National Aeronautics
and Space Administration

LIS Validation Studies Using Lightning at the KSC-ER

NRA-97-MTPE-03 ANNUAL REPORT

December 4, 2001

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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 been attempting to:

- Validate 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);
- Investigate 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);
- Develop new and improved tools for analyzing lightning data obtained at the KSC-ER and for quantifying the response of the LIS sensor; and
- Examine 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.

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.

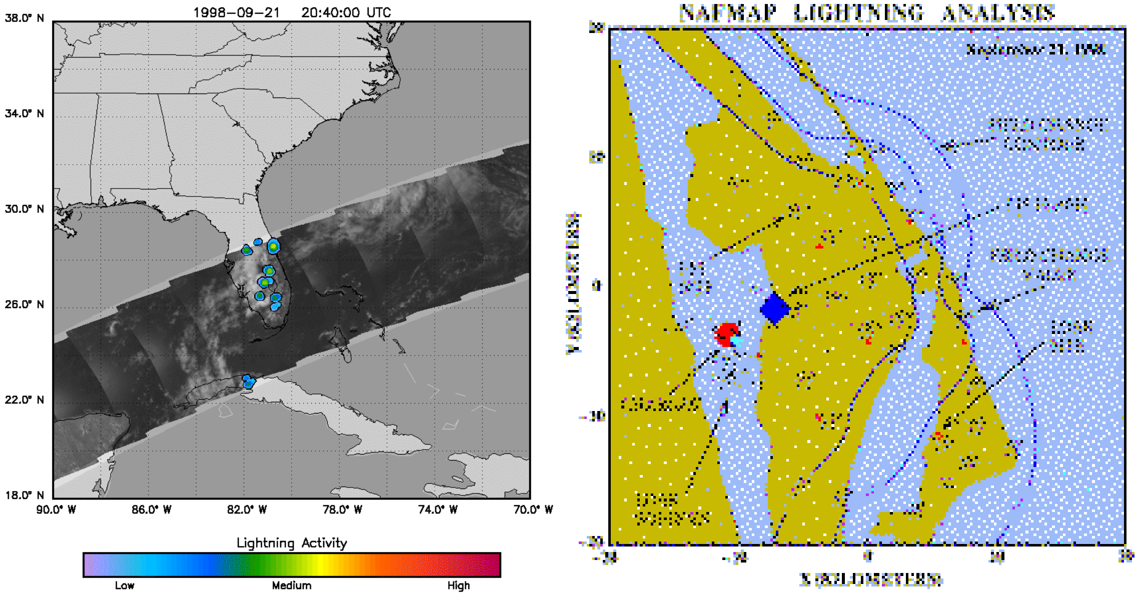


Figure 1. Sample LIS overpass of the KSC-ER adapted from the AGU presentation. The left hand figure is the LIS orbital pass, and the right hand figure is the NASA Field Mill Analysis Package (NAFMAP) analysis of one particular flash that occurred during the overpass [dots = VHF LDAR sources, circles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

Flashes not reported by LIS were divided into either a Legitimate Miss (**LM)** or a Not Processed (**NP)** type. For example, the **LM**s are due to: LIS data post-filtering, "pixel splitting" of radiance, and cloud attenuation. The **NP**s 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 **LM**s (mostly of the data post-filtering type), and eleven were **NP**s (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 (between Flash Optical Output and other Lightning Properties)

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 *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** below provides a sample of LIS flash radiance and field mill derived flash charge.

In order to overcome the limited sample size, WJK has developed new widget-based Interactive Data Language (IDL) code called AMPS.PRO for intercomparing NLDN-derived peak current and multiplicity with optical radiance detected from space. Rather than use LIS (which is limited to the tropics), WJK has selected the entire 5 year data set 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. Since the NLDN detects a high percentage of all CGs nationwide, all CGs detected by OTD over the US can be inter-compared with NLDN results.

To date, the entire year of 1997 has been reduced. For example, OTD flash radiance versus NLDN peak current for August 1997 is shown in **Figure 3**. Note the large sample size in the plot. We intend to reprocess this data to quality check the comparison, and we will also concatenate all the monthly files of 1997 so as to obtain correlative plots for the entire year of 1997. Eventually, we shall generate correlative plots for all 5 years of OTD data.

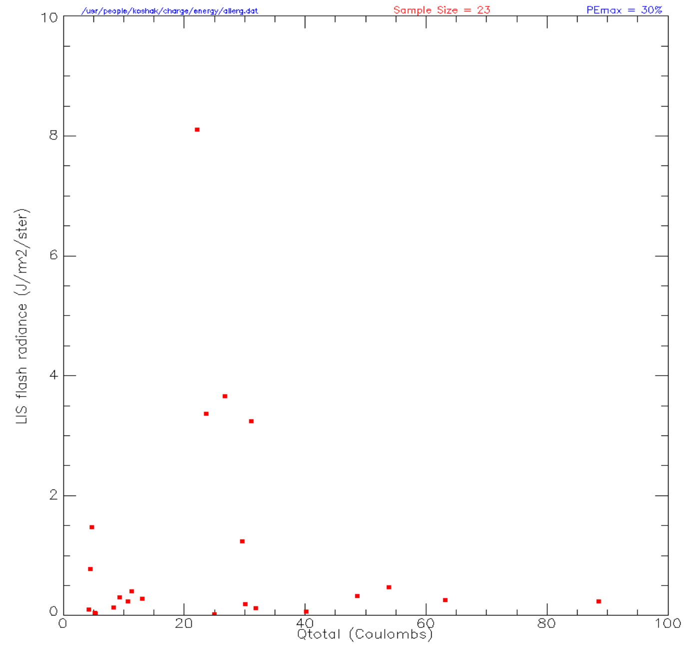


Figure 2. Sample plot of LIS flash radiance versus field mill derived flash charge. A low sample size, variable cloud attenuation, and differences in the spatial/temporal integration of the FM/LIS instrumentation result in minimum detectable correlation between the variables.

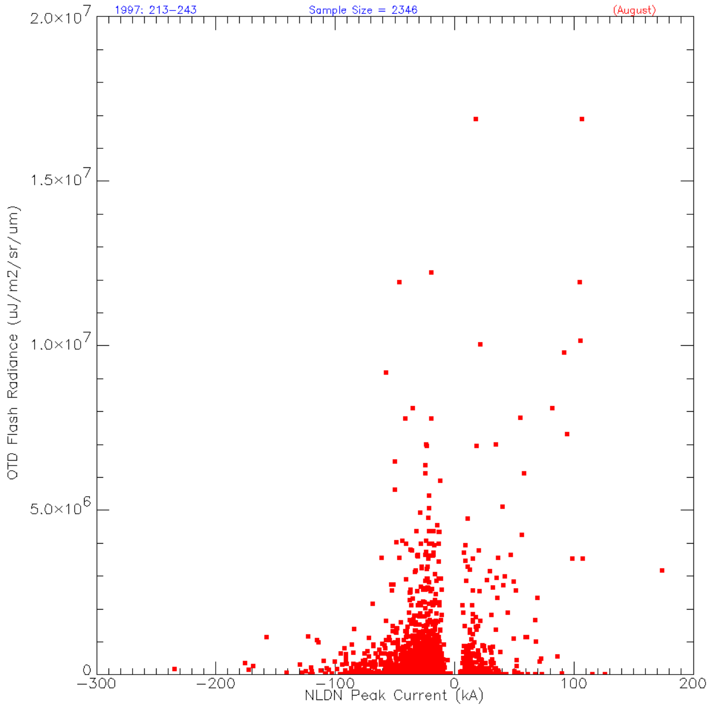


Figure 3. Plot of OTD flash radiance versus NLDN peak current for 2346 CG flashes over the US in August 1997. This plot is one of some fifty plots produced by the new IDL program AMPS.PRO; the software is being used to examine spatial, diurnal, and seasonal correlations between OTD/NLDN datasets.

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 independently by WJK, 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 4** 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 4a**), automatically detects flashes in the records with user adjustable flash detection criteria (see **Figure 4b**), computes the values of lightning ΔEs, plots ΔE contour maps (see **Figure 4c**), inverts the ΔEs, and plots the resulting charge solutions in space and in time (see **Figure 4d**). 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 4d**).

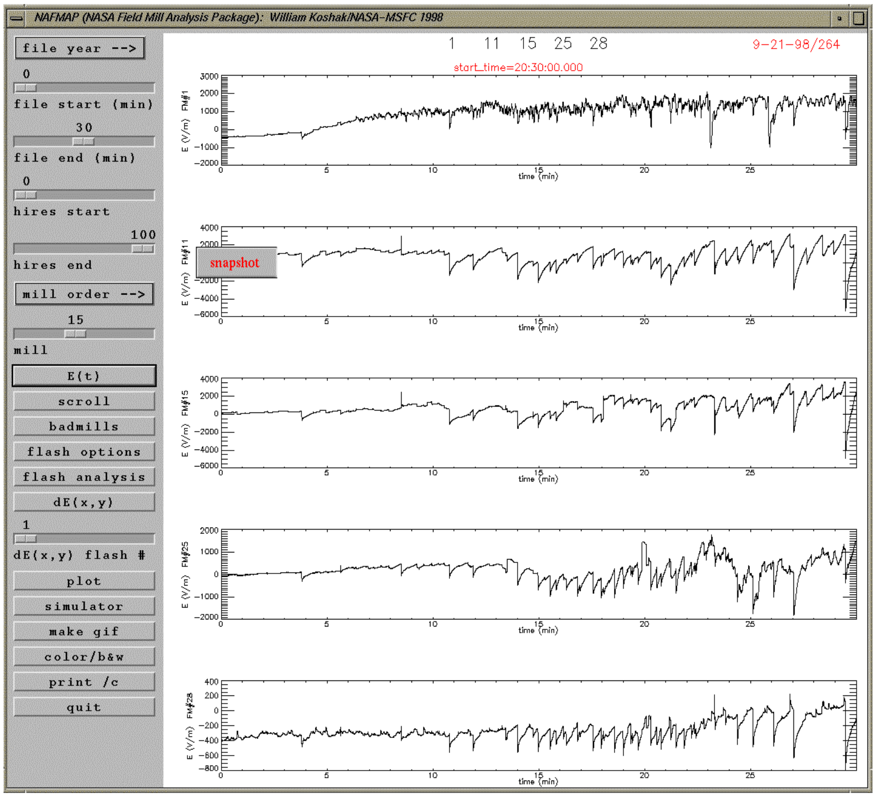
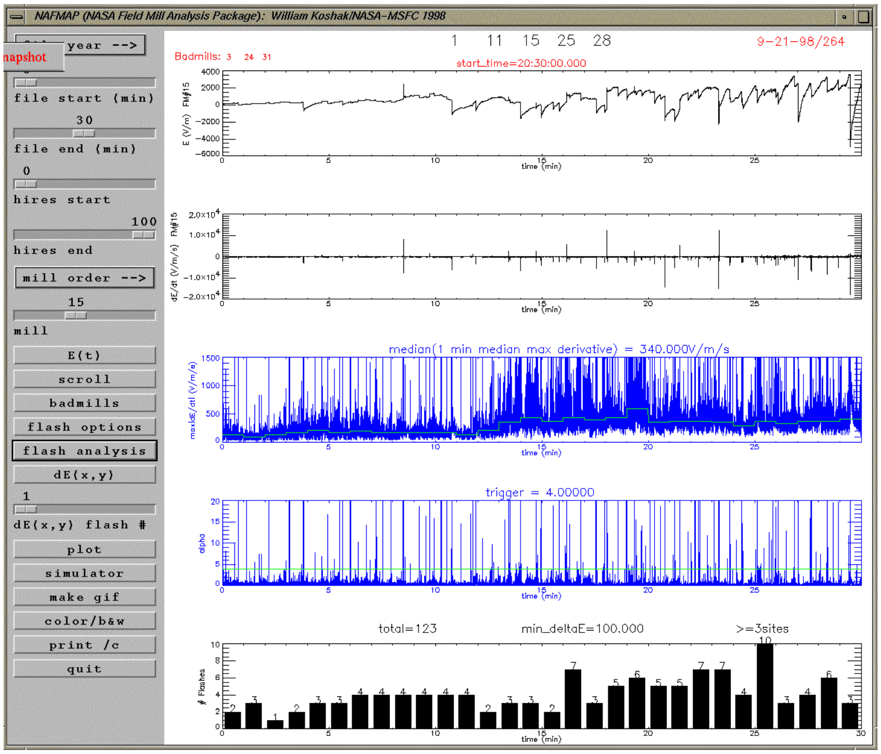


Figure 4a. Sample NAFMAP window showing KSC-ER field mill outputs. The user can quickly scan any field mill sensor in the network for arbitrary time intervals. This makes it easy to find poor data (one selects the "badmills" widget to remove certain mills from further analyses).



NAFMAP (NASA Field Mill Analysis Package): William Koshak/NASA-MSFC 1998

Badmills: 3 24 31

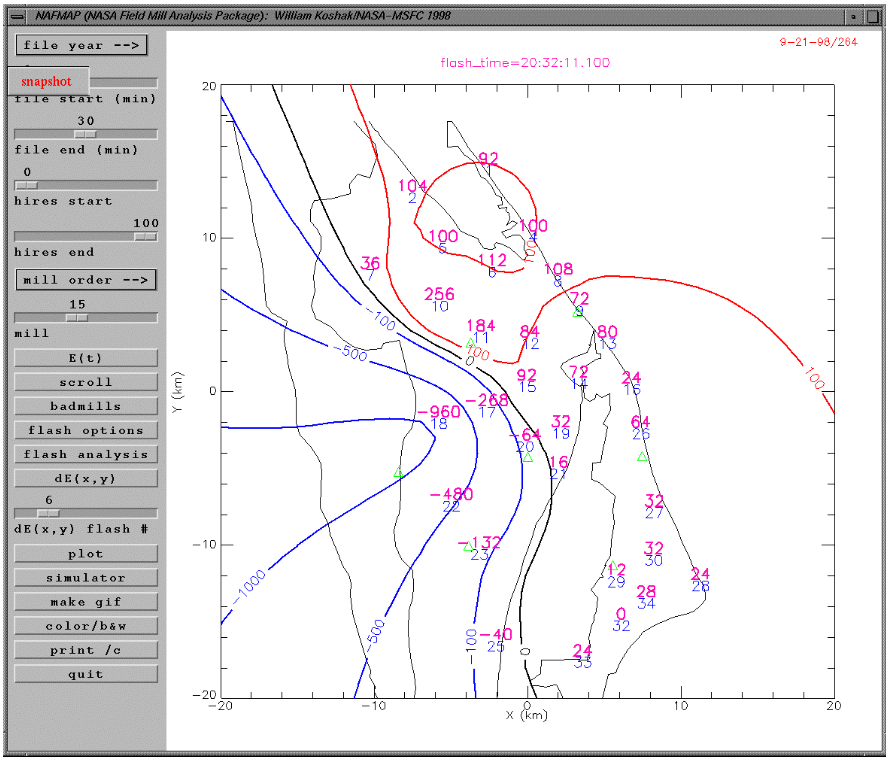
start_time=20:30:00.000

median(1 min median max derivative) = 340.000V/m/s

trigger = 4.00000

total=123 min_deltaE=100.000 >=3sites

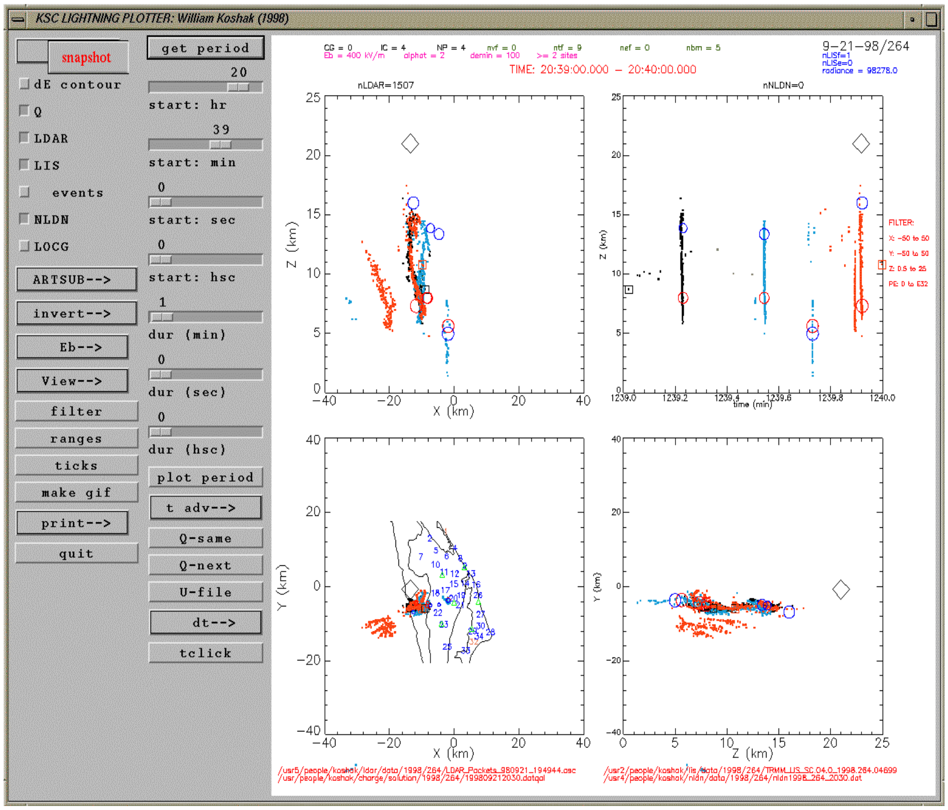
Figure 4b. This window is obtained by clicking the "flash analysis" widget which scans the interval to determine the flashes. A variety of flash detection criteria (e.g., threshold settings) are selectable using the "flash options" widget.



NAFMAP (NASA Field Mill Analysis Package): William Koshak/NASA-MSFC 1998

flash_time=20:32:11.100

Figure 4c. By clicking the "dE(x,y)" widget, the pattern of lightning electric field changes (ΔEs) 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.


KSC LIGHTNING PLOTTER: William Koshak (1998)

```
CG = 0    IC = 4    NP = 4    nvf = 0    ntf = 9    nef = 0    nbm = 5
Eb = 400 kV/m    alphat = 2    demin = 100    >= 2 sites
TIME: 20:39:00.000 – 20:40:00.000
9–21–98/264
nLISf=1
nLISe=0
radiance = 98278.0
nLDAR=1507
nNLDN=0
FILTER:
X: –50 to 50
Y: –50 to 50
Z: 0.5 to 25
PE: 0 to E32
/usr5/people/koshak/ldar/data/1998/264/LDAR_Packets_980921_194944.asc
/usr/people/koshak/charge/solution/1998/264/199809212030.datqal
/usr2/people/koshak/lis/data/1998/264/TRMM_LIS_SC.04.0_1998.264.04699
/usr4/people/koshak/nldn/data/1998/264/nldn1998_264_2030.dat
```

Figure 4d. 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 5** for OTD optical radiance of CGs during August 1997.

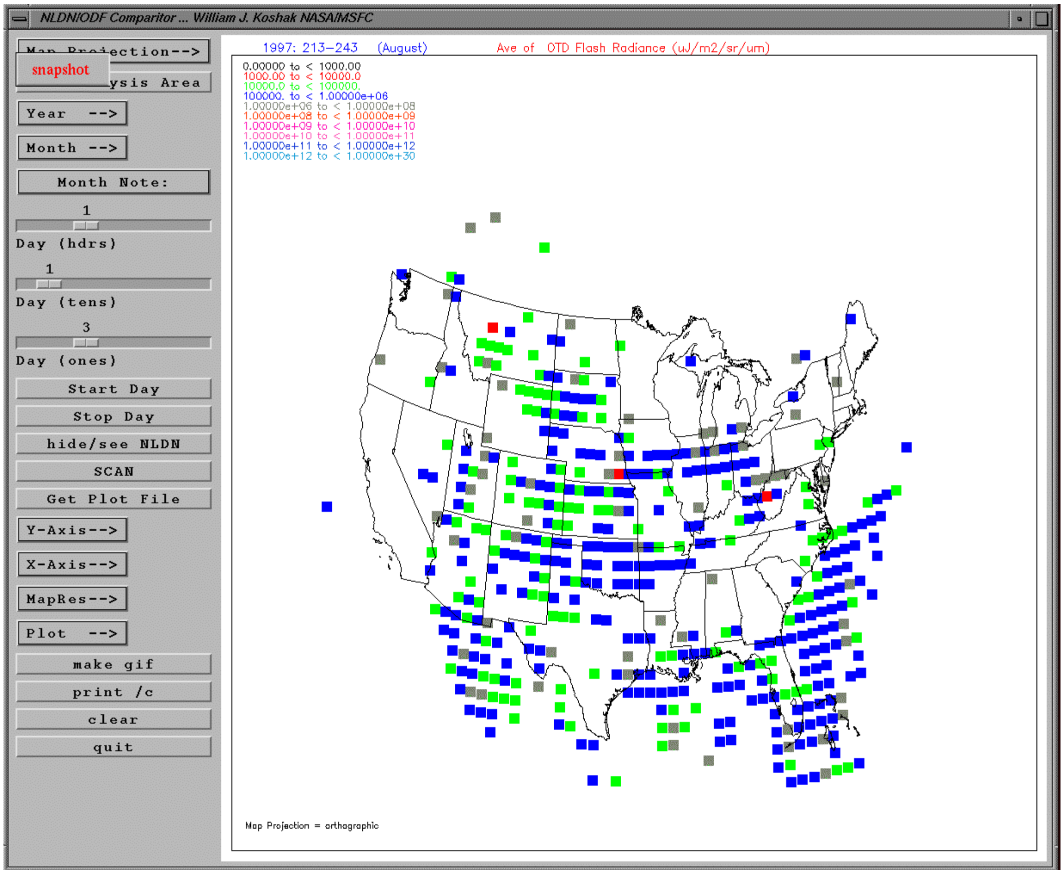


Figure 5. Sample window from the AMPS.PRO software tool for comparing OTD and NLDN characteristics. This plot shows the US spatial distribution of the average OTD CG flash radiance for August 1997. Many other plot types are possible as described in the report text.

In addition to the above accomplishments, WJK has 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 recent 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 developed a portable data collection platform for lightning measurements. The system was developed from off-the-shelf digital components to provide the capability of making optical and electrical measurements of lightning in conjunction with digital video imagery and precise GPS timing. Below is a summary of the salient features of this system.

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

Acknowledgements:
- Funded in part by a LIS Validation Grant under NRA-97-MTPE-03 (NASA grant NAG5-9208)
- NLDN and LDAR data provided by Global Atmospherics, Inc., Tucson, AZ
- Hardware assistance from Dr. Charles Weidman, University of Arizona

4. Studies of Lightning and Convective Rainfall

Bruce Gungle and E. P. Krider have completed a study of relationships between CG lightning and convective rainfall at the NASA Kennedy Space Center, and Nicole Kempf and E. P. Krider have examined the relationship between CG lightning and the rainfall that produced the Great Flood of 1993. Manuscripts describing these studies in detail are currently being prepared for publication.