

CHAPTER VI. OPTICAL CHARACTERIZATION AND MODELING OF PARENT STORMS.

VI.1. Optical signatures as seen from satellite platforms: One of the key issues under investigation is the expected optical signatures of TREMEs' parent lightning from a space-based detector. This is a key issue for CTBT optical monitoring, for analysis of the LANL FORTE PDD detector data, and for the NASA/OTD/LIS (lightning imaging system). The fundamental issue is the efficiency of detection of events through clouds. Upon review of the analytical approach (Thomason and Krider, 1982) and the numerical approach (Koshak et al, 1994), we have concluded that the fundamental unknown is not the scattering process itself, which appears to be treated adequately, but (1) the distribution of cloud particles within the cloud and (2) where in the cloud the discharge occurs. Neither of these phenomena has yet to be adequately modeled, although in collaboration with others in the community (discussed below) we have made some progress in characterizing them. This issue is amply demonstrated by space-based imagery as shown in Figure 1. These are three captured frames from the shuttle-based video on mission

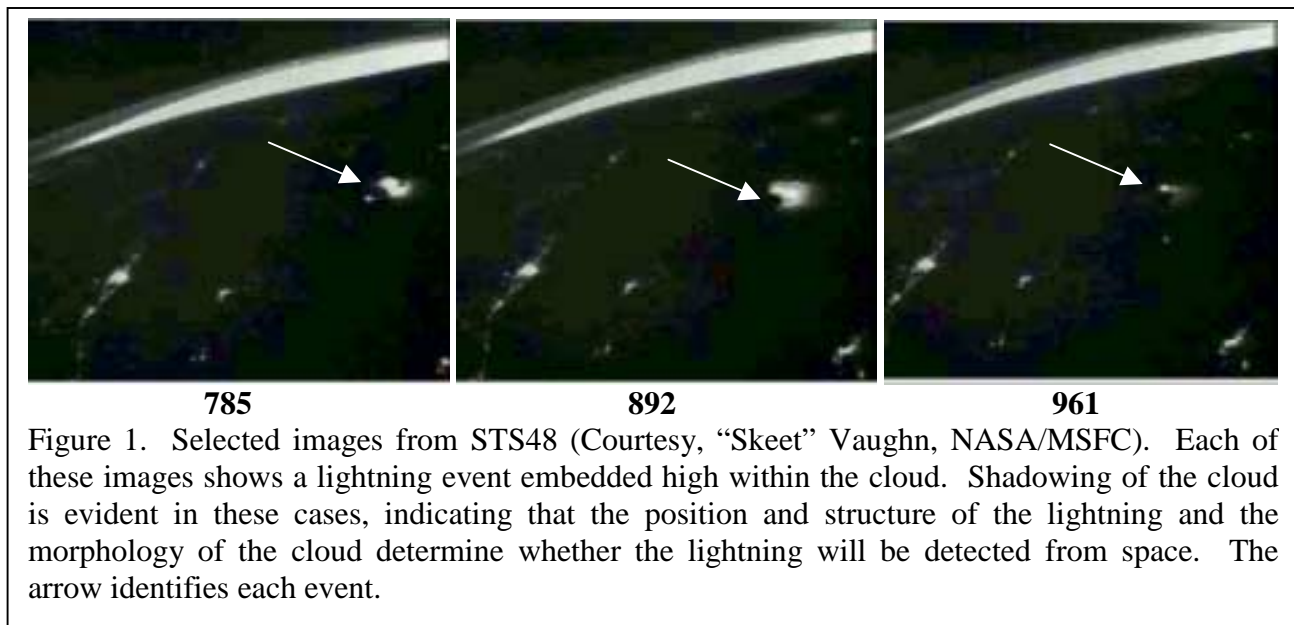
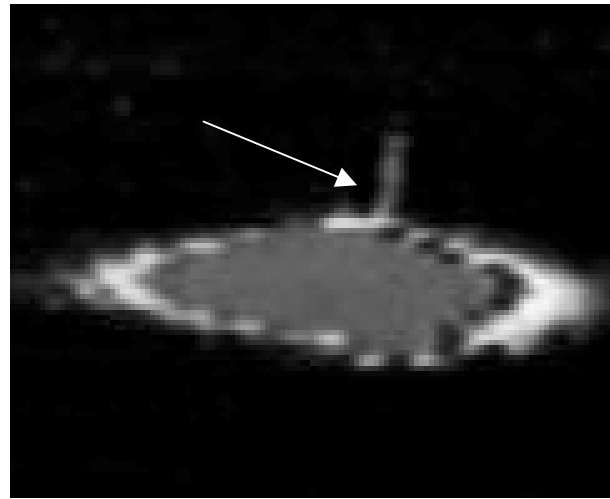


Figure 1. Selected images from STS48 (Courtesy, “Skeet” Vaughn, NASA/MSFC). Each of these images shows a lightning event embedded high within the cloud. Shadowing of the cloud is evident in these cases, indicating that the position and structure of the lightning and the morphology of the cloud determine whether the lightning will be detected from space. The arrow identifies each event.

STS-48 (Vaughn, 1992, 1998). In all frames, one can identify “shadowing” of the lightning by the cloud. It is also clear, after careful review of the shuttle-based movie sequences that the lightning detected from space usually occurs high up in the cloud, not from cloud-to-ground (CG). This effect is shown in Figure 2. Figure 2(a) shows an image taken from a U-2 aircraft which clearly shows the shadowing of a CG by the intervening cloud. Figure 2(b) shows an image taken from the Space Shuttle (Vaughn, 1998) where the TREME is evident, the very bright cloud-top discharge actually saturates the detector, but the parent CG cannot be seen. In fact, analysis of FORTE data indicates that less than 6% of the negative CGs are detected and less than 9% of the positive CGs are detected from the satellite (Suszcynsky et al, 1999). This is in complete agreement with other investigations by the NASA/OTD/LIS research teams (e.g. Boccippio, et al, 1998, Thomas, et al, 1999). NASA/TRMM/LIS often does *NOT* detect the early development of the charge redistribution which occurs typically at about the freezing level in the stratiform region, ~6 km - *the cloud obscuration precluded satellite observation*. This is the altitude location of many dendritic lightning structures connected to CGs with continuing



(a)



(b)

Figure 2. Images of lightning events from high-altitude. (a) Image from the NASA U-2 aircraft showing the cloud obscuration, and (b) image from the Space Shuttle of a lightning event with an attendant TREME. The apparent shadowing of the top of the cloud is actually a lightning discharge which saturated the imager. (Courtesy, Skeet Vaughn, NASA/Marshall)

current as recorded by from Yucca Ridge (for example, Figure 3). Also evident is the fact that LIS *does* detect the charge redistribution which occurs at higher altitude in the cloud, similar to



Figure 3. Image of a large parent CG and associated Initiation of a large horizontal dendritic channel structure. (Lyons).

that shown in Figure 2(b). What is not known, and cannot be determined from any data collected to-date, is the character of the cloud morphology that results in obscuration of the lower-altitude discharges and visibility of the higher-altitude discharges. The relevance to the DOE detection mission is that satellite observations of small-yield NUDETS may be constrained by optical transmissions through clouds. Conversely, the very bright discharges which occur near the cloud top, may be a source of clutter in discrimination algorithms. This renders potential NUDET-generated transient electromagnetic events at high altitudes more important.

Another not-well-defined characteristic of lightning is the time-waveform as detected from space as a function of the cloud morphology and lightning structure discussed above. The importance of this is demonstrated in Figure 4, where we compare the expected total power waveform from nuclear events, as calculated with the RADFLO code (McCartor, 1997 – the single high-altitude case was from MODEL3), the waveform derived from shuttle video of lightning, and a waveform derived from ground-based high-speed video of lightning. The optical signatures from NUDETS can be very complex, especially for shallow-buried cases or for cases where cloud obscuration occurs. A review of a number of lightning optical waveforms, such as shown in Figure 4(b,c), also reveals a complex waveform for both cloud-to-ground (CG) channels

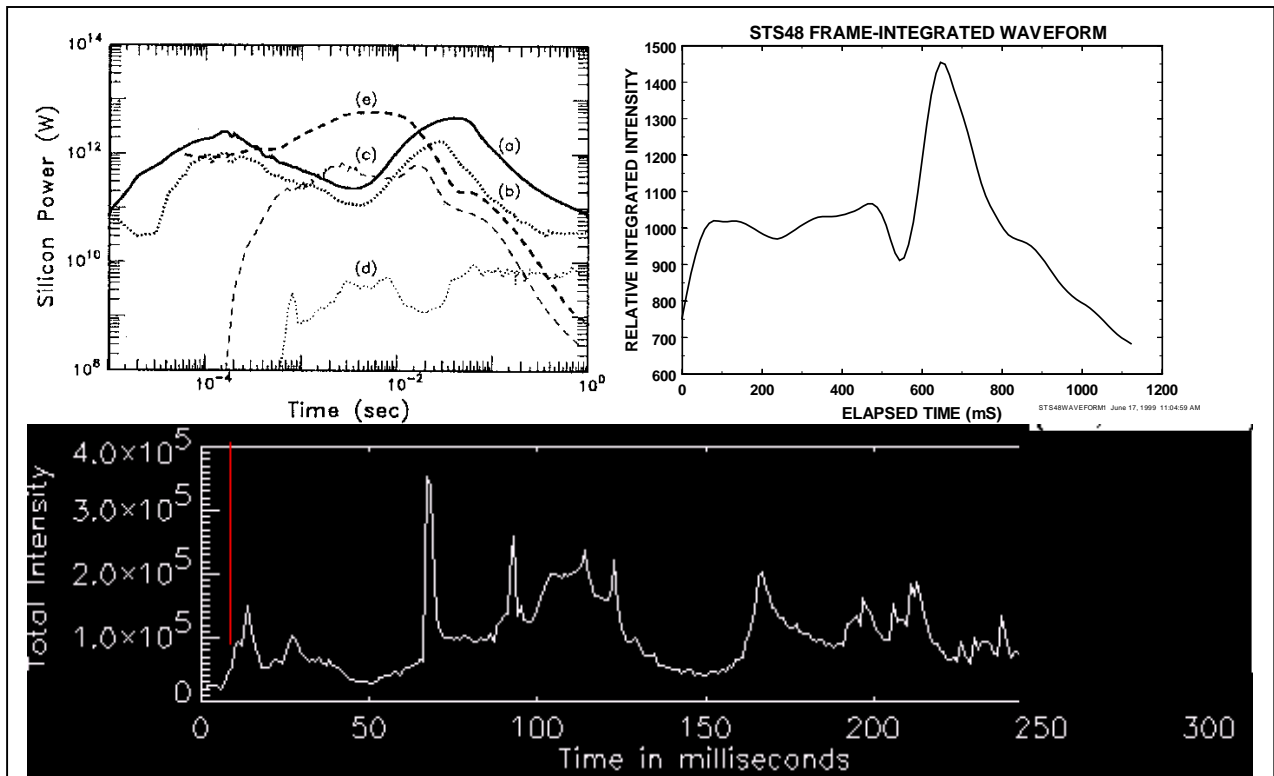


Figure 4. Temporal waveforms comparing (a) expected nuclear total optical power, (b) relative integrated intensity from a space-detected lightning event and (c) relative integrated intensity from a ground-detected lightning channel. The nuclear signals are for different burst-position conditions (shallow-buried to high-altitude) and are not corrected for atmospheric attenuation. The space-observed lightning signal is derived from the STS48 shuttle mission video records (e.g. figure 1, above) and the ground-observed lightning signal is derived from high-speed video taken at Yucca Ridge, CO.

where continuing current is present and for inter-and-intra-cloud (IC) charge redistribution. Contrary to relatively recent belief, lightning events often persist for several hundred milliseconds, with many persisting for well over one second. The relationship between continuing current in CGs and extended waveforms for the corresponding ICs is not yet well established. This is a key topic for future investigation since it appears that continuing current and charge redistribution within the cloud are key components of TREMEs.

VI.2. Modeling of storms and the attendant optical obscuration: In order to address the issue of cloud obscuration, we have initiated a data-and-model based prediction program for the development of thunderstorms and the cloud particles contained therein. After a half decade of observations and analyses, it is becoming clear that TREMEs, while occurring above many parts of the globe, are associated only with certain classes of storms and lightning discharges which exhibit distinctive (though only partially understood) characteristics (Lyons et al, 1999). Therefore the use of “standard” clouds and “standard” lightning models, based upon generic studies, is likely to lead to erroneous conclusions with respect to the transmission of light from TREMEs parent lightning discharges as viewed from space-borne sensors.

During the past decade there have been significant advances in meteorological data assimilation technologies which allow synthesis of disparate meteorological data sets, both *in situ* and remote, into physically consistent, detailed, time-dependent 3-D portraits of storm systems. These “data fusion systems,” which are in fact the initialization portions of complex mesoscale and cloud-scale prognostic models, can ingest a wide variety of sources including GOES digital visible and infrared data, surface cloud reports, automated aircraft reports, wind profiler soundings, and most importantly, Level II NEXRAD radar reflectivity and velocity data. What emerges is a 3-D portrait at sub-kilometer scales of the dynamical and microphysical structure of storms. The system initiated here is based upon ADAS (The ARPS Data Analysis System – ARPS is the Advanced Regional Prediction System) developed by the University of Oklahoma’s Center for the Analysis and Prediction of Storms (an NSF/FAA-funded center of excellence - Brewster, 1997). ADAS has been further adopted by Lyons and Moon (1998) for NASA KSC to include an advanced objective analysis scheme based upon the natural neighbor method (the Voronoi Tessellation). This permits physically consistent analyses of data which are highly heterogeneous in space and time. The ADAS scheme can, in turn, initialize either the ARPS or MM5 cloud-scale models to produce time-evolving simulations of actual storms. The result is a realistic 3-D distribution of state variables (temperature, pressure, wind) as well as microphysical parameters (cloud droplets, rain droplets, ice crystals, snow, graupel, hail, etc.). An advanced interactive visualization system called the environmental WorkBench (EWB) allows the model output to be visualized, animated and operated upon (Moon et al, 2000; Lyons et al, 2000).

This software will allow us to retrieve atmospheric state variables and cloud microphysical properties along any arbitrary line of sight path (such as from a space-borne detector). Using this information as an input to the scattering models (e.g. Thomason and Kreider, 1982) and adding the atmospheric transmission from PLEXUS and the characteristic discharge patterns from LMS (Krehbiel et al, 1999), we will be able to rapidly generate reliable predictions of optical transmission of lightning (and NUDETs) through clouds to a satellite. This is directly applicable to the FORTE optical (PDD) data analysis activity at LANL (Suszcynsky, 1999).

Although we have by no means completed the development of this program during this contract effort, we have made significant progress. During the SPRITES’99 campaign, we significantly enhanced our mesoscale modeling capabilities. The NCAR/Penn State MM5 model was activated for use, both for preparing daily forecast production runs as well as post-event high resolution simulations. During the 6-21 August 1999 NASA balloon campaign the MM5 was run daily. It utilized the ETA 32 1200 UTC and 3 hourly forecast fields as initial and boundary conditions. The ADAS initialization scheme was employed (Brewster, 1997; Moon and Lyons, 2000). The model domain covered eastern Wyoming, Colorado, Nebraska and Kansas. The horizontal mesh employed was 15 km. Thirty vertical layers were used (to 20 km). The model run was exercised on dual Pentium III 500 MHz processors. Forecasts were available by 2100 UTC. They were primarily used for making go/no go discussions for stratospheric balloon deployments. The model performed exceptionally well on 18 August 1999 when it suggested a massive MCC would form over the western High Plains by sundown, as was the indeed the case.

In order to support analysis and interpretations, the MM5 was configured for fine-scale simulations. The 18 August 99 case was recomputed, using a much finer mesh. Two nested grids, at 9 and 3 km, with 40 vertical levels and full microphysics were employed. Run times

were approximately 5x real time on the Pentium III processors. Initial fields and boundary conditions were extracted from the RUC2 NCEP gridded analysis fields and GOES digital infrared files. The initial runs have shown significant promise in simulating many of the key features of the mesosynoptic regime for that case. Unfortunately, there has been a delay in obtaining the Level II NEXRAD radar data tapes from the archives at the National Climatic Data Center (NCDC) due to administrative problems. Experience shows that assimilation of the Level II radar reflectivity data is of considerable importance in refining post-event simulations of this type.

We also configured a new visualization software system called WxPortal (Moon et al., 2000), in

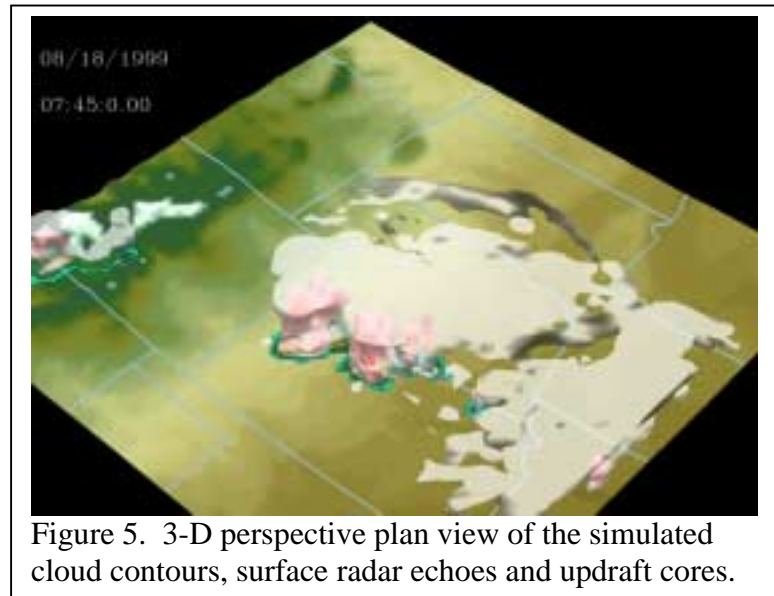


Figure 5. 3-D perspective plan view of the simulated cloud contours, surface radar echoes and updraft cores.

order to perform 3-D visualization and animation of these storms, its attendant lightning and sprites. Figure 5 (left) shows a 3-D perspective plan view of the simulated cloud contours, surface radar echoes and updraft cores. Surface wind streamlines, temperature, surface rainfall rates and cloud condensate ($> 0.1 \text{ g/m}^3$) are displayed in Figure 6. This analysis software also allows us to retrieve atmospheric state variables and cloud microphysical properties along any arbitrary line of sight (such as from a spaceborne detector).

VI.3. Characterizing the development of storm charging, and lightning as they affect optical character:

TREMEs have captured the interest of a wide range of atmospheric researchers (Rowland, 1998; Rodger, 1999; Winckler, 1997). Several basic mechanisms have been postulated, with many variations, to explain the observed luminous structures. These include electrical heating from quasi-electrostatic (QE) mechanism (Pasko et al., 1995), sprite production by runaway electron beams (Roussel-Dupré and Gurevich, 1996; Bell et al., 1995), and

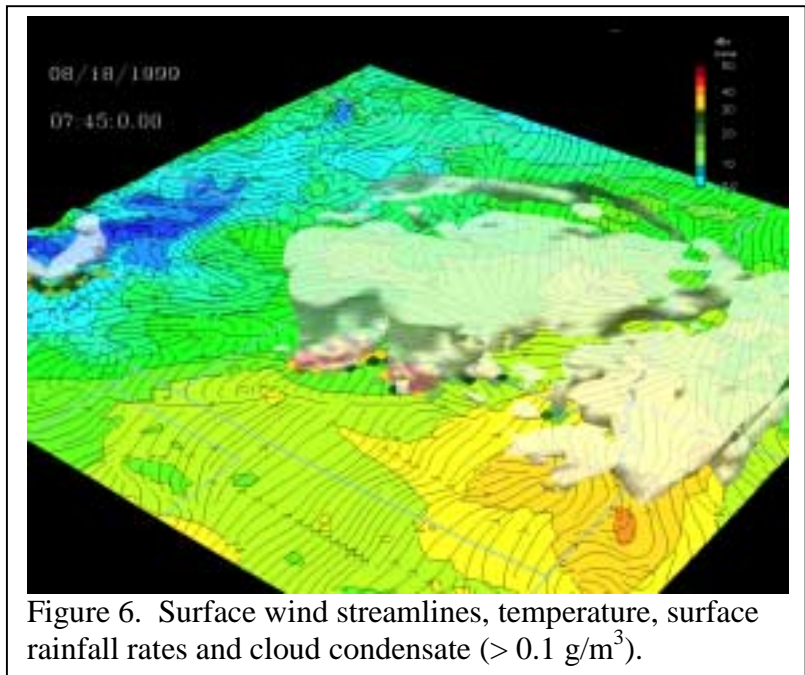


Figure 6. Surface wind streamlines, temperature, surface rainfall rates and cloud condensate ($> 0.1 \text{ g/m}^3$).

electromagnetic pulses (EMP) (Taranenko et al., 1993; Inan et al., 1996). Sprites exhibit a bewildering variety of shapes and sizes (Moudry et al., 1999). Evidence suggests that all the above processes may be operating, though on different temporal and spatial scales, in order to produce the complex optical appearances of sprites. Spatial scales range from sub-100 meter (individual streamer-like elements - Armstrong et al., 1998) to almost 100 km wide clusters. Absent from almost all of the many published modeling papers, however, are specific data on key parameters associated with lightning flashes that actually produced sprites. Many modelers refer to standard reference texts (Uman, 1987) or summary papers (Rakov, 1998). These summaries, however, tend to compile data taken in storm types and locales that are not representative of the nocturnal High Plains environment. Specifically, many invoke the conventional view that the positive charge reservoir for the lightning is found in the upper portion of the cloud at altitudes of ~ 10 km. The positive dipole (or tripole) storm model has been found wanting in many mid-continental storms (MacGorman and Rust, 1998; Williams, 1998). Table 1 summarizes the lightning parameters selected by investigators in a number of theoretical TREME modeling studies. While the height of the vertical +CG channel ranges from 4 to 20 km, there is a clear preference for 10 km and above. The amount of charge lowered ranges over three orders of magnitude, as does the time scale over which the charge transfer occurs. Only a few papers consider the possible role of horizontal spider component of the +CG discharge (e.g. Figure 3, above).

These uncertainties may be critical in determining the success of models of storms which will predict the optical obscuration. With so many parameters employed in these models, inaccuracy in one term may be compensated by errors in another, perhaps resulting in an apparently correct answer but for the wrong reason, further confounding a fundamental understanding of the problem. The charge moment (C-km), not the peak current as measured by the NLDN, appears to be the key parameter driving the basic QE heating mechanism. This was first proposed by Wilson (1925) who considered conventional breakdown from strong lightning electric fields as a likely source for stratospheric optical emissions. Bell et al. (1995) noted the key physics of the problem involves both the magnitude and altitude of the removed charge - two of the parameters about which there exists little agreement. Many theorists noted that even with an assumed tall +CG channel (~ 10 km), this still requires extremely large (~ 100 Coulombs) charge transfers, typically ten times larger than in "conventional" lightning. Some models (Pasko et al., 1996) yield a thousand-fold enhancement in TREME optical intensity at 75 km for a doubling of the lightning charge removal altitude from 5 to 10 km. The use of shorter channels to ground, say 5 km, would thus imply truly immense charge transfers. Yet evidence is accumulating that indeed such may be the case. As Williams (1998) points out, lightning charge transfers of hundreds of Coulombs from the 4-6 km altitude range may be required to obtain consistency between theories of sprite optical intensity and observed ELF Q-burst intensities.

While the various models reproduce optical emissions bearing some (though in many cases very minimal) resemblance to the observations, such wide ranges in the lightning source term parameters do not appear physically realistic. If in fact such a range of lightning characteristics could produce sprites, why does only a very small subset of +CGs (estimated at $<1:20$) actually produce TREMEs? It appears that most models have made assumptions about the lightning in order to produce something resembling a TREME - rather than starting with hard physical

Table 1. Lightning Characteristics Assumed in Selected Theoretical Modeling Studies of TREMEs.

<i>Study</i>	<i>CG Channel Height (km)</i>	<i>Total Charge Transfer (C)</i>	<i>Contin. Current Time Scale* (ms)</i>	<i>Horizontal Discharge Considered</i>	<i>Mechanism</i>
Bell et al. (1995)	>10	>250	N/A	None	Runaway Electrons
Bell et al. (1998)	10	32-100	~ 1 ms	Sometimes	Quasi-electrostatic
Lehtinen et al. (1997)	5, 10	225	~ 1 ms	None	Runaway Electrons
Pasko et al. (1995)	5, 10	200-300	~ 1 ms	None	Quasi-electrostatic
Pasko et al. (1996)	10	200-475	1-19 ms	None	Quasi-electrostatic
Taranenko & Roussel-Dupré (96)	15	100	N/A	None	Runaway Electrons
Roussel-Dupré & Gurevich (96)	18	100	N/A	None	Runaway Electrons
Yukhimuk et al. (1999)	8-10	280-400	5-20 ms	None	Runaway Electrons
Milikh et al. (1995)	10	N/A	20 ms	>10 km	RF Breakdown
Roussel-Dupré et al. (1998)	11.5	200	3-10 ms	None	Runaway Electrons
Rowland et al. (1995)	10	55-300	0.05 ms	Yes-6 km	EMP
Inan et al. (1996)	10	200	0.10 ms	None	EMP
Valdivia et al. (1997)	N/A	100	~1 ms?	100 km	EMP (100 kA I _{max})
Cummer and Inan (1997)	10	25-355	5 ms	None	Quasi-electrostatic
Fernsler & Rowland (1996)	12-20	200	0.10 ms	None	EMP/QE
Cho & Rycroft (2000a,b)	5	200	0.025 ms	50 km	EMP/Interference
Marshall et al. (1996)	4	380-37000	N/A	20-200 km	QE

*Estimated time constant for scaling the continuous current believed associated with sprite producing +CGs

constraints on the source term. The reason, of course, is that there is very little data on the actual CGs which generate specific TREME occurrences.

We note the relatively simplistic models of the mid-1990s are gradually giving way to more complex codes which invoke 3-D, time-dependent lightning sources, such as Cho and Rycroft (2000a,b). To simulate complex TREMEs, models will require information on total charge removed, the altitude from which it was removed and the rate (including during the continuing current) of removal, the geometry of the horizontal component of the discharge, and the

propagation of the vertical and especially horizontal channels. These data are rarely available for any lightning event, much less TREME producers.

VI.4. Upcoming Investigations to obtain fundamental data: The STEPS field campaign, scheduled for the summer of 2000, with its deployment of state-of-the-science lightning and RF sensors, radar, aircraft, and video and photometric measurements, may be the first to begin seriously addressing the issues of storm development, cloud structure electrification and discharge characteristics. Using limited observations, theoretical considerations and initial findings from ELF transient measurements (Huang et al., 1999), we have formulated a conceptual model of the meteorological conditions and lightning associated with TREMEs. We believe those CGs involved differ dramatically from those in “ordinary” convection in many respects. We expect to find extremely high charge transfers and large charge moments, unusual continuing current characteristics and, for sprites, a likely association with horizontally extensive (~100 km) “spider” lightning discharges. These are thought to occur near the melting layer in MCS stratiform regions, typically around 4-5 km. As discussed above, numerous theoretical models invoking several fundamental mechanisms for TREMEs, have been proposed. These models, however, all suffer from a common weakness in that there are no available data on the characteristics of specific lightning discharges which actually produced a sprite or elve.

The Severe Thunderstorm Electrification and Precipitation Study (STEPS), planned for 22 May - 16 July 2000, promises to obtain for the first time a coherent description of the evolution of the dynamics and microphysics of TREME producing storms and the physical characteristics of +CGs which produce them. STEPS is a multi-agency field program that will allow for multi-platform remote and in situ measurements of electrically active High Plains severe storms. The STEPS observation domain will be centered near the intersections of Colorado, Kansas and Nebraska (Figure 7). This region, located between 200 and 400 km distant from YRFS, has

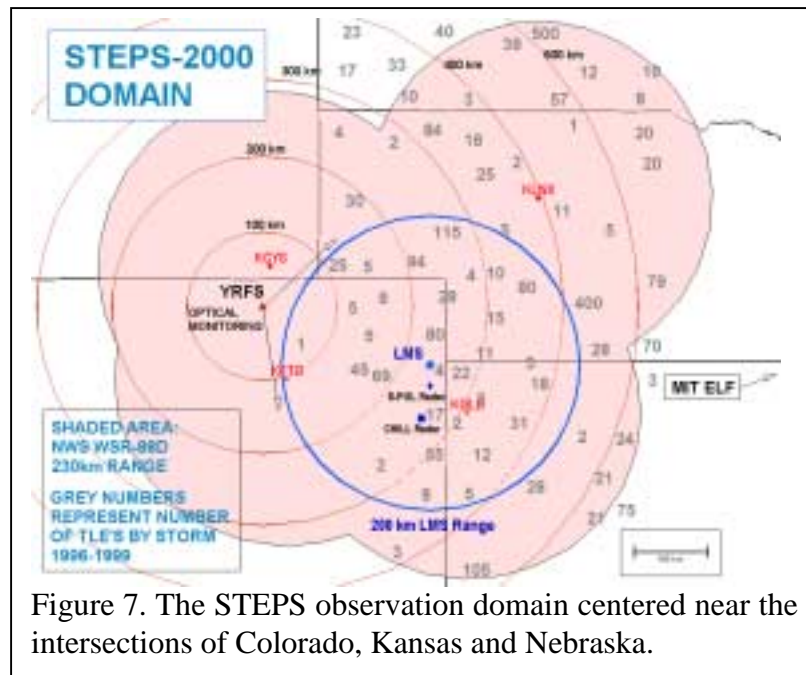


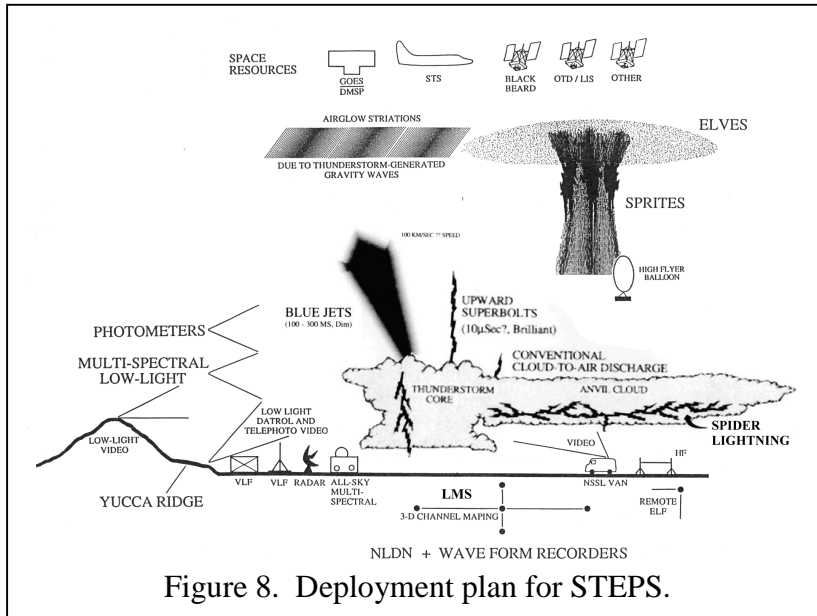
Figure 7. The STEPS observation domain centered near the intersections of Colorado, Kansas and Nebraska.

frequent TREME-bearing storms. Between 4 and 8 TREME-producing storms are anticipated to pass through or near the region during the program. A complete suite of aircraft, multi-parameter radars, lightning sensors, mobile laboratories and balloon systems is planned for deployment (Figure 8). For details, visit www.mmm.ucar.edu/community/steps.html.

Of particular relevance to TREME research will be the deployment of the New Mexico Tech 3-D Lightning Mapping Array (LMA) and associated

field mills and slow antennas (Krehbiel et al., 1999). The LMA will for the first time allow

mapping and characterizing the 3-D structure of lightning discharges which do and do not, produce TREMEs (Figure 9). This will permit coordinated observations of TREMEs (low-light television, multi-color photometers), and in many cases, their associated lightning events (using conventional and high speed cameras) along with ELF transient recordings at several locations worldwide. One of the objectives is to create a unified description of the lightning discharges which do and do not produce sprites and elves in the context of the parent storm dynamics and microphysics. The lightning characterization will provide improved parameterizations for various theoretical TREME models. Specifically the planning objectives are to:



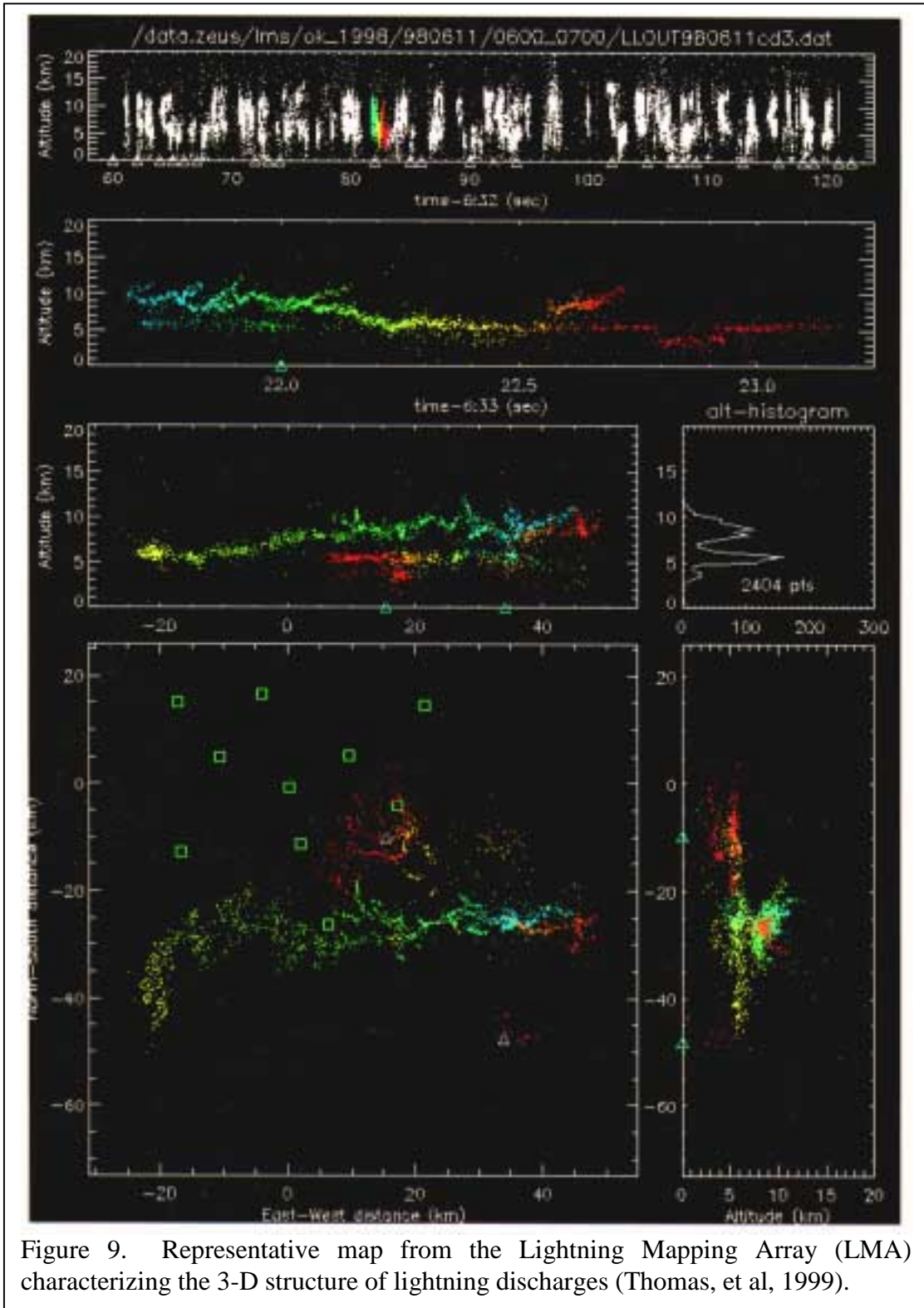
- Document and characterize, using optical and RF methods, the occurrence of TREMEs above storms in and near the STEPS domain and coordinate this information with STEPS investigators and other colleagues.

- Synthesize the several lightning related measurements to determine the physical distinctions between the +CG events which do and do not produce sprites and elves. The continuing current characteristics and extensive horizontal

dendritic components of the +CGs as mapped by the LMS are of particular interest.

- Categorize those convective storm structures which do, and do not, generate TREMEs, and specifically isolate those regions within the storm and periods during its life cycle that lightning capable of generating TREMEs occurs.

- In conjunction with MIT (Earle Williams) and Tel Aviv University (Colin Price), collect data which will quantify the reliability of ELF Schumann resonance signatures (Huang et al., 1999) as the basis for a global sprite detection and location system by determining the probability of detection and false alarm rates for TREME occurrences from +CGs.



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