 1997. Many other plot types are possible as described in the report text.

In addition to the above accomplishments, we have completed IDL widget software to analyze data from multi-station Advanced Lightning Direction Finder (ALDF) networks. The ALDF networks combine TOA technology with wide-band magnetic direction technology to optimally locate CG events. A study of ALDF data has helped assess LIS geolocation accuracy independent of assessments made at the KSC-ER. Data from one ALDF network located in Darwin, Australia, and another network in Rhodonia, Brazil have been studied. Analytic algorithms developed specifically for analyzing the ALDF network data include the Linear Planar (LP), Quadratic Planar (QP), Linear Spherical (LS), and Iterative Oblate (IO) methods. Formal studies using all of these methods are provided in the following publications:

- Koshak, W. J., R. J. Blakeslee, and J. C. Bailey, Data retrieval algorithms for validating the Optical Transient Detector and the Lightning Imaging Sensor, *J. Atmos.Oceanic Technol.*, **17**, No. 3, 279-297, 2000.
- Koshak, W. J., and R. J. Solakiewicz, TOA lightning location retrieval on spherical and oblate spheroidal Earth geometries, *J. Atmos.Oceanic Technol*, **18**, No. 2, 187-199, 2001.

Additional recent publications directly related to validation of LIS/OTD are:

- Koshak, W. J., M. F. Stewart, H. J. Christian, J. W. Bergstrom, J. M. Hall, and R. J. Solakiewicz, Laboratory Calibration of the Optical Transient Detector and the Lightning Imaging Sensor, *J. Atmos.Oceanic Technol.*, **17**, 905-915, 2000.

- Boccippio, D. J., K. Driscoll, W. J. Koshak, R. J. Blakeslee, W. Boeck, D. Mach, D. E. Buechler, H. J. Christian, S. J. Goodman, The Optical Transient Detector (OTD): Instrument Characteristics and Cross-Sensor Validation, *J. Atmos.Oceanic Technol*, **17**, 441-458, 2000.

- Koshak, W. J., E. P. Krider, and M. J. Murphy, A multipole expansion method for analyzing lightning field changes, J. Geophys. Res., 104, 9617-9633, 1999.

- Phanord, D. D., W. J. Koshak, R. J. Solakiewicz, and R. J. Blakeslee, Calculation of the bulk electromagnetic properties of thunderclouds using a two-space scattering formalism, Appl. Phys. B - Lasers and Optics, 68, No. 4, 1999.

3.2 Hardware Development

With the guidance of EPK, Nathan G. Parker has developed a portable data collection platform for lightning measurements. This low-cost system was developed from off-the-shelf digital components and provides the capability of making optical and electrical measurements of lightning in conjunction with digital video imagery and precise GPS timing. The salient features of the system are summarized below:

Motivation:

Investigate Luminous Phenomenology of Lightning
- Development of beta leaders (attempted leaders)
- Multiplicity of ground strike points, NCF/ACF ratios (e.g. Valine and Krider [2001])
- Length of branch channels and branching probability as a function of height and time
- Overall dimensions
- Speed and geometry of (slow) air discharges (spider lightning)

Make Radiometric Measurements of CG and IC Lightning
- Radiance vs. time
- Integrated radiant energy
- Inferred return stroke velocity
- Electric field used to determine type of process and timing

Validate Ground- and Satellite-based Lightning Detection Systems -- NLDN, LDAR, LIS, ThOR, etc.
- Detection efficiency
- Stroke vs. flash count
- Location accuracy
- Process type (IC, CG)
- False alarms

Develop Technology for Future Experiments
- Build up to six mobile stations
- View a single storm from many angles
- Reconstruct 3D path of lightning to refine 2D measurements
- Distance between multiple strike points
- Effects of complex geometry on radiated fields

Hardware:

Ruggedized, Luggable PC (Dolch FlexPAC):
- 866 MHz Pentium III, Windows 2000
- TrueTime GPS receiver PCI card for accurate time (to 1us) and station location (to 15m)
- DATEL four-channel digitizer PCI card, 2.5 MHz with "pre-sample" capability
- IEEE 1394 ("Firewire") 400 Mbps serial PCI card, for digital video capture

Calibrated Photo Diode (UDT Sensors 14-00-001):
- 1 sq. cm, flat spectral response
- 50ms decay time with adjustable gain
- Electrically shielded with fine wire mesh
- Used to measure multiplicity and luminous power output

Electric Field Antenna:
- 1 sq. m, flush plate dipole (TSA)
- Adjustable gain and decay time
- Waveform used to determine type of lightning process

Digital Video Camera (Canon GL1):
- 720x480 pixels, 30 frames/sec (60 fields/sec, odd and even lines written separately)
- Frames are compressed within the camera for increased throughput
- IEEE 1394 serial output for real-time streaming to PC
- MINI-DV tape format for onboard digital recording. Can copy to PC after recording data.

Software:

Waveform Capture:
- 5 ms pre-trigger interval (typical) and 600 ms post-trigger at 500 KHz
- Writes data to disk and rearms in < 200 ms
- Records GPS time of trigger with 1 micro second accuracy
- Computes numerical parameters of each event to ensure optimum data capture
- Provides audio feedback of errors (over-range, premature triggers, buffer overruns, etc)

Streaming Video Capture:
- Video data are transferred from IEEE 1394 card to disk without processing
- GPS time-stamps are interlaced between frames in standard AVI file format
- PC operating system manages all buffers and DMA access

Automated Video Postprocessing:
- Video sequence is broken into short clips (1-45 frames) based on optical trigger times
- Each 720x480 pixel frame is deinterlaced into two 720x240 pixel fields
- Above deinterlacing doubles the time resolution but halves the vertical resolution
- Fields are re-sampled to full 720x480 pixel frames by bi-cubic interpolation
- Each frame is labeled with a dataset name, the frame number, and the GPS time/date
- Video clips are recompressed and metadata are entered into Excel database

Software Technology Utilized:
- Microsoft Visual C++
- Microsoft Direct Show COM objects for processing streaming video with GPS time-stamps
- VirtualDub and AVIsynth open source video applications for de-interlacing, resampling, labeling, and recompressing video frames
- Adobe Premiere for longer video editing
- Microsoft Excel used as database for 250+ video clips (date/time, location, direction, etc)
- Perl scripts used to automate video postprocessing

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A publication that describes this system and some of the initial results is given in **Attachment 2**.

4. Studies of Lightning and Rainfall

Nicole Kempf and E. P. Krider have examined relationships between CG lightning, rainfall, and streamflow during the Great Flood of 1993, and a publication describing the results is given in **Attachment 3**. Bruce Gungle and E. P. Krider have also examined CG lightning and convective rainfall in Lagrangian reference frames centered on the storms as they moved over the NASA Kennedy Space Center, and a publication on the results is currently being prepared for publication in the *JGR-Atmospheres*.