HEAT – First Planning Workshop – Lightning Summary
(21 April 2004)

Introduction

Cloud-to-ground (CG) lightning data have been analyzed for a twelve year period, 1989-2000, centered on Houston, TX (Orville et al. 2001; Steiger et al. 2002). The studies show a 58% enhancement in CG lightning flash activity over the urban area in the summer. In this Houston Lightning Anomaly (HLA), they also found a decrease (-12%) in the percentage of positive CG flashes (Steiger et al. 2002) which suggests that the polarity of the electrical structure in some thunderstorms may be affected by the urban atmosphere over Houston. Curiously, this effect was noted in a region that experienced greatly enhanced positive CG lightning percentages and peak currents during the spring 1998 Mexican smoke incursion into the U.S. (Murray et al, 2000; Lyons et al. 1998).

There are several factors that could cause elevated CG flash densities over Houston relative to the surrounding areas: (1) urban heat island (UHI) effects that produce enhanced thermodynamic instability and convergence, (2) irregularities in the shape of the coastline that lead to localized areas of enhanced convergence along the sea breeze front and (3) increased levels of air pollution from anthropogenic sources. Several theories have been proposed to explain such effects. Among these are enhanced counts of CCN that increase the production of small droplets, thereby reducing the mean droplet size. This effect might also cause enhanced updrafts and a deeper mixed phase region, and lead to more charge separation in the presence of supercooled water. Any increase in the charge separation might lead to an enhancement of lightning in the polluted area.

SCIENTIFIC OBJECTIVES – LIGHTNING

<u>OBJECTIVE L1:</u> Fully Characterizing Total Lightning, Lightning Flashes and Strokes

PROCESS TO BE STUDIED: The results of Orville et al. (2001) and Steiger et al. (2002) are based on reports of CG flashes provided by the U.S. NLDN and are incomplete because these data say nothing about the behavior of cloud flashes or the other key metrics for characterizing thunderstorm electricity in the Houston area. According to climatology, approximately 70% of lightning occurring over the continental U.S. are cloud discharges that never contact ground (Boccippio et al. 2001). Therefore, a total (cloud and CG) lightning mapping system is necessary to help quantify the distribution of all lightning in urban and rural areas near Houston, TX. The NSF has funded the installation of such a network before the summer of 2005. The network will consist of 12 VHF sensors separated by 15 to 30 km baselines. This network will have an expected total lightning flash detection efficiency of over 99% and a VHF source location accuracy of 100-200 m (Demetriades et al. 2002, 2004). The 3-dimensional range of the network will depend upon the specific sites selected for VHF sensor installation, but it certainly will cover the urban zone of Houston and much of the surrounding rural areas. The 2-dimensional range of the network will extend over 200 km from the urban area of Houston. Data from the U.S. National Lightning Detection Network (NLDN) will also be available for the HEAT project. This network has recently been upgraded and studies in Arizona and Florida now show a CG flash detection efficiency of ~95%, CG stroke detection efficiency of ~80% for all strokes, CG subsequent stroke detection efficiency of ~70% and location accuracy of 500 m (Jerauld et al. 2004, Kehoe and Krider 2004; upcoming ILDC). The combination of the NLDN and the LDAR

II predecessor (the New Mexico Tech LMA) has already proven its usefulness in projects such as STEPS (Lyons et al. 2003a, Lang et al. 2004).

The combination of the Houston LDAR II network and U.S. NLDN will allow researchers to obtain a number of valuable statistics including: (1) the location and amplitude of the first lightning flash produced by a radar cell, (2) cloud flash rates, (3) CG flash rates, (4) the evolution of cloud/CG flash ratios, (5) the geometrical extent of cloud discharge channels, (6) the initiation points of cloud and CG flashes, (7) altitude from which the primary charge is lowered, (8) the area and volume in which charge is altered by lightning, (9) the polarity of CG strokes, (10) estimates of the peak currents in CG strokes and (11) measurements of the multiplicity of strokes in CG flashes in the HLA domain.

The LDAR II network and U.S. NLDN are essential observing systems for many of the objectives of the HEAT program. Unfortunately, the NLDN does not detect all CG strokes and flashes; in fact, the performance of the NLDN has never been independently validated in the Houston area. Therefore, supplementary observing systems will help to determine whether the HLA contains just more CG flashes, or more CG strokes as well, and/or whether there are just more CG flashes with fewer strokes per flash. During HEAT, two relatively low-cost technologies will be applied to independently detect and characterize lightning at the stroke level within the storms under investigation. These are digital lightning imaging (DLI) systems (using both low and high time-resolutions) and measurements of the electromagnetic transients using broadband and ULF/ELF/VLF receivers. The combination of the NLDN, LDAR II, DLI and ULF/ELF/VLF in Houston and the surrounding areas (the HLA) will in fact provide one of the most complete characterizations of cloud and CG flash characteristics obtained to date. Although stroke polarity and peak current are important parameters, it is also becoming clear that the lightning parameters in different regimes of deep convection are different, and that certain fundamental parameters, like the change in the charge moment (ΔMq) and the total charge lowered to the ground, ΔQ (Hu et al. 2002, Cummer and Lyons 2004, Lyons et al. 2003a) depend on the storm and the larger meteorological environment. It is also reasonable to propose that other parameters such as the peak current and stroke multiplicity, the duration and amplitude of the continuing current, and multiplicity of attachment points may also depend on the storm and be different in the HLA. Until recently such measurements have been costly and difficult to make, and nearly impossible to implement over an extended geographical region.

The development of new ULF/ELF/VLF analysis techniques (Cummer and Lyons 2004) allow remotely sensed quantification of ΔMq and Q (within the LDAR II range). Such measurements, now being routinely made at Duke University, would ascertain whether enhanced urban CG lightning rates are caused by thunderstorms that generate charge at faster rates or by thunderstorms that generate charge at similar rates as rural storms, but lower less charge to ground with each lightning flash. The combination of the Duke ULF magnetic field sensors (0.1 Hz to 400 Hz) and ELF/VLF magnetic field sensors (50 Hz to 30 kHz) enables measurement of lightning charge moment waveforms that include both return stroke and continuing current components. With proper analysis, the ELF/VLF sensors provide approximately 100 microsecond time resolution (sufficient to partly resolve the return stroke) and a maximum duration of approximately 10 milliseconds (although this limit depends on the local signal to noise ratio). The ULF sensors provide approximately 5 ms time resolution, a duration of at least a few hundred milliseconds, and a sensitivity that is distance and noise dependent but is often equivalent to a few hundred amps or less. Combined, these measurements can provide accurate remote measurements of the major lightning charge transfer processes. With data from the LDAR II, it then becomes straight-forward to derive the charge lowered to ground, and a time series of the current flow in the return stroke and continuing current, as well as the volume of cloud from which the charge was removed. (We note that other ELF investigators worldwide will also be invited to contribute their observations of ΔMq as well (Sato et al. 2003, Price et al. 2002).

In theory, a network of ground-based electric field mills (EFM) can be used to determine the location and amplitude of lightning-caused changes in the cloud charge distribution and the net charge removed by the CG flashes. When operated in conjunction with an LDAR II system, such a network can also resolve the second and higher-order moments of the changes in cloud charge. This could provide another option for determining charge moments. EFMs are relatively inexpensive to install and operate and they operate at a very low data rate. For optimum results, the Houston area would need to be covered by a large number of EFMs at uniform sites, separated by 3-5 km baselines. The sensors would also have to be carefully calibrated in order to correct for any non-uniform surface features or field enhancement factors. The newly developed ULF/ELF/VLF lightning transient detection and analysis techniques are able to quantify key lightning characteristics, including charge lowered and continuing currents, on an operational basis over the entire HEAT domain at a highly affordable cost. Still, some local EFM instrumentation would be valuable.

The electromagnetic fields that are radiated by lightning return strokes and isolated cloud discharges are not well understood in the Houston area, but clearly the observations of Orville et al. (2001) and Steiger et al. (2002), coupled with observations by Vaisala staff, suggest that waveforms in the HLA may differ from those in nearby regions, and in Florida and Arizona. The unusually large negative first strokes (peak field strength) in CG flashes striking the Gulf of Mexico (salt water) and the unusually high percentage of isolated, small positive events that are probably cloud discharges (Cummins et al. 1998) are clearly anomalous. Proper classification and evaluation of these events will require broadband electric field measurements in conjunction with simultaneous video imagery and optical waveforms.

Given the high incidence of CG flashes in the region of the HLA, it is likely that the first stroke waveshapes will be different. Of particular interest will be the complexity of the radiation field that follows the initial peak – usually for a period of 5 to 50 microseconds after the peak. This interval contains a complex superposition of the fields from the main return stroke channel, the fields radiated by branch currents, and the effects of the complex 3-dimensional structure (and the associated impedance discontinuities) of these channels (Weidman and Krider 1982). Large branches are also frequently associated with the formation of multiple ground contacts.

During the 1998 and 1999 High Plains sprite field campaigns, high speed imaging (HSI) systems monitored individual CG strokes and optical continuing current durations (Lyons et al. 2003b), yielding true flash multiplicity, stroke intervals, branching and multi-attach point behavior, and the duration and optical intensity of the continuing currents common in both –CG and +CG flashes. The combination of HSI with remote ULF measurements (Swaminathan et al. 2003) allows retrieval of estimates of the duration and intensity of continuing currents to values as low as hundreds of amps. New digital HSI systems can achieve rates to 10,000 fps. The HSI system will be installed on a tall structure, affording a 360-degree monitoring capability for lightning storms. Using filters, a region of >3000 sq. km. within the 3-D LDAR II domain will be routinely covered during the day (greater ranges can be obtained during nocturnal storms). The HSI will be positioned to detect strokes occurring within the HLA, surrounding rural areas, and over adjacent salt water.

These measurements would be supplemented by two or more highly-portable (but lower time-resolution) digital video recording systems of the type described by Parker and Krider (2003). These systems will also record broadband optical and electric field waveforms with microsecond time-resolution that are precisely synchronized to GPS time. When these data are combined with the NLDN, LDAR II, and radar measurements, investigators should be able to determine: (a) how the amplitude, polarity, and shapes of the lightning radiation fields in the Houston area compare with those in Arizona and Florida; (b) how the parameters listed above are affected by the altitude of the initiation point in the cloud, the heights of the major branch points, and/or the stage of storm development; (c) whether and how the amplitudes and/or shapes of these fields are affected by the conductivity of the surface that is struck (i.e. ocean water or land);

and (d) whether the small positive (and negative) NLDN reports are produced by cloud or CG impulses.

The system developed by Parker and Krider (2003) is a relatively low cost, PC-based, data acquisition system that combines digital video imagery with optical and electric field waveform measurements, all synchronized to GPS time. In order to optimize the data acquisition, the system is portable and can easily be operated by unskilled personnel, such as students. Valine and Krider [2002] have previously investigated the geometrical development of cloud-to-ground flashes in Arizona using low time-resolution video cameras and have quantified the fraction of CG flashes that strike the ground in more than one place and how the number of strike points is distributed among CG flashes. These authors have also shown that the presence or absence of long branches and/or a long continuing current can alter the chances that a multiple-stroke flash will produce more than one strike point. Kehoe and Krider (2004) have shown that the actual (and the NLDN) multiplicity of return strokes in CG flashes varies considerably from storm-to-storm.

It is important to note that low cloud bases and relatively poor visibility in Houston will limit the area over which a single video camera can provide useful information. This has become clear in an experiment in North Texas, and it is in stark contrast to the relative ease of obtaining clear lightning images in Arizona. Obtaining single video camera images in Houston should be even more difficult than in North Texas. For this reason, at least two portable data collection systems will be operated simultaneously, and more if resources permit. When these measurements are combined with the fixed-based HSI and ULF/VLF recordings, the chances for a statistically meaningful database will be greatly increased.

If the visibility permits, the conventional video cameras could also document the convective cloud development in the HLA during the daytime (a useful resource for case study analysis).

GOALS OF STUDY: An overall goal will be to fully characterize the development of CG strokes and flashes, the presence and characteristics of the continuing currents, and the changes in the cloud charge and the charge moment during HEAT. The combined suite of NLDN, LDAR II, DLI, and ULF/ELF/VLF systems are expected to provide a unique combination of lightning metrics for many hundreds and perhaps even thousands of strokes. These results will provide the baseline data to rigorously evaluate any differences in the lightning parameters that relate to changes in land use, pollution levels, storm type and phase of life cycle, and microphysical characteristics of storms (determined by other HEAT investigators) inside and outside of the HLA.

As a natural outcome of the science objectives described above, the measurements made during the HEAT campaign can also be used to validate and calibrate the NLDN in the Houston area. Such a calibration has already been carried out near Tucson (Parker and Krider 2003, Kehoe and Krider 2004), and studies are currently underway in North Texas. Vaisala, who is the operator of the NLDN, has sponsored both of these field campaigns. Given the year-to-year variations in the lightning climatologies we have seen in North Texas, we believe it will be important to determine if the NLDN performance in North Texas can be extrapolated to the Houston area, and to quantify any regional differences that exist.

This NLDN validation study will determine what fraction of the actual CG flashes and strokes that occur (as determined by video, optical and electric field waveform measurements) are reported by the NLDN, as a function of the peak field. In addition, we will make a preliminary assessment of the NLDN location accuracy by comparing the reported NLDN stroke locations on different return strokes that are known to remain in the same channel.

An ancillary objective of the program will be to address the long-standing issue of whether the enhanced negative peak currents over the salt water of the Gulf of Mexico and Galveston Bay are real or NLDN artifacts. Part of the LDAR II domain and the HLA cover this area. The high density of > 200 kA negative CG flashes over salt water, but not the adjacent land, was first pointed out by Lyons et al. (1998). A lack of any comparable affect on +CGs has been noted by subsequent investigators. The ULF/ELF/VLF and DLI systems working in tandem could estimate peak current intensities for comparison to the contemporaneous NLDN measurements. If these large peak current –CG flashes prove to be a network artifact, reanalysis of some existing lightning climatologies will be required. If the –CG peak current enhancement is real, the underlying physics will clearly need to be explored. And just might the possible presence of negative "superbolts" over oceans be related to the apparent preference for giant blue jets to occur above maritime storms? The HSI system fitted with an image intensifier will be on stand-by to monitor for giant blue jets over any nocturnal storms over the Gulf of Mexico as targets of opportunity.

MEASUREMENT REQUIREMENTS:

Table 1. Summary of HEAT Lightning Observations and Derived Parameters (NLDN, LDAR II, DLI, ULF/ELF/VLF)

NLDN
Flash/stroke location
Polarity
Flash/stroke peak current
CG flash rates
Estimates of stroke multiplicity over a large area

LDAR II
Height of charge removal (Zq)
Geometrical extent of cloud and CG flashes
Location of first flash in a radar cell
Cloud and CG flash initiation points
Cloud flash rates
Cloud/CG ratio
Area/volume of charge removal
Duration of Cloud+CG event

DIGITAL LIGHTNING IMAGERS
True stroke multiplicity
Number of attachment points per flash and stroke
Stroke intervals
CG flash optical duration
Branching behavior
Cloud channel characteristics
Duration and intensity of continuing currents within each stroke
M-components and other fluctuations in channel luminosity

ULF/ELF/VLF TRANSIENT ANALYSIS (combined with above systems)
Charge moment change per stroke, stroke rates
Charge lowered to ground by return strokes (within LDAR II domain, estimated outside)
Estimated return stroke peak currents
Estimated continuing current magnitude and charge lowered

OBJECTIVE L2: Thunderstorm electric field profiles over Houston and over non-urban environments

PROCESS TO BE STUDIED: To further quantify the electrical aspects of thunderstorms in the Houston area, electric field measurements must be taken through both urban and rural thunderstorms. The gross charge structure and altitudes of the main charge layers in urban and rural thunderstorms are critical components to many of the lightning, cloud microphysics, urban heat island and complex coastline objectives of HEAT. Observations of the electric field in thunderstorms are needed in order to determine if the gross charge structure is different in urban versus rural storms. This will help determine whether the 12% decrease in the percentage of positive CG flashes in Houston is due to changes in charge structure associated with urban versus rural storms. Observations of the height of the main charge layers in radar reflectivity cells will help determine whether urban heat island, complex coastline and pollution effects cause elevated charge layers in urban storms as opposed to rural storms.

There are four major ways of obtaining electric field profiles in thunderstorms (1) through balloon-borne electric field soundings, (2) through aircraft measurements, (3) through a ground-based EFM network and (4) through LDAR II lightning mapping observations. Balloon-borne electric field soundings will be able to measure the charge distribution as a function of altitude in urban and rural thunderstorms over time periods of about 1.5 hours. These measurements will give a snapshot of the charge structure within a thunderstorm. However, the charge structure of a storm can change over shorter time periods than 1.5 hours and the balloons carrying the electric field sensors are often displaced large distances downwind of the storm in strongly sheared environments. The temporal issues can be overcome by launching balloons over shorter time intervals, such as every 30 minutes. This would require tracking multiple electric field sounding balloons at the same time.

Aircraft measurements of the electric field by the University of North Dakota Citation aircraft would allow the temporal evolution of the electric field in the clouds to be measured. The Citation can be outfitted with six field mills and the technical expertise to install and operate the mills resides at NASA MSFC, which has extensively calibrated the aircraft geometry for electric field measurements. Other aircraft installations will require the same intensive and time-consuming calibration. NASA MSFC has developed software to retrieve the ambient Ex, Ey and Ez from the airborne field mills. Another big advantage of the Citation aircraft is that it also carries the requisite precipitation and aerosol microphysics probes that are an essential part of the HEAT program. However, an aircraft will only be able to measure the electric field in the region of the cloud through which it is flying. In order to obtain the vertical charge structure of a thunderstorm, the aircraft will have to make many passes at different altitudes through the storm.

In theory, a ground-based electric field mill (EFM) network could allow continuous inferences of the vertical charge structure of thunderstorms in regions through which lightning is propagating. As mentioned in Objective L1, EFMs are relatively inexpensive to install and operate and the data they generate is very low. However, EFMs can not be used to identify charge regions that are not involved in lightning or identify subtle features in charge regions. The Houston area would need to be covered by a large number of EFMs, separated by 3-5 km baselines. Also, EFM measurements can not be coupled with in situ microphysical measurements, such as on the Citation aircraft. Still, some local EFM instrumentation would be valuable.

The LDAR II network will allow a limited, but continuous set of observations of the vertical charge structure of thunderstorms (Detwiler et al. 2002, Stolzenburg et al. 2003, Rison et al. 2001). The gross charge structure of storms can be inferred from the distribution of RF sources detected within lightning flashes. Since negative leader propagation through positive charge regions produces a more powerful signal at VHF than positive leader propagation through negative charge regions, the portion of a lightning flash that propagates through a positive charge layer will produce a higher density of RF sources than the portion of that flash that propagates through a negative charge layer. The direction of initial breakdown within a lightning flash also helps to elicit the locations of positive and negative charge layers because breakdown always occurs from the negative to the positive charge regions within cloud flashes. However, LDAR II can not be used to infer charge regions that are not involved in lightning or identify subtle features in charge regions.

GOALS OF STUDY: **Fill in from printed version**

MEASUREMENT REQUIREMENTS:

Table 2 summarizes the parameters that need to be observed during the HEAT program to fully quantify the lightning activity in urban versus rural thunderstorms in the Houston, TX area.

Table 2. Summary of the parameters that need to be observed during the HEAT program in order to fully quantify thunderstorm electrification and lightning activity in urban versus rural thunderstorms in the Houston, TX area.

Parameter to be Observed	Observing Systems (PIs)	Considerations	Priority	Cost
CG lightning flashes	U.S. NLDN (Dr. Orville??)	Continuous monitoring of CG lightning data in the Houston, TX area	Essential	Receive data for free
Total lightning flashes	LDAR II (??)	Continuous monitoring of total (cloud and CG) lightning data in the Houston, TX area	Essential	Funded by NSF ~$450,000
Charge Moment (Option 1)	ULF/ELF/VLF sensors (Dr. Lyons, Dr. Cummer, Dr. Huffines)	The necessary sensors are already installed and being operated in the continental U.S. by Duke University. Will monitor storms over entire region.	Essential, unless ground-based EFM network is installed	~$150,000 in data processing
Charge Moment (Option 2)	Ground-based EFM network (No one yet)	Can also continuously monitor the gross charge structure in lightning producing storms	Essential, unless ELF sensors are used	Does not exist $$??
True CG flash multiplicity and continuing currents	HSI+ULF System (Dr. Lyons, Dr. Cummer, Dr. Huffines)	DLI will measure true multiplicity and continuing currents of CG strokes that are within visible range of the system. Visibility limitations prevent coverage of the entire LDAR II domain.	Essential to characterize multiplicities, continuing current and other behaviors	$$??
True CG flash multiplicity and continuing currents	Two or more low speed, digital cameras, photodiodes and electric field antennas (Dr. Krider, Dr. Cummins)	DLI will measure the true multiplicity and continuing currents of CG flashes that are within visible range of the system, limited to less than the full LDAR II domain. A major benefit is these systems are mobile. But, it has lower temporal resolution than HSI system.	Essential to characterize multiplicities, continuing current and other behaviors	$$??
Gross charge structure in thunderstorms (Option 1)	Balloon-borne electric field soundings (??)	Can monitor the vertical structure of the electric field, in detail, regardless of lightning production, but it provides only a snapshot, not continuous monitoring	Essential	$$??
Gross charge structure in thunderstorms (Option 2)	Citation aircraft equipped with EFMs (Dr. Christian, Dr. Bateman, Dr. Petersen)	The NASA MSFC EFMs have already been calibrated for the Citation aircraft, the Citation has the requisite microphysics probes and it can monitor the vertical structure of the electric field, in detail, regardless of lightning production	Essential	$$??
Gross charge structure in thunderstorms (Option 3)	Ground-based EFM network (No one yet)	Continuous monitoring of the gross charge structure as long as lightning is occurring in the storm (it will not be able to detect all the charge layers, however it is better than inferences of charge layers by LDAR II), also can measure the charge moments of lightning flashes	Essential, unless balloon soundings, Citation aircraft measurements and LDAR II meet the needs of HEAT	$$??
Gross charge structure in thunderstorms (Option 4)	LDAR II (??)	Continuous monitoring of the inferred gross charge structure as long as lightning is occurring in the storm, however not very detailed (it will not be able to detect all the charge layers). Major benefit: system is already funded.	Essential	Funded by NSF ~$450,000

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