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FINAL REPORT

Sensor System to Monitor Cloud-to-Stratosphere Electrical Discharges

submitted to

National Aeronautics and Space Administration
John F. Kennedy Space Center
Kennedy Space Center, Floirda 32899

under

NASA SBIR Phase II
Contract NAS10-12113

submitted by

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Principal Investigator

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25 April 1996

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*** APPENDIX VOLUME ***

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EXECUTIVE SUMMARY

This report summarizes the findings from the Phase II SBIR project, "Sensor System to Monitor Cloud-to-Stratosphere Electrical Discharges, " from the NASA Kennedy Space Center, Contract NAS10-12113. The major tasks included (1) improving the understanding of the physics of transient luminous events, (2) forecasting their occurrence, (3) developing and testing sensor systems to detect and characterize the phenomena, (4) assessing their impact including the threat posed to aerospace operations, and (5) establishing an information exchange for observations and theoretical studies. Two field programs were conducted, SPRITES'94 and SPRITES'95 which resulted in the compilation of a very large library of video, audio and digital data from a suite of optical and RF sensors.

Anecdotal reports of unusual forms of "lightning" discharging into the "stratosphere" have been reported globally for over a century (Lyons and Williams, 1993) and theoretically postulated (Wilson, 1925). It remained for a chance observation from a low-light video system in 1989 to actually document that such events existed (Franz et al., 1990). Subsequently, low-light video imaging systems on board the Space Shuttle (Vaughan et al., 1992), on aircraft (Sentman et al., 1995) and at ground stations (Lyons 1994 a,b; 1995; 1996) have revealed that large stratospheric and mesospheric transient luminous events (TLEs) above mesoscale convective systems (MCSs) are rather common. Observations each summer since 1993 from the Yucca Ridge Field Station (YRFS), 20 km northeast of Ft. Collins, CO, have documented over 2000 such events. The YRFS field programs have documented three types of TLEs: sprites, elves and a blue jet.

During 1994, the emphasis was on developing forecasting techniques and data acquisition systems. Low-light imagers were operated in conjunction with a high speed photometer and several VLF receivers. A major discovery was the strong correlation between sprites, positive polarity cloud-to-cloud (+CG) flashes, and ELF transients called Q-bursts (Boccippio et al., 1995). Initial evidence of brief ionospheric flashes (now called elves) were also found. The SPRITES'95 observational effort evolved into a major international field program with the participation of 48 scientists from 16 organizations representing four countries. The deployment of high resolution pointing photometers (Fukunishi et al., 1996) resulted in the definitive identification of a new class of transient luminous event, elves (emissions of light and VLF perturbations from EMP sources). For the first time, a ground-based LLTV captured an apparent blue jet (Lyons, 1996). The relationship between sprites, +CGs and Q-bursts was further confirmed (Inan et al., 1995; Fullekrug et al., 1996). Distinct signatures of sprites were also found in the VLF. The presence of VLF slow tails appears to distinguish between large peak current +CGs that do and do not produce sprites (Reising et al., 1996). Blue jets are not associated with specific +CGs but may be spawned in storms having a high rate of -CG activity.

The first known climatology of large peak current CGs of both polarities was prepared from 14 summer months of NLDN data. A remarkable disparately was uncovered in the distribution of large positive and large negative CGs. The positives were strongly clustered in the High Plains and Upper Midwest, the region under surveillance by the YRFS sensors. The large -CGs were concentrated in the southeastern US, especially over the waters of the Gulf and Atlantic, including the KSC region. Whether blue jets are far more common in that area is still uncertain.

Using the CG climatology, an estimate was made of the chances of the Space Shuttle being involved in a sprite or elve during descent into KSC. The probability, on the order of one in hundred, is markedly higher than the chances of being directly struck by conventional lightning. Several techniques have been developed that could allow for routine monitoring of electrical discharges having a high likelihood of generating sprites or elves. The measurement of ELF transients could provide nearly global coverage, and by connecting several sensors already deployed in the U.S., the airspace over KSC could be routinely monitored for sprites and elves. Also prepared was an extensive bibliography of papers from several disciplines relevant to the observations and theoretical understanding of transient luminous events. An appendix volume presents summaries of the data sets available, and key research papers generated by the project staff and cooperating groups. A companion video describes the project and its results. Follow-on studies (SPRITES'96) are being funded by the U.S. Air Force Office of Scientific Research.

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The results from SPRITES'94 and rapidly growing interest from the scientific community resulted in the SPRITES'95 observational effort becoming a major

international field program with the participation of 48 scientists from 16 organizations representing four countries. The deployment of high resolution pointing photometers (Fukunishi et al., 1996) resulted in the definitive identification of a new class of transient luminous event, elves (emissions of light and VLF perturbations from EMP sources). For the first time, a ground-based LLTV captured an apparent blue jet (Lyons, 1996). The relationship between sprites, +CGs and Q-bursts was further confirmed (Inan et al., 1995; Fullekrug et al., 1996). Distinct signatures of sprites were also found in the VLF. The presence of VLF slow tails appears to distinguish between large peak current +CGs that do and do not produce sprites (Reising et al., 1996). Blue jets are not associated with specific +CGs but may be spawned in storms having a high rate of -CG activity.

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Among the accomplishments of the Phase II effort, many made in conjunction with cooperating science teams, include:

- Sprites and elves are common occurrences in certain classes of thunderstorms
- Surface-based imagers can detect sprites at ranges up to 1000 km under ideal conditions; Triangulation confirms sprites and +CG are collocated within 50 km

- Above the High Plains, sprites and elves only occur with large (>20,000 km^2) mesoscale convective systems producing +CG events; It is possible to forecast with high accuracy those storms which will generate sprites
- Sprites and elves are quasi-electrostatic and EMP responses respectively to +CG flashes generally having much larger than average peak current
- The brightest portion of the sprite may have a duration on the order of 1-10 ms, followed by a long decay in luminosity; Elves are even more transient, lasting less than 1 ms
- There are likely several additional different classes of transient luminous phenomena to be found above thunderstorms
- Spectra confirmed the presence of the N_2 first positive bands in sprites and elves
- High resolution photometers confirmed presence of 427.8 nm band in sprites
- Clear-cut "VLF Sprite" signatures were discovered including the observation that those +CGs having a VLF slow tail (as measured at Palmer Station, Antarctica) had a much higher probability of being sprite producers; This suggests a key role for a continuing current in sprite-associated +CGs
- Initial calculations indicate significant production of NO by sprites in the stratosphere/mesosphere and a potential to influence climate change processes
- Firsts included coordinated launching of balloon-borne electric field mills into a sprite storm and attempts at radar mapping of sprites
- Evidence of airglow enhancement from thunderstorm-generated gravity waves
- Extensive press and media coverage (Discovery Channel, BBC, NY Times, New Scientist, Science, Discover Magazine, San Francisco Chronicle, etc.)

Also prepared was an extensive bibliography of papers from several disciplines relevant to the observations and theoretical understanding of transient luminous events. An appendix volume presents summaries of the data sets available, and key research papers generated by the project staff and cooperating groups. A companion video describes the project and its results, along with sample "highlights" from several of the major case study days. Follow-on studies (SPRITES'96) are being funded by the U.S. Air Force Office of Scientific Research.

1. INTRODUCTION

This document is a final written report under the NASA Kennedy Space Center Phase II SBIR contract NAS10-12113 entitled, "Sensor System to Monitor Cloud-to-Stratosphere Electrical Discharges."

In 1992, when the original Phase I solicitation was announced, there was little real understanding of transient luminous events (TLEs) in the middle and upper atmosphere, much less of their relationships to tropospheric electrical activity. The solicitation requested "a characterization of upward traveling lightning discharges from the tops of electrified clouds and their frequency of occurrence. Sensors that can operate unintended for long intervals are needed to acquire the data required." At the time, only a single non-ambiguous video observation of such an event existed (Franz et al., 1990), along with some tantalizing clues from Space Shuttle video that the phenomenon might not be a total rarity or "freak of nature" but a more commonplace accompaniment of thunderstorm electrical discharges (Vaughan et al., 1992). Yet nothing was known as to whether one or more types of such phenomena existed, how often they occurred and under what conditions, anything about their phenomenology and morphological characteristics, much less their basic physics or potential impacts. There wasn't even an adequate technical vocabulary extant with which to discuss the topic.

During the early 1990s, many atmospheric scientists were familiar with "cloud-to-stratosphere"(CS) lightning reports as summarized in the *Handbook of Unusual Natural Phenomena* (Corliss, 1977). This book is replete with reports of meteorological esoterica such as turtles encased in hailstones, half meter wide snowflakes and toads falling during rain showers. The "freak" CS event therefore tended to be viewed as an interesting meteorological conversation piece, but of little consequence. Yet an underlying current of thought suggested the CS may well be a routine and important feature of thunderstorms.

In early 1993, what was then called (by some) the cloud-to-stratosphere (CS) event was a most elusive phenomenon in the domain of atmospheric electricity. The occurrence of upward electrical discharges from thunderstorm tops has been speculated upon and occasionally observed for many decades. "It is quite possible that a discharge between the top of the cloud and the ionosphere is a normal accompaniment of a lightning discharge to earth...but one which is only likely to be visible under very special conditions...a diffuse discharge between the top of the cloud and the upper atmosphere...many years ago I observed what appeared to be discharges of this kind from a thundercloud below the horizon. They were diffuse, fan-shaped flashes of greenish color extending up into a clear sky" (Wilson, 1956). Many descriptive accounts of CS events are in a similar vein to the following: "The lightning phenomenon...appears to be the rare type of discharge known as *flachenblitz*. It is not peculiar to the tropics; in fact most of the recorded accounts refer to temperate latitudes. In its most typical form it consists of flames appearing to shoot up from the top of the cloud or, if the cloud is out of sight, the flames seem to rise from the horizon (Ashmore, 1951).

The larger question centered around potential impacts. Are these light displays of no more import to aerospace operations than rainbows? Or does the CS event pose a threat to Space Shuttle operations or, taking a broader view, to future aerospace plane flights which will operate in parts of the region from 15 to 80 km? The conventional lightning threat to the Space Shuttle system has been quantified by Mach (1989), who notes that for the STS during the launch phase the probability of a direct lightning strike is once in 160 years for a 4 km clearance from an active storm. Triggered lightning is obviously a concern to spacecraft, as witnessed by the Apollo 12 and AC/67 incidents (Uman, 1988; Christian et al., 1989). It has seemed far fetched that a TLE—the generic term we now prefer to use—could interfere with an orbiting shuttle. Yet nothing is known about changes in the electrical fields at higher altitudes that might accompany such phenomena. On the other hand, interaction with a TLE during launch or descent can not be discounted. A stratospheric analog to triggered lightning is a disturbing thought. The next generation of supersonic transports and the Space Plane will routinely overfly thunderstorms in the 20 to 50 km msl range. So little was known about the energetics of the TLE that any consideration of its ability to cause physical damage to an aerospace vehicle was pure speculation in the early 1990s. But given the ever increasing use of sensitive microelectronics in aerospace vehicles, disturbances in communications, telemetry and automated control systems seemed at least plausible.

Studies by Hays and Roble (1979) indicate that electric fields from large thunderstorms can penetrate to the altitude of low earth satellites and are detectable as perturbations to the background ionospheric conditions. A case of momentary enhancement of the airglow layer at 95 km coincident with an in-cloud discharge was noted by Boeck et al. (1992). Electrical discharges through this region constitute a highly nonlinear component of the global electrical circuit and point to possibly strong electrostatic induction effects in the ionosphere and magnetosphere.

The phenomenon was also of potential importance to other disciplines within atmospheric science. The role of TLEs in stratospheric NOx production (Drapcho et al., 1983; Chameides, 1986; Davis et al, 1983) may be of consequence. What is certain is that the interactions of tropospheric electric discharges with the stratosphere and ionosphere are complex and poorly understood.

The Phase I report from this program provided an extensive survey of TLE literature citations that have sporadically been appearing for over 100 years. These are summarized here. The earliest known report was that of Toynbee and Mackenzie (1886). Other well known visual observation reports in the literature include those of Everett (1903), Boys (1926), Gates (1982) and Fisher (1990). We obtained actual copies of virtually all the published reports in order to base our analyses on original sources wherever possible. Figure 1-1 shows, by decade, the number of TLE reports in the technical literature. Aside from a short burst during the 1950s, the majority of the references on this topic have appeared within the last decade and a half. The majority of the observation-based publications have been during the last five years. Several researchers, notably B. Vonnegut (SUNYA) and O.H. Vaughan, Jr. (NASA Marshall) summarized the growing catalogue of TLE event descriptions. These include a variety of qualitative accounts from credible witnesses (Vonnegut, 1980; Vaughan and Vonnegut, 1982; 1989). TLE reports have been widely dispersed geographically (Figure 1-2), with a broad distribution from equatorial regions to above 50° latitude (Figure 1-3). The large majority of the TLE sightings (>88%) were made at night. About 75% of the reported TLEs occurred over land, almost half were multiple events, and about 40% appeared to be somewhat tilted off the vertical. A preliminary analysis of the extant reports of eyewitness visual observations shows that they share at least one common characteristic—they are perceived as highly unusual and atypical of "normal lightning" (see Figure 1-4). Cloud-to-air (CA) discharges may extend outside of the main body of the cloud, sometimes terminating at the ground (the "bolt from the blue"). CA discharges extending a kilometer or so above active storm tops were documented in U-2 photographic overflights by Brook et al. (1985). Dendritic or "spider" lightning in the anvil regions of active or severe cumulonimbus clouds, often associated with severe weather, has been noted for years. These do not appear to explain any of the TLE events reported in the literature.

The TLE discharge is often associated with electrically active convective cloud systems with tops usually (but not invariably) in the vicinity of the tropopause. The discharge sometimes is described as a typical CG flash, except for terminating at an altitude many kilometers above the highest cloud tops. But other reports suggest a variety of luminous columns, beams, jets, fountains, and shafts. The rather bewildering panoply of descriptions lead one to wonder, by early 1993, if indeed we were discussing just one or a wide variety of "freak events" bearing little relationship to one another. It was our considered opinion that with the exception of a few "outliers", the CS reports tended to fall into several categories: (1) plumes, fans, or columns which are much fainter, more diffuse, and rather unlike any conventional lightning, often occurring at very great heights, (2) a fountain-like discharge which appears to emerge from the cloud top, and (3) the "bolts" or channels, more or less like "normal" cloud-to-ground (CG) discharges, but extending upwards to two or more times the height of the cloud. Figure 1-5 is an example of the first category. It is the much discussed Minnesota "plume" (Franz et al., 1990), a phenomena now called a sprite. Figure 1-6 may be an image of the second type. This was obtained from photographer Peter Jarver of Darwin, Australia and was taken in the late 1980s. It clearly shows a nighttime picture of a lightning channel extending almost vertically from the top of what is most likely a very tall and still developing cumulonimbus. The most intriguing aspect is the abrupt transition from the yellow-white channel to a fan-like, blue discharge extending to great heights with slowly diminishing intensity. This could well be the first known image of the phenomenon now called a blue jet. Figure 1-6 represents the third category. It is an artist's sketch of an observation reported by a Colorado resident (a non-meteorologist). Looking very much like a CG channel it discharged vertically "to very great heights above the cauliflower portion of a large thunderstorm over the Colorado eastern plains..." There are other eyewitness reports of such events, but no documented evidence of this phenomenon yet exists. There may be a fourth category that would be appropriate - that is, all the other observations that don't seem to fit any of the above. This residuum will be discussed at greater length below.

The current era of research into lightning-induced transient luminous events (TLEs) began with the first sprite video image (Figure 1-5) obtained by the University of Minnesota SKYFLASH program on 6 July 1989. The space physics community has long monitored atmospheric light pulses in search of evidence for cosmic x- or gamma-ray bursts manifesting themselves as upper atmospheric fluorescence. Their interest in TLEs stems from the possibility that they may represent direct coupling between lightning storms and the ionosphere and magnetosphere and may produce whistler waves and other disturbances (Franz et al., 1990). SKYFLASH uses an observing site about 60 km northwest of the Minneapolis-St. Paul metropolitan area (45°N, 93°W). During the night of 5-6 July 1989, they were testing a low-light-level TV camera, intended for a sounding rocket flight, by observing stars and a distant lightning storm. The camera was an ITT model 4562 ICID with a sensitivity of 10^{-5} lux and was capable of recording 6.5 magnitude stars in normal, real-time operation. At 0414:22 UTC 6 July, while directing the camera to the northern horizon, they recorded a twin flash originating in distant cloud tops and discharging into the stratosphere. The flash lasted for two 1/60-s TV fields with the greatest intensity occurring in the first field. This flash duration must be characteristic of the source, as the persistence time of the image in the intensified charge injection device (ICID) camera was less than one field. The TV camera did not record any other upward flashes during the remainder of the night or in subsequent monitoring. GOES imagery of that storm suggests that the sprite occurred within a mesoscale convective complex located just north of the Minnesota-Ontario border. Radar summary charts showed radar echo tops up to 14.8 km at 0435 UTC. The National Lightning Detection Network (NLDN) cloud-to-ground flash data showed a relatively low flash rate storm, although it did produce a rather large number of positive flashes. There was no CG flash reported concurrent with the CS event. Assuming the sprite came from within the general area of the storm, it was located about 200-250 km north of the camera site, within the anvil area of the cloud system. The flash was separated into two fountain-like jets as imaged by the TV, but the two structures were simultaneous in time within the 17-ms time resolution of the TV sweep. The separation of the two jets was estimated at 4 km or more.

The Minnesota observation prompted scientists at NASA's Marshall Space Flight Center to examine low-light television (LLTV) images taken from the Space Shuttle payload bay TV camera system. This work has been summarized in a series of papers by Vaughan et al. (1990) and Boeck et al. (1991a,b; 1993; 1995). To date, 18 cases of apparent electrical discharges into the stratosphere have been identified. The observations often resemble "luminous fingers of glowing gas stretching into the stratosphere". The evidence presented, in retrospect, makes it fairly certain that with one possible exception the TLEs observed were sprites. The TLEs appeared to be part of the thunderstorm discharge process. As shown in Lyons and Williams (1993) the vertical projection event occurred after the initiation of cloud illumination, presumably from inter-cloud (IC) or CGs, and generally very close to the time of maximum cloud brightness (Figure 1-8). To date they have all been singular events. Some of the visible discharges were estimated to extend more than 35 km above the 20 km high storm clouds (Vaughan et al. 1992). Boeck et al. (1991) concluded that the frequency of occurrence for TLEs was on the order of *1 per observed 5000 CG/IC discharges* and thus could be termed "unusual", but not rare. If one notes the range of annualized planetary lightning rates (Brooks, 1925; Orville and Spencer, 1979), Boeck's ratio implies between 0.6 and 2.5×10^6 CS events per year (every 12.5 to 50 seconds).

After intensive and repeated viewing of the Space Shuttle video imagery and compilation of detailed statistics on their phenomenology, one was left with the distinct impression that there is a rather high degree of repeatability in many aspects of the TLEs from event to event.

Given the results of the SKYFLASH group and the analysis of the Shuttle LLTV images, and the literature review showing a likely connection between TLEs and large mesoscale convective systems (MCSs), an experiment was conducted during Phase I using a low-light image intensified CCD camera from 7 July through 23 July 1993 at the site northeast of Ft. Collins, CO. The goal was to image the region above mesoscale convective systems some 200 to 900 km distant. On seven of ten nights, sprite discharges were found at heights estimated from 20 to perhaps 80 km (Lyons 1994 a,b). Literally hundreds of images were obtained, 248 on the night of 6-7 July alone. Figure 1-9 shows one of the many 1000+ sprite images since obtained from the Yucca Ridge Field Station (YRFS) using LLTV. These images apparently show the same phenomenon as observed by Franz et al. (1990) in the Space Shuttle imagery and the "plume" type discharges described by Ashmore (1951), Wilson (1956), Malan (1937) and others. Many of the TLEs occurred simultaneously with in-cloud flashes, although the great range of the storm system made many cloud flashes difficult or impossible to see. For the 7 July case, the average duration of the sprite was 5.9 video fields (98 ms). Most frequently the sprite reached maximum luminosity within the first or second frame (<33 ms), and then gradually dimmed. It was noted that not only did the sprites attain great altitudes, but they could at times be more than 100 km wide. Assuming circular symmetry implied the volumes involved could total hundreds of thousands of cubic kilometers. Initial estimates suggest that there were maybe one TLE for at least every 500 in-cloud flashes, an order of magnitude higher than the Boeck et al. (1992) estimate. Almost none of the events were visible to the naked eye. Only a few (the very brightest on video tape replay) could be seen with the dark-adapted eye.

Only one day after the initial 7 July 1993 discovery of frequent sprites above a large MCC, the Geophysical Institute of the University of Alaska (GI/UOA) obtained airborne images of apparent sprites. The NASA DC-8, using LLTV equipped with a fish-eye lens, imaged a number of sprites above a large MCC over Iowa (Sentman and Wescott, 1993). By this time it was becoming clear that sprites were anything but a rare event, at least above large High Plains and Midwestern thunderstorm systems.

The initial visual observation made by the PI that some of the sprites could be seen by the naked eye and appeared salmon-red in color was confirmed by the GI/UOA to attempt airborne reconnaissance using special color cameras previously employed in auroral research. The first full-color sprite images (Sentman et al., 1994) confirmed that the upper portion of the sprite was invariably red, though the trailing tendrils faded to blue at lower altitudes (Figure 1-10). The airborne measurements also yielded the startling discovery of what are now called blue jets (Wescott et al., 1995). As shown in Fig. 1-11, these blue-colored collimated sprays emerge from the cloud, moving upwards at greater than 100 km/sec, sometimes reaching heights of 40 to 50 km. Lasting on the order of 100-200 ms, they are distinctly different phenomena from sprites. They can be seen with the naked eye suggesting the visual observations reported by Fisher (1990) from a commercial aircraft were almost certainly blue jets. These fit the pattern of the second class of TLE.

Ground-based LLTV imaging of sprites continued from YRFS during the summers of 1994 and 1995, and a 1996 campaign is currently being readied. As the field of sprite investigation rapidly matured, the emphasis shifted from merely imaging TLEs to taking coordinated multi-spectral measurements. These became the focus of the Phase II effort and will be described in great detail below. As an example, during 1995, a series of high speed pointing photometer measurements by the team from Tohoku University (Fukunishi, 1996) revealed an entirely new phenomenon, now called elves. While actually brighter than sprites, they are so transient (lasting less than 1 ms) as not likely to be visible to the naked eye.

It appears likely that as more and more sensors are deployed over a wider variety of storm types, additional TLEs may be discovered. The postulated upward superbolt, the "true cloud-to-stratosphere" lightning channel that has been reported by reliable eyewitnesses has yet to be captured. Figure 1-13 summarizes the phenomena that have been documented (or in the case of superbolts, suspected) to date.

This report will describe in great detail the increasingly detailed investigation of sprites phenomenology and their causative mechanisms, what little is known about blue jets, the growing information on elves, and speculate on what other TLEs may be present. Included in this project report are summaries of the techniques developed with which to detect and characterize TLEs. The observations are also being widely used by the scientific community to develop and test theoretical models of TLEs. Finally some speculation on the impacts of the TLEs is provided.

1.2 Scope of the Project

A motivation behind this study is the evaluation of any threat posed by the processes associated with TLEs to the Space Shuttle, unmanned missions and future space planes which traverse the stratosphere and lower mesosphere. If they do indeed pose a threat, however, Phase I indicated we must now consider it much more so than previously due to (1) the far greater number of occurrences than once suspected, and (2) the very large volumes of atmosphere involved. Reports solicited from pilots (Vaughan, personal communication) include two cases in which jet aircraft overflying thunderstorms by many thousands of feet were struck from below by an upward traveling discharge. Another pilot reported straight, blue shafts of light, about a quarter mile wide, extending upwards to above 100,000 feet. While little information was available at the start of Phase II on the energetics of TLEs, it seemed prudent to begin investigations of their RF characteristics to assess whether the potential existed for the disruption of telemetry and communications, and perhaps on-board electrically sensitive hardware/software systems. Until the potential threat such as it is can be adequately quantified, might it not be prudent to avoid clouds that have the potential for producing CS events? Given that TLEs can extend to above 300,000 feet, storms some 2500 km distant from KSC may have the potential to impact a descending vehicle. We should also note that TLEs may be the visible manifestation of processes which may extend to even much greater heights. Some of the outstanding questions present in early 1994 when the Phase II effort was about to commence include:

- While often referred to as "upward electrical discharges," do we really have any knowledge of their direction of propagation or what actual currents are involved?

- What is the frequency of TLE events (absolute and as a fraction of CGs or ICs)?

- Do the reports of "blue columns" projecting from cloud tops represent a separate form of cloud-to-stratosphere discharge or are they just the unresolvable part of the overall phenomenon visible in the red-sensitive low light video of distant storm tops?

- Do TLEs represent some type of coupling between tropospheric and magnetospheric electrical processes? Are they related to whistlers?

- How high into the mesosphere can TL effects extend?

- What are the temporal and geographic distributions of CS events? Specifically, do TLEs tend to occur above certain definable cloud features at certain times during their life cycle, and are these conditions common in Florida?

- Can we propose and test a TLE prediction technique using routinely available meteorological data resources (radar, satellite, NLDN, etc.)?

- Is the CS event part of the IC/CG discharge process?

- Is an in-cloud or external trigger required to produce a TLE?

- What are the ranges of atmospheric conditions during which they can occur?

- Are CS events associated with positive CGs or some other easily identifiable event?

- What accounts for their curious structures, including the tendency for a "bright band" at roughly 70 km altitude and the wavelengths of the striations?

- Do CS events have a unique RF (or perhaps radar) signature that can be separated from the other waveforms generated by concurrent discharges? Specifically is the Schumann Resonance Q-burst a reliable (and unique?) signature of the CS event?

- Would optical measurements with better than 17 ms resolution reveal additional details helpful in understanding their physics?

- Is it feasible to operationally monitor TLEs temporally and, perhaps, spatially?

- Are there features of the CS which may allow it to be detected by spaceborne lightning mapping systems (Christian et al. 1989; Christian and Goodman, 1987)?

- What is the potential impact of the CS on aerospace operations? Are there grounds for altering current launch and descent rules for the Space Shuttle at KSC?

Within the resources and time allotted to a Phase II SBIR project it was not possible to address all of the above issues. Our initial plan, based upon our then current level of scientific understanding of TLEs included five major technical goals for the Phase II effort:

I. <u>SENSOR SYSTEMS TO DETECT AND CHARACTERIZE TLEs:</u> Design and conduct two field programs, beginning with a 1994 campaign in Colorado, which deployed a suite of sensors, both optical and RF, with the aim of automatically detecting and possibly locating the presence of TLEs, or alternately those phenomena with which they were associated. Once one or more signatures could be identified from the new data sets, operational tests could be designed and conducted in the KSC region for 1995 and thereafter in Phase III activities. The Phase

II field program consisted of a core *observation program* plus expanded efforts to facilitate the participation of *third party cooperating scientists* and their sensors.

II. IMPROVE UNDERSTANDING OF THE PHYSICS OF TLEs: Basic research was required to understand the underlying nature of the TLE luminosity, the electrodynamics of the phenomena, its radio emissions, possible atmospheric chemical consequences and its relationship, if any, to tropospheric/ ionospheric/mesospheric processes. Working with existing science teams to assist in developing and testing hypotheses was seen a vital component of the project.

III. FORECASTING THE OCCURRENCE OF CS EVENTS: The growing realization that TLEs represent one or more extremely complicated phenomena certainly suggested that while our understanding of them would increment during Phase II, we were still far from completely understanding them. On the other hand, there was strong evidence that they occur within certain well-bounded ranges of convective storm parameters, and are therefore predictable. Formulation and testing of predictive schemes (for both occurrence and non-occurrence) first for Colorado and the Florida was a priority.

IV. ASSESSING THE THREAT TO AEROSPACE OPERATIONS: While TLEs have been discussed for over a century they have not been perceived as a threat to stratospheric aerospace operations because (1) of their presumed rarity and (2) the notion that they represent low current discharges in the rarefied air above the tropopause. Given the apparent unexpectedly high sprite frequency implied by the Phase I findings, their potential impact on telecommunications, on-board electronic systems and flight operations had to be assessed in light of new understanding of the physics of the TLE likely to emerge.

V. ESTABLISH AN INFORMATION EXCHANGE FOR OBSERVATIONS AND THEORETICAL STUDIES: This function would continue and expand the Phase I efforts to compile all known literature references, summaries of observations obtained by the Project as well as third parties, and provided a focal point for information exchange with those scientists and organizations concerned with the phenomena. The purpose was not to supplant but to facilitate the activities of other research groups by providing a common point of contact of relevant and especially late breaking information in this multi-disciplinary area. To facilitate this goal, Phase II results were widely disseminated as quickly as possible to the various disciplines in order to obtain rapid feedback on our initial conclusions, and to incorporate quickly new developments from third party researchers.

The proposed process for this Phase II was of necessity somewhat different from other scientifically-oriented studies in which a clear and well defined hypothesis is initially stated and then tested according to a defined methodology. At the onset, TLEs were little understood, and new theories relating to their physical nature and therefore their optical and RF properties were emerging almost daily. Therefore, we adopted a process for Phase II planning that allowed for a high degree of flexibility while avoiding dilution of the effort by following too many leads and staying focused on several basic and achievable goals (within available resources). Some overall guidelines used in our planning process included:

- Given that our understanding of the physics behind TLEs was minimal, though evolving rapidly, we avoided becoming "locked into" preconceived notions as to their nature and possible signatures; thus we attempted to start with a clean slate, being open to new ideas from other disciplines besides conventional atmospheric electricity, such as the space physics community which has long speculated upon tropospheric/ionospheric/mesospheric linkages.

- In the same vein, we avoided attempting to impose our presumptions about the nature of TLEs on the data but rather let the new data "speak for itself."

- The TLE phenomena were of such apparent complexity that it was well beyond the resources of a Phase II project to address, much less solve all major issues; given this, we adopted a vigorous outreach program to entrain other scientific disciplines and research teams as cooperators in both the 1994 and 1995 field programs as well as the analysis and interpretation of the data.

- Give the limited time to prepare for 1994, we used to the greatest extent possible field-tested equipment and software, along with experienced personnel.

- "Negative" results were valuable. For example, if we could confirm that TLEs were not the source of the long light pulses in the SKYFLASH photometer data, this helped further bound the problem.

- Project management continuously reached out to other research teams to assure that its work was complementary rather than competitive with their ongoing efforts.

- Free and open exchange of data with participating scientists after appropriate quality control measures was essential.

- Much of the data obtained was best displayed and interpreted in video formats; thus scientific image processing and professional video production tools were used to display the various data sets and analyses in an more easily comprehensible manner (video project reports).

A number of identifiable tasks were proposed. They can be summarized as follows:

Task 1: Continued Analysis of Available Data
Task 2: Continued Synthesis of Third Party Observations and Theories
Task 3: Outreach Program to Interested Scientists and Organizations
Task 4: Formulate Experimental Design
Task 5: Design and Fabrication of Sensor Systems
Task 6: Build Primary Data Acquisition System
Task 7: Supporting Data Acquisition Systems
Task 8 : Visualization System
Task 9: Develop Data Displays and Analytical Tools
Task 10: Video Productions
Task 11: Develop Forecasting Algorithms
Task 12: Conduct 1994 Colorado Field Program
Task 13: Review and Interpretation of 1994 Data Sets
Task 14: Preliminary Florida Tests (1994)
Task 15: Revise Experimental Design
Task 16: Plan and Conduct 1995 Colorado Field Program
Task 17: Plan and Conduct 1995 Florida Field Program
Task 18: Analysis and Interpretation of 1995 Results
Task 19: Monitor Related Studies
Task 20: Synthesis of Data and Findings
Task 21: Risk Analysis To Aerospace Operations
Task 22: Sponsor Briefings and Reporting Functions

On the whole the author contends that Phase II was successful. While not evolving exactly in the manner planned, many of the principal goals were achieved and tasks accomplished. Most importantly, the SPRITES'95 field campaign at YRFS proved to be an unusually productive exercise involving scientific teams from literally around the world. An entirely new phenomenon (elves) was documented and significant quantitative information on sprites, blue jets and elves was obtained. The Phase II funding was able to be leveraged in a way that greatly multiplied the resources applied. An enormous database was assembled, only the smallest portion of which has been mined. Most importantly, there developed a community of interested scientists whose interests spanned from the purely observational to the highly theoretical, interacting in a cross disciplinary manner quite unprecedented in the experience of the PI. Phase II's success has led to follow-on studies that are expected to continue for several more years, with the anticipated results being of direct benefit to the sponsor. The following sections will attempt to enumerate and summarize the results of the Phase II program.

1.3 Summary of Accomplishments

The two year Phase II project begun in April 1994 permitted the formulation of an observational design plan which included field programs in Colorado and Florida during 1994. During this time sensor systems were tested and techniques developed. Based upon the results of the first year fields studies, plus an ongoing series of interactions with other science teams, a much larger program (SPRITES'95) was conducted at Yucca Ridge in the summer of 1995. A second follow-on effort was also attempted in Florida during the late summer of 1995.

This report summarizes the various systems deployed, techniques utilized, and results obtained, with material presented largely in the context of case studies. For orientation purposes we will briefly summarize the key technical and scientific results of the Phase II, as well as the information exchange activities.

1.3.1 Technical and scientific

There have been, and will continue to be, numerous technical and scientific findings emerging from the Phase II efforts, both from the contractor directly or in cooperation with the various teams that have participated in the many stages of the project. Many of the accomplishments below were made by these external cooperating science teams which relied heavily on the coordinated measurement program at Yucca Ridge. Some of the more important items are summarized in bullet form below:

- Documented and studied at least three major classes of transient luminous events (TLEs) associated with cloud electrical activity (sprites, blue jets, elves)

- Created a very large database of over 1000 TLEs and supporting meteorological, optical and RF measurements that can be further investigated by cooperating science teams

- Confirmed that sprites and elves are frequent occurrences above High Plains Mesoscale Convective Systems (MCSs)

- Documented that sprites can involve many tens of thousands of cubic kilometers of the stratosphere and mesosphere; elves generally are found in the layer between 80 and 105 km band and can expand outward to cover more than 400 km in diameter

- Demonstrated relationship of sprites and elves to positive CGs, especially those having large detected peak currents

- The relationships between sprites, +CGs and Q-bursts was identified; Schumann resonance transients can potentially diagnose the presence of sprites and/or elves on a global basis using either single station or multiple site direction finding techniques

- Evidence is accumulating that only +CGs associated with large continuing currents may generate sprites; this suggests that the role of horizontally extensive "spider" lightning (dendritic anvil lightning) may be extremely important as the mechanism whereby large quantities of charge are transported

- Stereo imaging confirms that sprites are generally spatially coincident to less than 50 km with their parent +CG

- Developed sprite forecasting criteria for High Plains mesoscale convective systems based on +CG and radar echo size criteria that has proven unusually successful

- Demonstrated that long range optical detection of sprites and elves was possible from YRFS to ranges of up to 1000 km

- Documented at least one event from the ground that appears similar to the blue jet phenomena

- Multi-channel high speed photometry identified the lower ionospheric flash as separate transient luminous event (elves)

- Obtained numerous optical spectra which confirmed the presence of the Nitrogen First Positive band as the primary emission in sprites

- Coordinated optical and RF measurements of specific sprite events has begun to shed light on the degree of ionization within the luminous volume

- Confirmed presence of "VLF sprites" both in transmitted signals and emitted from the sprite volume itself

- Sprite detection using perturbations in transmitted VLF signals along given paths was demonstrated

- Demonstrated that VLF techniques which detect and locate sprite volumes may be a feasibility using relatively simple equipment

- Narrow band photometry (4172A band) provides some evidence of significant ionization in sprites and/or elves

- Initial calculations of sprite impacts upon upper atmospheric chemistry suggest sprites and elves could be a significant regional source of oxides of nitrogen previously unaccounted for in global atmospheric chemical models

- High speed infrared optical and infrared measurements (IROCS) attempted to obtain high temporal resolution images of sprites

- Active probing of sprites using both radar and bi-static HF transmissions was undertaken

- Successfully vectored a van to launch balloon-borne electric-field measurements above a Kansas mesoscale convective system demonstrating the feasibility of using low level (20 km) balloons for sprite studies

- Imaged gravity waves emanating from sprite producing storm systems

- Obtained evidence of other types of luminous phenomena

More results are emerging on an almost daily basis. It is expected that within six to twelve months major new insights will be obtained, both from the analyses of the data and the theoretical investigations underway. The above are just a few of the more salient findings as of the date of this writing.

1.3.2 Information Exchange

One of the keys to the success of the project has been the free and open exchange of information between the various participating science teams as well as the broader community of interested parties. ASTeR's role during the last year became one of facilitator, that is providing LLTV, lightning and meteorological information to other teams conducting case studies. This has resulted in substantial cross fertilization of ideas and a large number of results already being published.

Extensive written, fax and e-mail communications between SPRITES'95 participants occurred before, during and after the experiment. Drafts of papers have been freely circulated. Several workshops and symposia were conducted in which the focus was the SPRITES'95 data and its interpretation. An active publication schedule is being maintained. Large numbers of conference presentations (12 at the Fall 1996 AGU meeting alone) have been presented by participants in SPRITES'95. There has been considerable press interest in the findings. Numerous newspaper, magazine and television reports covered the activities of the various participants in considerable detail.

1.3.2.1 Publications and Technical Symposia

Figure 1-13 summarizes the known peer-reviewed publications and conference preprint articles that have been generated by personnel of the contractor, its consultants or members of the cooperating teams. Much of the material presented in this report consists of synopses of these more detailed papers.

A significant number of conference presentations have been made by contractor personnel, either singly or in conjunction with members from other science teams. A selection of the technical presentations made is shown in Figure 1-14. Included in the general symposia were presentations made at Lawrence Livermore National Laboratory, Fermi Lab, and the AMS chapters at Colorado State University, the University of Northern Colorado, the NWS Office in Cheyenne, WY and the National Center for Atmospheric Research.

It should also be mentioned that several SPRITES'94 and SPRITES'95 related workshops have been held over the past 18 months. Among these are:

- SPRITES WORKSHOP, held in Dec., 1995 in conjunction with the Fall AGU meeting. Over 40 persons were in attendance. At the three hour meeting data, analyses and draft reports were exchanged. Summary presentations on the state of the analyses were presented by over 15 groups (see Figure 1-16 for the agenda).

- AFOSR/Phillips Lab, held in October, 1995, a one day assembly of approximately 70 scientists working on various aspects of the sprite program. A video project summary was prepared and presented.

- AFOSR/Phillips Lab, held in April, 1996, smaller working session of 20-25 scientists who reviewed results from SPRITES'95 and began preparation for the next season of data acquisition under Air Force sponsorship.

In addition to the AGU sessions, there have also been sprite-related sessions at both the 1994 and 1994 URSI conferences held in Boulder, CO. These provided opportunities for most participants to present results in the context of radio science as well as to informally network.

A similar session was held in conjunction with the 1995 IAMAP meeting in Boulder. The PI chaired a morning-long session on sprite related topics. Several social gatherings were also held at YRFS during the summer of 1995 which provided excellent opportunities for most of the interested parties to come together and informally discuss key scientific issues.

In addition, ASTeR, Inc. made regular contributions to the quarterly Atmospheric Electricity Newsletter that is edited by Earle Williams at the Massachusetts Institute of Technology. This newsletter is widely distributed to the entire atmospheric electricity community and keeps that community abreast of recent project developments.

1.3.2.2 Press conferences and press coverage

There has been considerable public interest in sprites, elves and related phenomena. ASTeR, Inc. has responded to literally dozens of press inquiries.

Two major press conferences were conducted in conjunction with the 1994 and 1995 American Geophysical Union meetings in San Francisco. The first was organized by Dave Sentman and colleagues from the University of Alaska. The 1995 conference was organized directly by ASTeR, Inc. Participating were W.A. Lyons, U.S Inan (Stanford), Stephen Mende (Lockheed Martin) and Russ Armstrong (MRC) Other program participants, including Dave Sentman, also attended from the audience. Both meetings, especially the latter, were very well attended (over 25 reporters). The news releases (See Figure 1- 17) are thought to have been picked up by several hundred newspapers in the U.S. and overseas. A selected sample of the press coverage is shown in Appendix C, including feature pieces in the *New York Times* (see Figure 1-18) and *Science News*. The journal *Science* also ran two feature stories which included the NASA-sponsored work. The level of popular interest in the topic is attested by the full color illustration in the June 1996 issue of Earth Magazine used in a feature story called "Fires in the Sky" (Figure 1-19).

A large (24 x 36 inch) full color poster of sprite images taken from the YRFS during SPRITES'95 was produced by Lockheed Martin. It is our understanding that over 10,000 of these posters were distributed to the scientific community and the public.

Television and radio coverage included:

(1) Columbine Cable Vision, northern Colorado Cable, feature story.
(2) NBC News, Denver, feature story.
(3) The Know Zone, feature story, shown widely on the Discovery Channel.
(4) BBC London, live radio interview during 1995 Florida study.

1.3.2.3 Video productions

Over 200 two-hour long video tapes of storms with sprite potential have been acquired, including 135 for SPRITES'95 alone (see Appendix A). Since much of the data obtained by the contractor is in video format, and the sprite, elves, blue jets and their associated RF signatures can only be appreciated through audio and video, four video tape presentations were prepared by the contractor. These have been used at conferences, seminars and have been widely distributed to interested parties. These tapes are:

(1) "The 1994 Colorado SPRITE Campaign," produced for the 1994 American Geophysical Union Fall Meeting, San Francisco.

(2) "SPRITES'95 - Initial Results", produced for the AFOSR/Phillips Lab workshop, Hanscom AFB.

(3) "The Colorado SPRITES'95 Campaign: Initial results'" produced for the American Geophysical Union Fall Meeting, San Francisco.

(4) "Processing, Integrating and Displaying Disparate Data Sources from the SPRITES'95 Field Program," produced for the 12th IIIPS for Meteor., Oceanog. and Hydrol., American Meteorological Society, Atlanta.

A compendium of these video productions has been assembled as an addendum to this final report. Also included are copies of the NBC and Discovery Channel stories, along with sample highlight sequences for three case study days (23 June, 15 July and 16 July 1995). The latter are compilations of all sprites, elves and blue jets with their associated VLF audio signatures.

All video was acquired using professional quality S-VHS tape and edited on a Media 100 digital non-linear editing system.

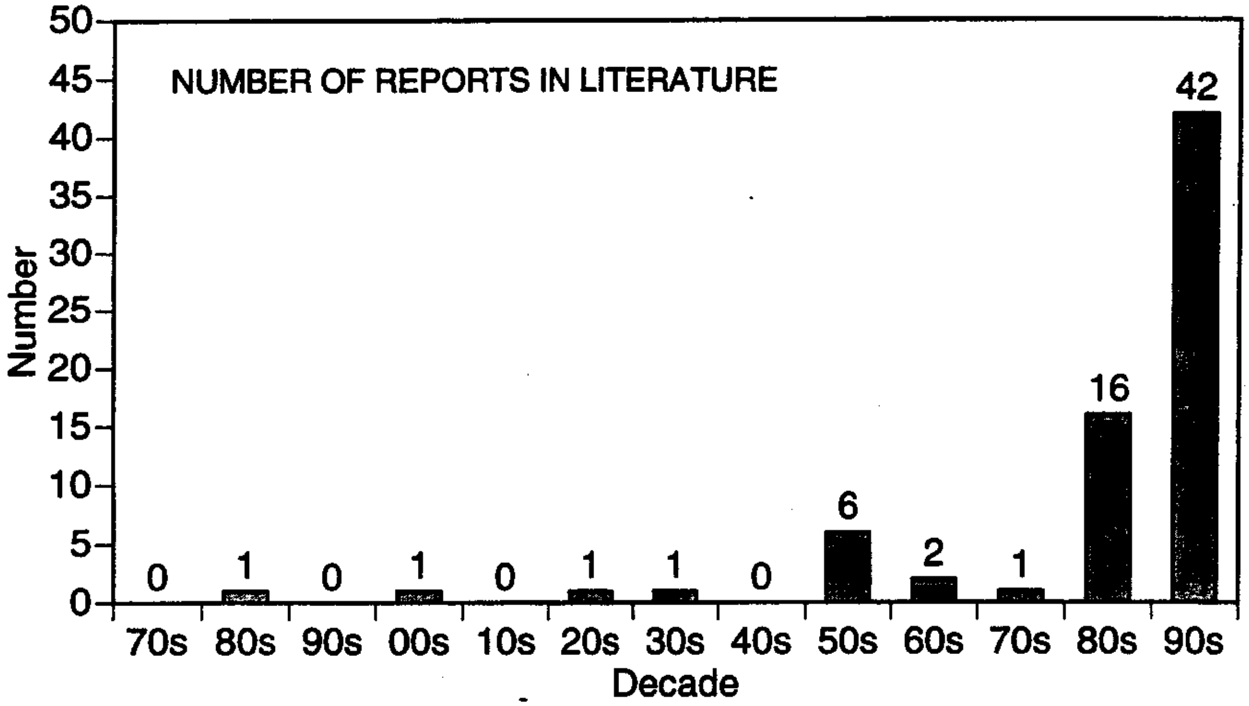

Figure 1-1. The number of literature reports of observations of transient luminous events above thunderstorms, by decade.

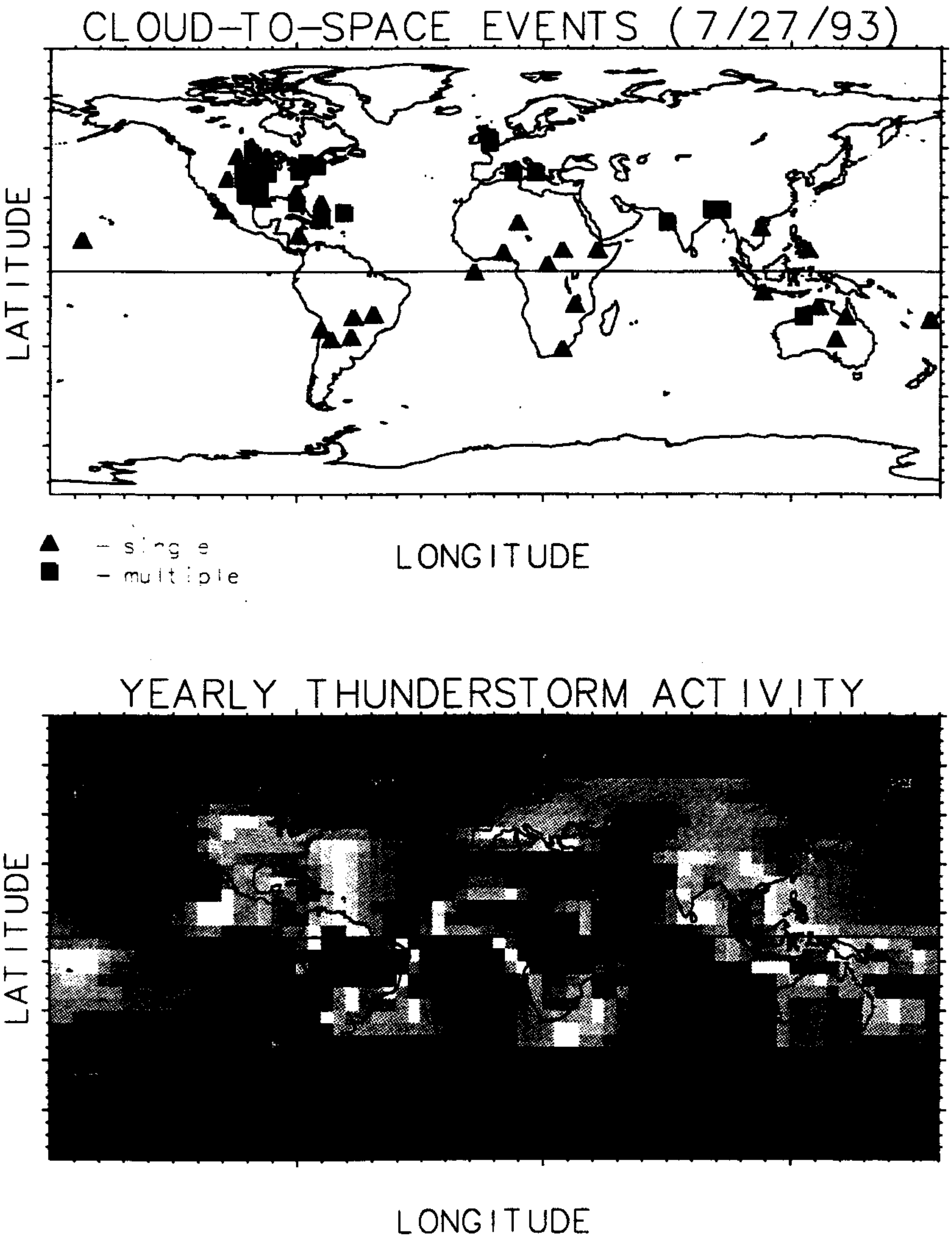

Figure 1-2. (Top) Geographical distribution of reports of transient luminous events since 1886, (bottom) global distribution of annual thunderstorm frequencies.

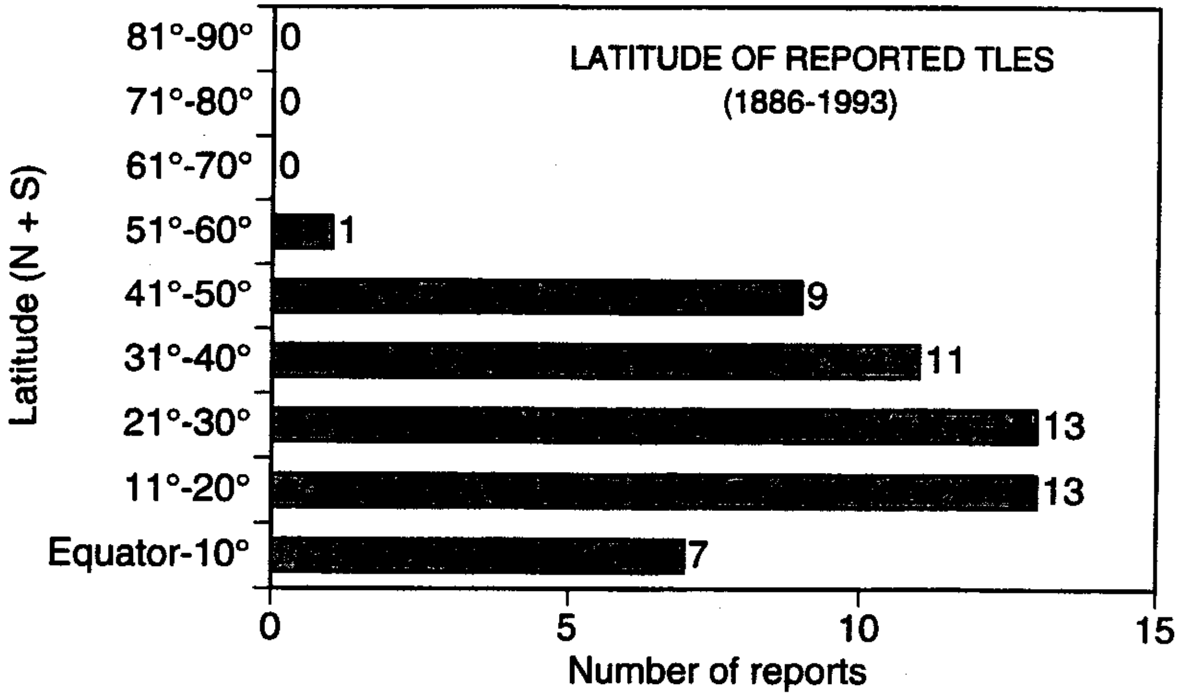

Figure 1-3. Distribution of reports of transient luminous events by latitude.

EXCERPTS OF DESCRIPTIONS OF THE CS EVENT

Everett (1903)	“...rocket lightning...a luminous trail...shot straight up... rather faster than a rocket...with minute waves, like ribbon lighting...the upper end was definite and did not branch or spread...”
Malan (1937)	“a long and weak streamer of reddish hue...some 50 km high”
Ashmore (1951)	“flames appearing to shoot up from the top of the cloud...”
Wood (1951)	“the beam...purple in color...similar to electrical discharges when it passes through air at reduced pressure...a normal lightning flash extended upwards from this point...after which the discharge assumed a shape similar to roots of a tree in an inverted position...”
Wilson (1956)	“diffuse, fan-shaped flashes of greenish color extending up into the clear sky...”
Powell (1968)	“..resembled a firework display...”
Vonnegut (1980)	“...like a beam of light, showing no branching of tortuosity...”
Gales (1982)	“...at least ten bolts of lightning went up a vertical blue shaft of light that would form an instant before the lightning bolt emerged...”
Vaughan and Vonnegut (1982)	“...vertical lightning bolts were extending from the tops of the clouds...to an altitude of approximately 120,000 feet...were generally straight compared to most lighting bolts...with no branching at the top...”
Vaughan and Vonnegut (1989)	“...bolt of lightning which discharged vertically...” “...vertical lightning shafts...” “...a lightning spike...” “...brilliant, blue-white spire...” “...ionized glow around an arrow-straight finger core”
Fisher (1990)	“...a faint plume of light extending from the top of the thunderhead above the pool of light from the lightning discharge...”

Figure 1-4. Selected excerpts from various published reports during this century of transient luminous events illustrating the wide variety of perceptions.

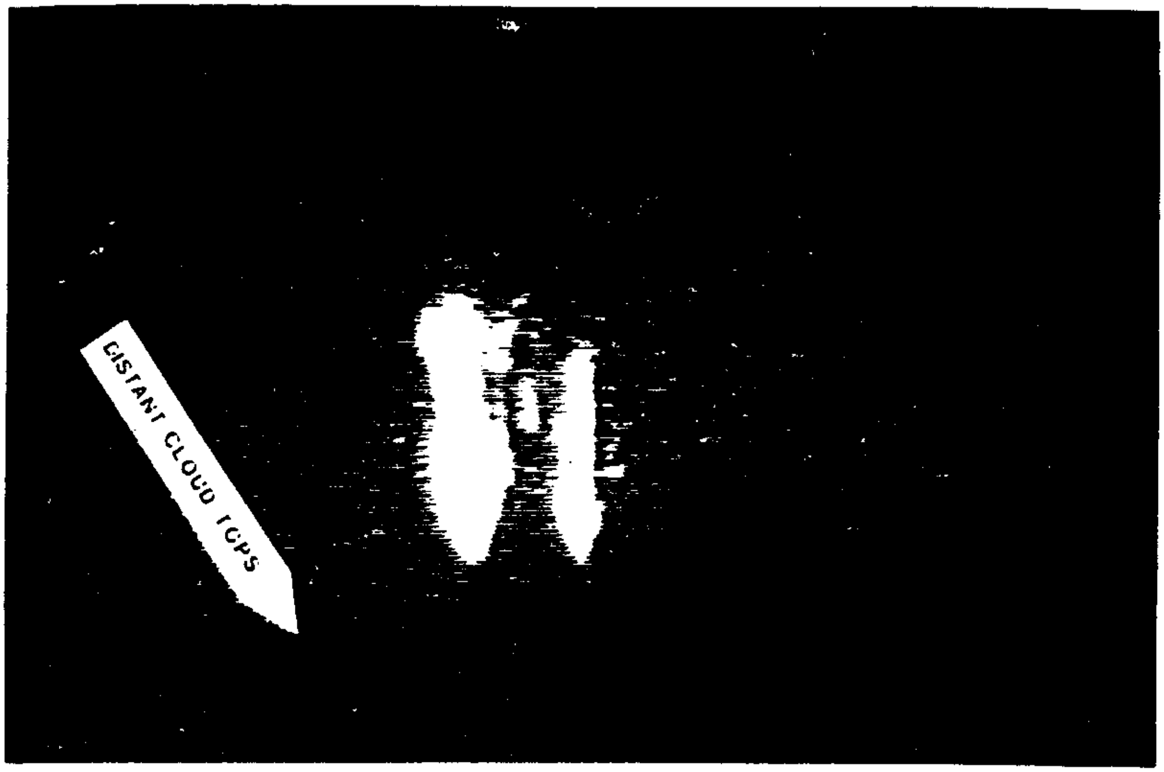

Figure 1-5. Print from S-VHS video made with an image intensified CCD camera showing a sprite over a thunderstorm complex in northern Minnesota on 6 July 1989. This is the first known image of a sprite (Franz et al., 1990).

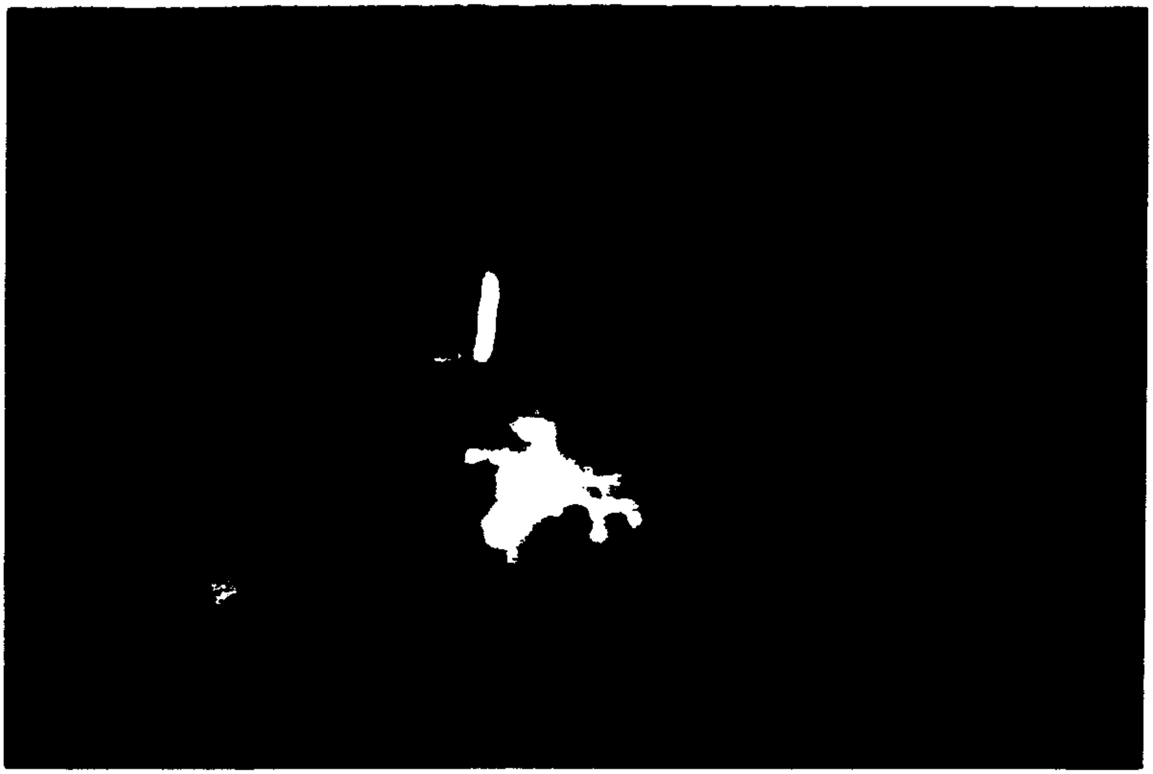

Figure 1-6. A print from a 35 mm transparency of what may be the first known image of a blue jet. This column with a blue, flame-like flare surmounting it was taken by chance by Australian photographer Peter Jarver near Darwin sometime in the mid 1980s.

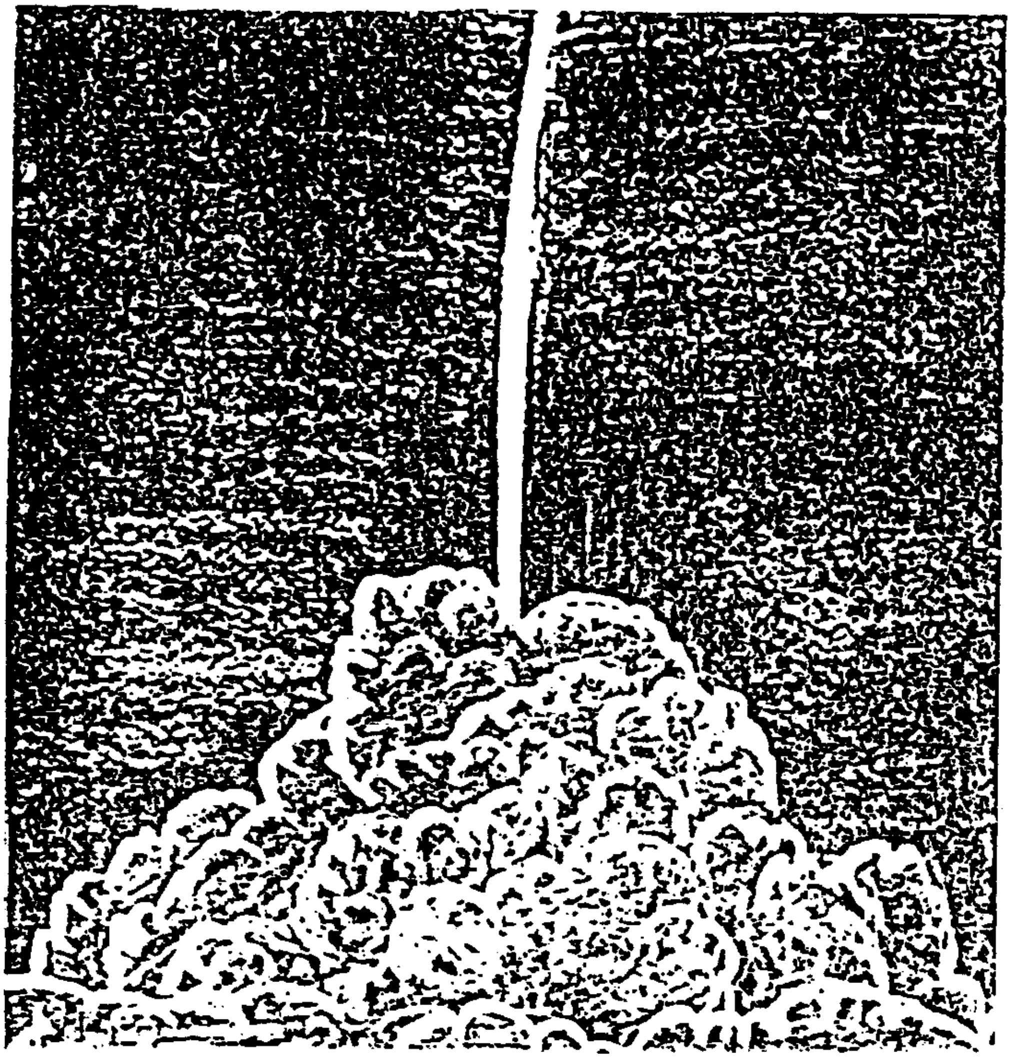

Figure 1-7. Sketch prepared by a Colorado resident illustrating one of two bright upward bolts of lightning that projected from atop growing Colorado thunderstorms to heights that may have been greater than 100,000 feet.

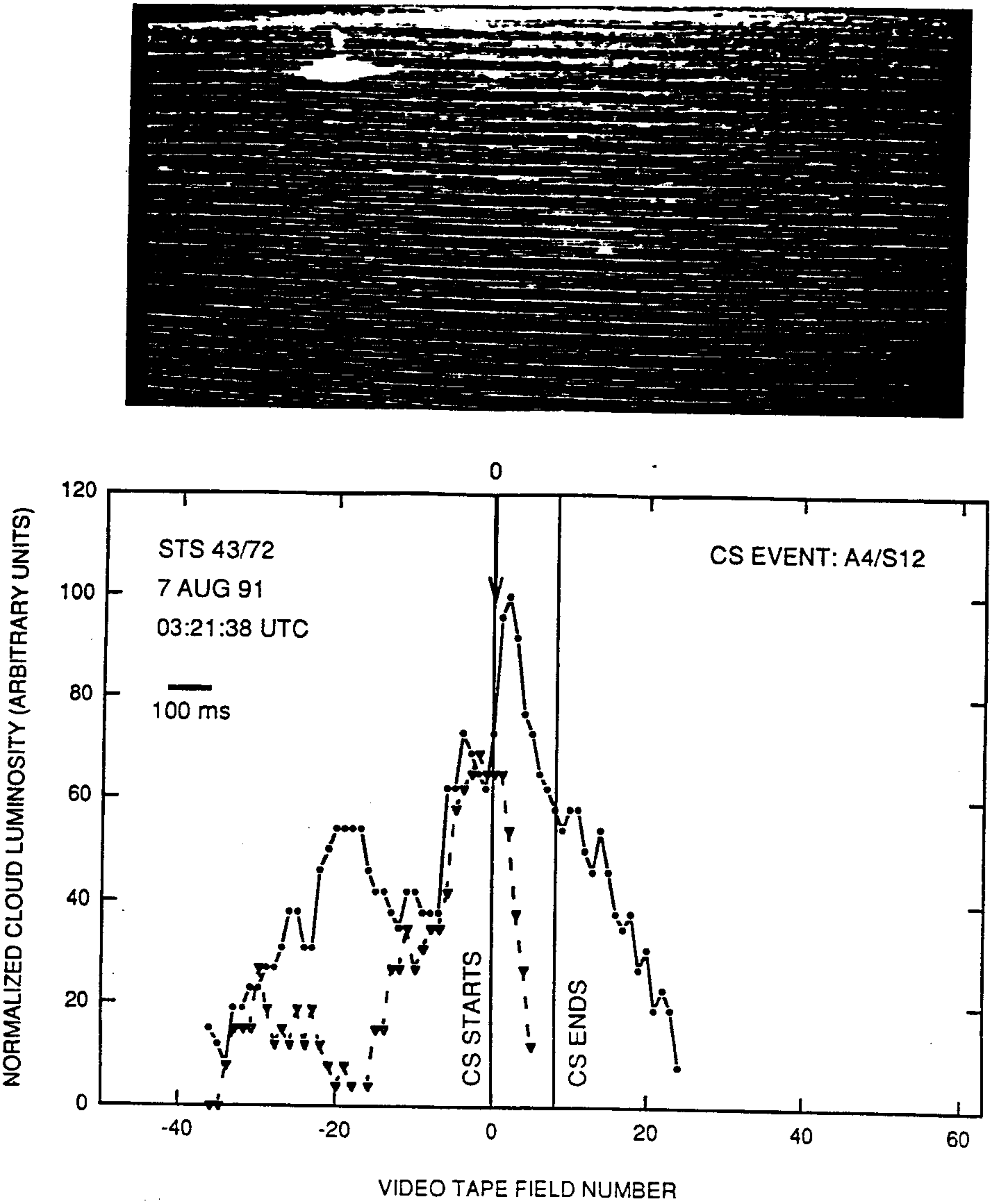

Figure 1-8. Analysis of Space Shuttle LLTV video showing (top) an apparent sprite protruding above the cloud illuminated by a lightning discharge and (bottom) the occurrence of the sprite with respect to the time history of the cloud luminosity. In almost all cases the sprite occurred near the maximum in-cloud luminosity.

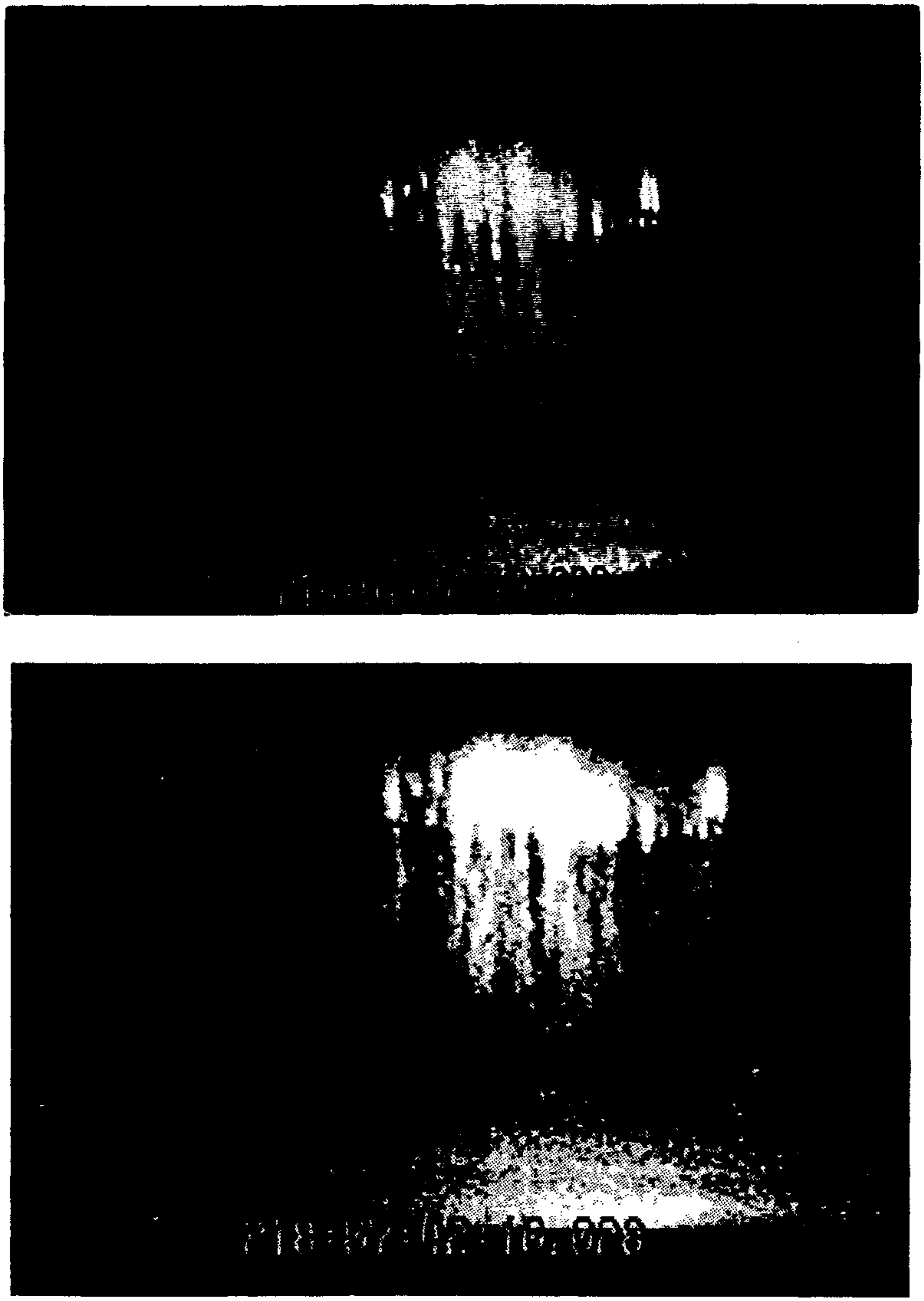

Figure 1-9. Examples of Xybion ISS-255 low light television image taken from Yucca Ridge Field Station of a sprite over Kansas. The original monochrome image is shown colorized (bottom) using an image processing program.

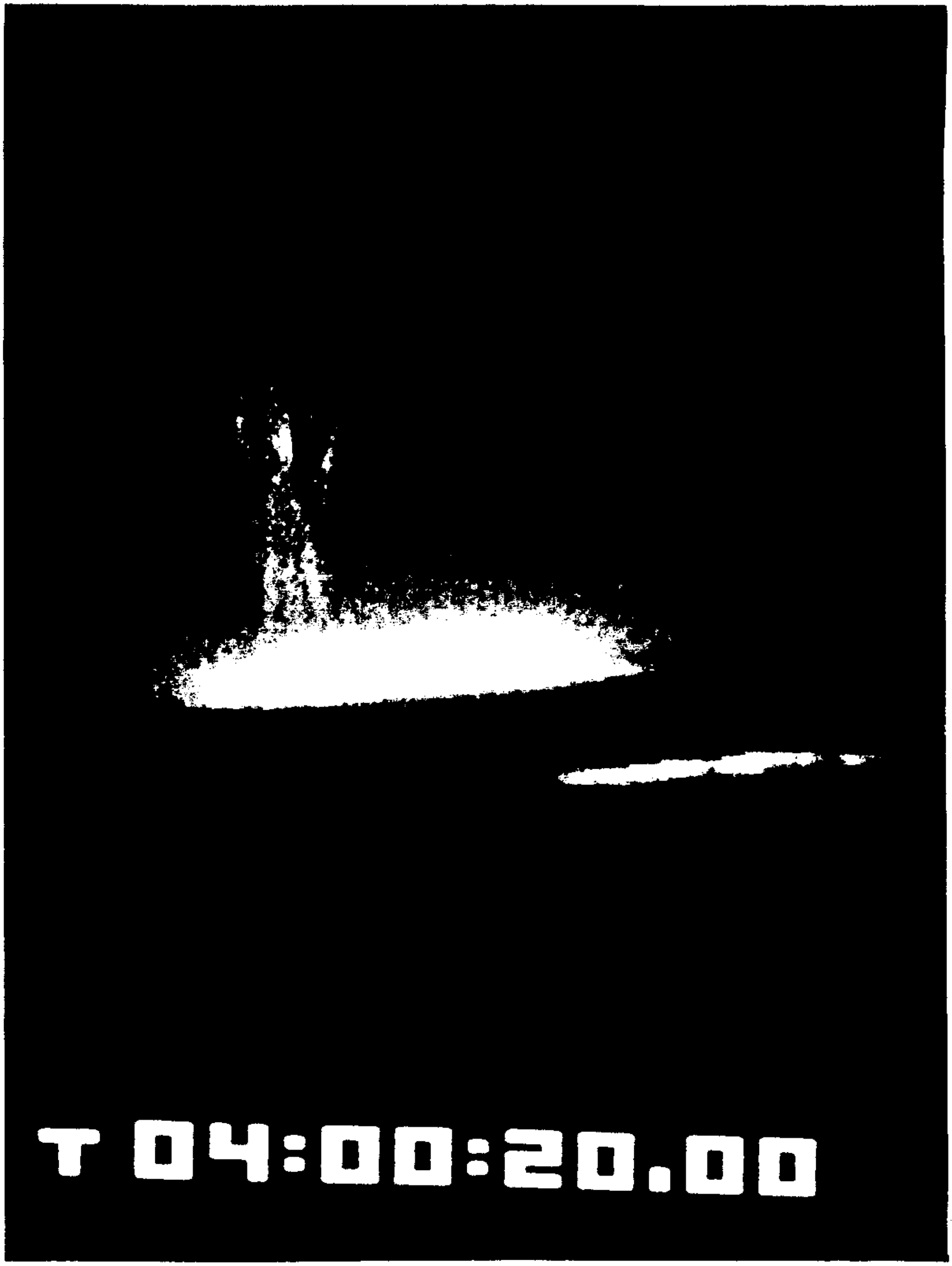

Figure 1-10. One of many full color video images obtained by the Geophysical Institute/University of Alaska airborne missions during the summer of 1994 (Sentman et al, 1994). The red/pink head of the sprite gives way partially to blue overtones in the lowest reaches of the tendrils. (Courtesy Dave Sentman).

Figure 1-11. Black and white image of one of many blue jets associated with an intense thunderstorm over Arkansas on 1 July 1994 obtained by the GI/UOA airborne mission (Courtesy Gene Wescott).

TRANSIENT, LUMINOUS EVENTS IN THE STRATOSPHERE AND MESOSPHERE INDUCED BY LIGHTNING

Sprites - Elves - Blue Jets

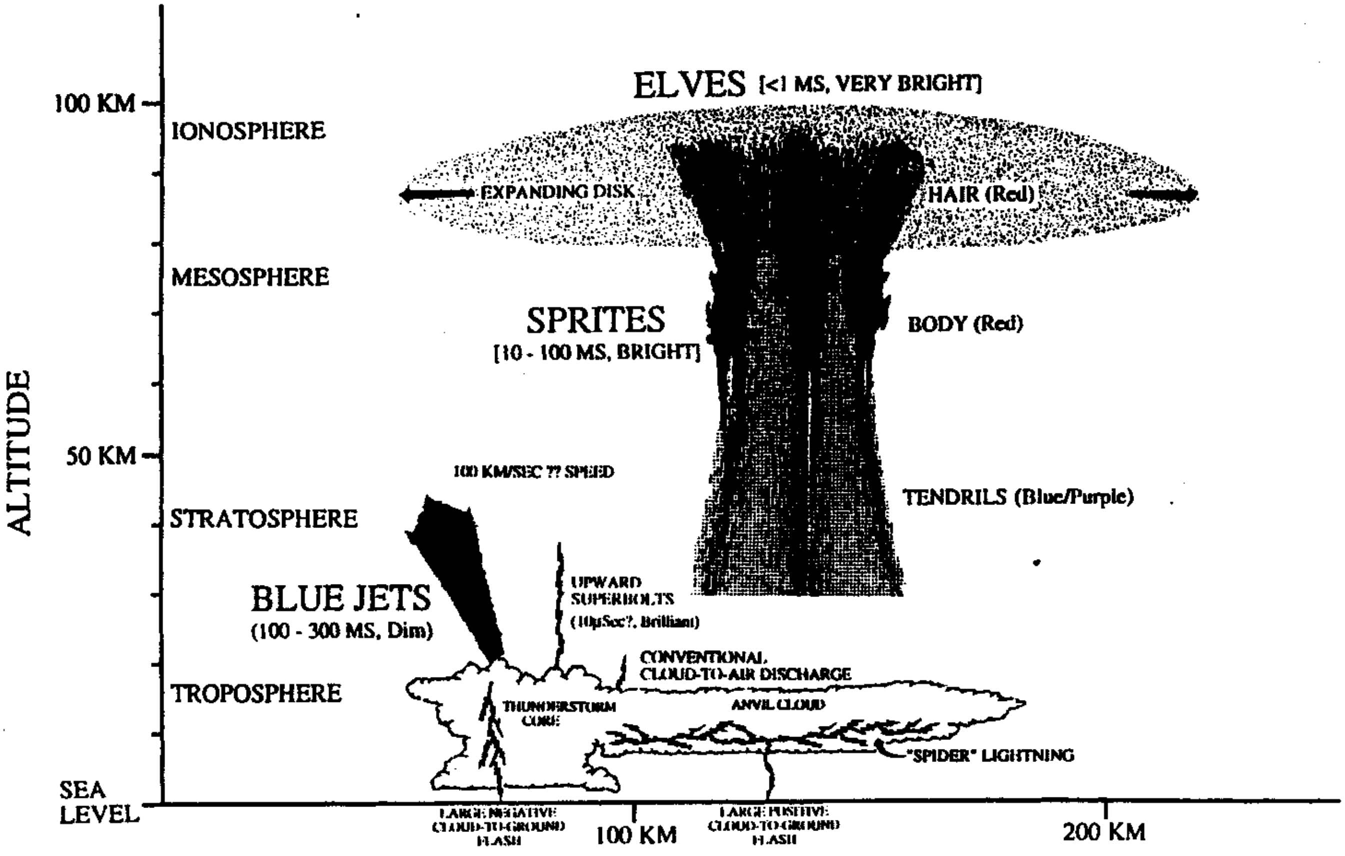

Figure 1-12. Schematic of known characteristics of transient luminous events.

Figure 1-13. SPRITE-RELATED PUBLICATIONS (NAS10-12113)

Lyons, W.A., 1996: Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems. J. Geophys. Res. (accepted with revisions).

Fullekrug, M., S.C. Reising and W.A. Lyons, 1996: On the accuracy of arrival azimuth determination of sprite-associated lightning flashes by Earth-ionosphere cavity resonances. Geophys. Res. Letts. (submitted)

Lyons, W.A., 1996: The SPRITES'95 field campaign: Initial results - characteristics of sprites and the mesoscale convective systems that produce them, Preprints. 18th Conf. on Severe Local Storms, AMS, San Francisco, 5 pp.

Reising, S.C., U.S. Inan, T.F. Bell and W.A. Lyons, 1996: Evidence of Continuing Currents in Sprite-Producing Cloud-to-Ground Lightning. Geophys. Res. Letts. (in preparation).

Williams, E.R., C. Wong, R. Boldi, and W.A. Lyons, 1996: Dual Schumann Resonance Methods for Monitoring Global Lightning Activity, J. Atmospheric Electricity, 16, (supplement), 5 pp.

Lyons, W.A. and T.E. Nelson, 1996: Processing, integrating and displaying disparate data sources from the SPRITES'95 field program. Preprints. 12th IIIPS for Meteor., Oceanog. and Hydrol., AMS, Atlanta, 6 pp.

Fukunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U.S. Inan and W.A. Lyons, 1996: Elves: Lightning-induced transient luminous events in the lower ionosphere. Geophys. Res. Letts., (in review).

Armstrong, R.A., J.A. Shorter, W.A. Lyons, N. Carron and W.A.M. Blumberg, 1996: Assessment of nitric oxide formation in discharge regions above thunderstorms. (in preparation).

Winckler, J.R., W.A. Lyons, T. E. Nelson and R.J. Nemzek, 1995: New high-resolution ground based studies of sprites. J. Geophysical Res., *101*, 6997-7004.

Dowden, R.L., J.B. Brundell and W.A. Lyons, 1996: Are VLF RORDs and optical sprites produced by the same cloud-to-ionosphere discharge? J. Geophys. Res., (in preparation).

Mende, S.B., R.L. Rairden, G.R. Swenson and W.A. Lyons, 1995: Sprite spectra: N_2 First Positive Band Identification. Geophys. Res. Lett., 22, 2633-2636.

Inan, U.S., T.F. Bell, V. P. Pasko, D. D. Sentman, E. M. Wescott and W. Lyons, 1995: VLF signatures of ionospheric disturbances associated with sprites. Geophys. Res. Lett., 22, 3461-3464.

Boccippio, D.J., E.R. Williams, W.A. Lyons, I. Baker and R. Boldi, 1995: Sprites, ELF transients and positive ground strokes. Science, 269, 1088-1091.

Dowden, R., J. Brundell, W. Lyons and T. Nelson, 1995: VLF scattering from sprites and elves. Geophys. Res. Lett. (submitted).

Lyons, W.A., 1995: The relationship of large luminous stratospheric events to the anvil structure and cloud-to-ground discharges of their parent mesoscale convective system. Preprints. Conf. on Cloud Physics, AMS, Dallas, 541-546.

Lyons, W.A., 1994: Characteristics of luminous structures in the stratosphere above thunderstorms as imaged by low-light video. Geophysical Research Letters, 21, 875-878.

Lyons, W.A. and E.R. Williams, 1994: Some characteristics of cloud-to-stratosphere "lightning" and consideration for its detection. Preprints. Symposium on the Global Electrical Circuit. Global Change and the Meteorological Applications of Lightning Information, AMS, Nashville, 8 pp.

Lyons, W.A., 1994: Low-light video observations of frequent luminous structures in the stratosphere above thunderstorms. Mon. Wea. Rev., 122, 1940-1946.

Lyons, W.A. and E.R. Williams, 1993: Preliminary investigations of the phenomenology of cloud-to-stratosphere lightning discharges. Preprints. Conference on Atmospheric Electricity, American Meteorological Society, St. Louis, 8 pp.

Figure 1-13. Sprite -Related Publications (NAS10-12113).

Figure 1-14. SPRITE RELATED CONFERENCE PRESENTATIONS

Lyons, W.A., 1996: Coordinated RF and optical measurements of sprites, jets and elves in the Colorado SPRITES'95 campaign. National Radio Science Meeting, Boulder, CO. (abstract only).

Lyons, W.A., 1996: The SPRITES'95 field campaign: Initial results - characteristics of sprites and the mesoscale convective systems that produce them, Preprints, 18th Conf. on Severe Local Storms, AMS, San Francisco.

Lyons, W.A., 1995-1996: Sprites, Elves and Gnomes: Solving a Hundred Year Mystery in Atmospheric Electricity. Lawrence Livermore National Laboratory.

Armstrong, R.A., J. Shorter, W.A. Lyons, L. Jeong and W.A.M. Blumberg, 1995: Evidence for ionization in sprites - N2+ 478.8 first negative emission measured in SPRITES'95 campaign. AGU fall meeting, San Francisco, EOS (abstract only).

Lyons, W.A., 1996: The Hundred Year Hunt for the Sprite. AMS Chapter Meetings, WSO Cheyenne; Colorado State University; University of Northern Colorado and the National Center for Atmospheric Research.

Fukunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U.S. Inan and W.A. Lyons, 1995: Lower ionospheric flashes induced by lightning discharges, AGU fall meeting, San Francisco, EOS (abstract only)

Lyons, W.A. and T.E. Nelson, 1995: The Colorado SPRITES'95 Campaign: Initial results. AGU fall meeting, San Francisco, EOS (abstract only).

Takahashi, Y., M. Kubota, K. Sakanoi, H. Fukunishi, U.S. Inan, and W.A. Lyons, 1995: Spatial and temporal relationships between lower ionospheric flashes and sprites. AGU fall meeting, San Francisco, EOS (abstract only).

Mende, S.B., R.L. Rairden, G.R. Swenson, and W.A. Lyons, 1995: Sprite spectra: N2 1 PG band identification. AGU fall meeting, San Francisco, EOS (abstract only).

Dowden, R.L., J. Brundell, W.A. Lyons and T. Nelson, 1995: Sprite structure implied by scattering of VLF transmitter signals. AGU fall meeting, San Francisco, EOS (abstract only).

Williams, E., D. Boccippio, C. Wong, W. Lyons, M. Ishii and W. Koshak, 1995: The physical origin of Schumann resonance excitation. AGU fall meeting, San Francisco, EOS (abstract only).

Inan, U.S., S.C. Reising, V.P. Pasko and W.A. Lyons, 1995: VLF signatures of ionospheric disturbances associated with sprites. AGU fall meeting, San Francisco, EOS (abstract only).

Lyons, W.A., 1995: Sprites. Fermi National Laboratory.

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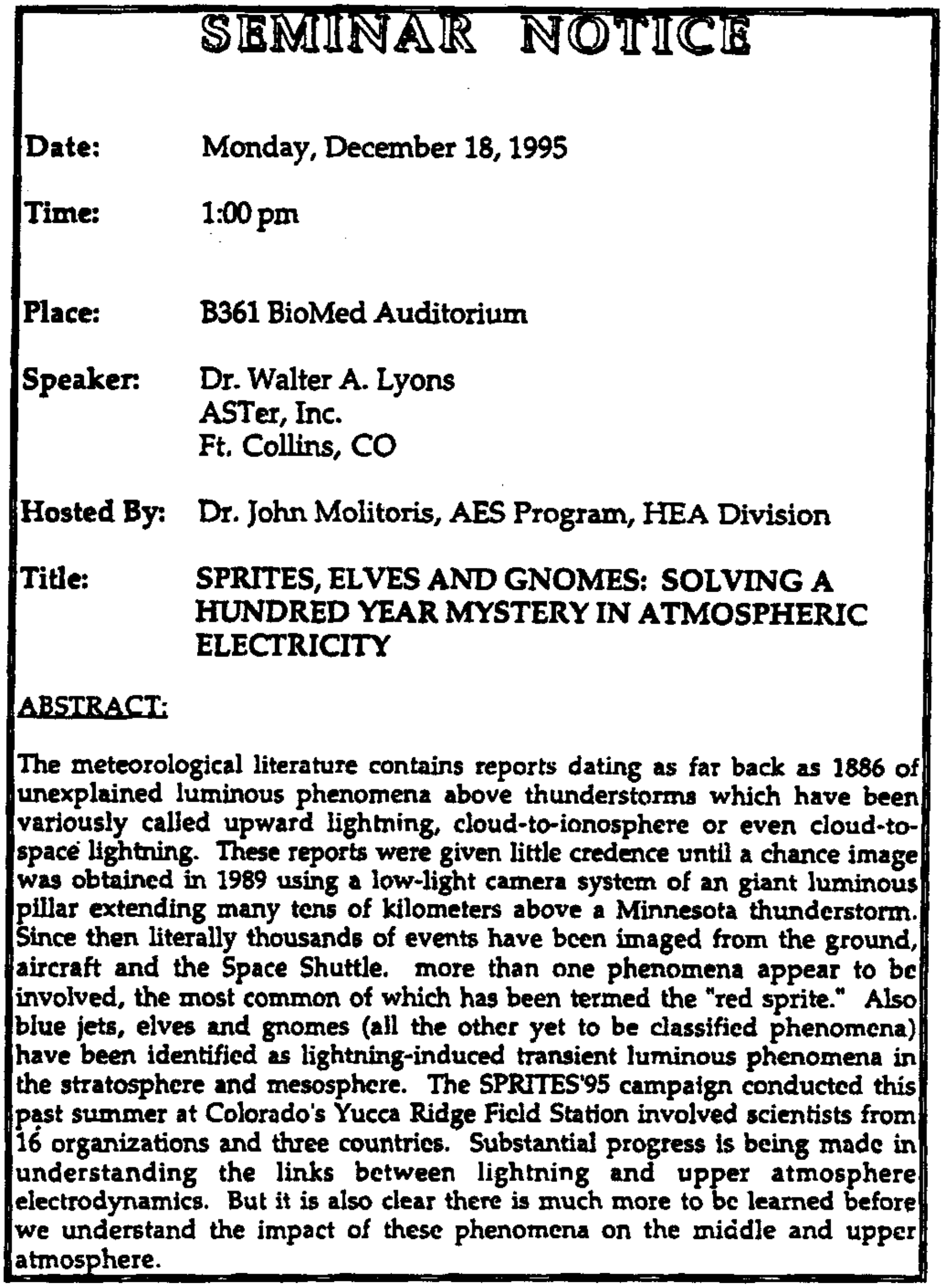
Figure 1-14. Sprite-Related Conference Presentations (NAS10-12113).



SEMINAR NOTICE

Date: Monday, December 18, 1995

Time: 1:00 pm

Place: B361 BioMed Auditorium

Speaker: Dr. Walter A. Lyons
ASTer, Inc.
Ft. Collins, CO

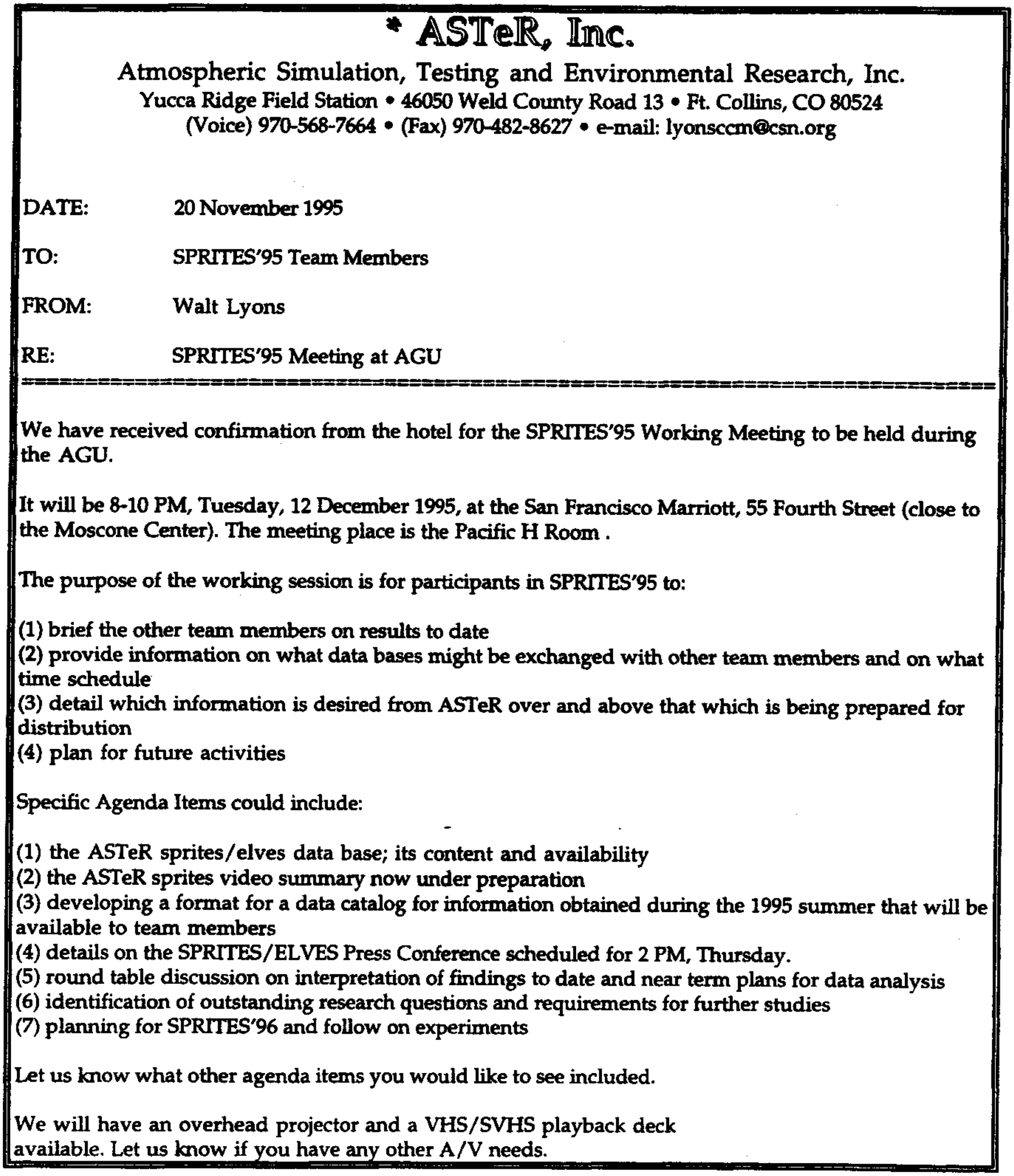
Hosted By: Dr. John Molitoris, AES Program, HEA Division

Title: SPRITES, ELVES AND GNOMES: SOLVING A HUNDRED YEAR MYSTERY IN ATMOSPHERIC ELECTRICITY

ABSTRACT:

The meteorological literature contains reports dating as far back as 1886 of unexplained luminous phenomena above thunderstorms which have been variously called upward lightning, cloud-to-ionosphere or even cloud-to-space lightning. These reports were given little credence until a chance image was obtained in 1989 using a low-light camera system of an giant luminous pillar extending many tens of kilometers above a Minnesota thunderstorm. Since then literally thousands of events have been imaged from the ground, aircraft and the Space Shuttle. more than one phenomena appear to be involved, the most common of which has been termed the "red sprite." Also blue jets, elves and gnomes (all the other yet to be classified phenomena) have been identified as lightning-induced transient luminous phenomena in the stratosphere and mesosphere. The SPRITES'95 campaign conducted this past summer at Colorado's Yucca Ridge Field Station involved scientists from 16 organizations and three countries. Substantial progress is being made in understanding the links between lightning and upper atmosphere electrodynamics. But it is also clear there is much more to be learned before we understand the impact of these phenomena on the middle and upper atmosphere.

Figure 1-15. Sprite Seminar Notice, Lawrence Livermore National Lab



*** ASTeR, Inc.**

Atmospheric Simulation, Testing and Environmental Research, Inc.
Yucca Ridge Field Station • 46050 Weld County Road 13 • Ft. Collins, CO 80524
(Voice) 970-568-7664 • (Fax) 970-482-8627 • e-mail: lyonsccm@csn.org

DATE: 20 November 1995

TO: SPRITES'95 Team Members

FROM: Walt Lyons

RE: SPRITES'95 Meeting at AGU

We have received confirmation from the hotel for the SPRITES'95 Working Meeting to be held during the AGU.

It will be 8-10 PM, Tuesday, 12 December 1995, at the San Francisco Marriott, 55 Fourth Street (close to the Moscone Center). The meeting place is the Pacific H Room .

The purpose of the working session is for participants in SPRITES'95 to:

(1) brief the other team members on results to date
(2) provide information on what data bases might be exchanged with other team members and on what time schedule
(3) detail which information is desired from ASTeR over and above that which is being prepared for distribution
(4) plan for future activities

Specific Agenda Items could include:

(1) the ASTeR sprites/elves data base; its content and availability
(2) the ASTeR sprites video summary now under preparation
(3) developing a format for a data catalog for information obtained during the 1995 summer that will be available to team members
(4) details on the SPRITES/ELVES Press Conference scheduled for 2 PM, Thursday.
(5) round table discussion on interpretation of findings to date and near term plans for data analysis
(6) identification of outstanding research questions and requirements for further studies
(7) planning for SPRITES'96 and follow on experiments

Let us know what other agenda items you would like to see included.

We will have an overhead projector and a VHS/SVHS playback deck available. Let us know if you have any other A/V needs.

Figure 1-16. Announcement of December 1995 SPRITES'95 Workshop.

Figure 1-17. Press Release for 1995 American Geophysical Union Meeting

ASTeR, Inc. **NEWS RELEASE**

Atmospheric Simulation Testing and Environmental Research
Yucca Ridge Field Station
Ft. Collins, CO 80524

SPRITES'95

Contact: Dr. Walter Lyons (970-568-7664) **FOR IMMEDIATE RELEASE**

Elves Light Up The Ionosphere When Lightning Flashes

Elves are yet another new lightning-related luminous phenomenon in the lower ionosphere uncovered in a research effort funded by NASA's Kennedy Space Center. Joining red sprites and blue jets are mysterious bright flashes in the upper atmosphere called "elves, " an acronym for Emissions of Light and VLF perturbations due to EMP Sources. They occur between approximately 70 and 105 km altitude and appear to be quite bright, but are largely undetectable to the naked eye since they last for less than one thousandths of a second. They are so brief, in fact, that even low-light video cameras can not easily distinguish them from the more common sprites. Only high speed photometers operating in conjunction with low-light video have unambiguously identified the new phenomenon from the ground. The elves were identified during the SPRITES'95 campaign held last summer at the Yucca Ridge Field Station outside of Ft. Collins, CO. They are also experimental confirmation of theoretical work initiated at Stanford University by Prof. Umran Inan and his student, Dr. Yuri Taranenko, now at Los Alamos National Laboratory.

The SPRITES'95 campaign director, Dr. Walter Lyons, senior scientist of ASTeR, Inc., said "the goal was to obtain coordinated measurements across the electromagnetic spectrum of sprites - and whatever else might be up there." On several dozen nights many of the 40 participating scientists, representing more than a dozen organizations from three countries, trained their sensors above the massive nighttime thunderstorms that sweep the U.S. High Plains on many summer evenings. Yucca Ridge's panoramic vista, excellent visibility and cloud-free lines of sight allowed new observations of sprites and elves over great distances. On one night numerous sprites and elves were imaged over central Texas, almost 1000 kilometers away.

The existence of elves was documented by researchers from Tohoku University, Sendai, Japan, including Prof. Hiroshi Fukunishi, Yukihiro Takahashi and Minoru Kubota, who worked with Prof. Umran Inan of Stanford University to design an experiment specifically targeted to observe brief (less than a millisecond) airglow enhancements. By aiming their specially designed, high-speed photometers above distant thunderstorms they captured time profiles of the brightness of not only sprites but of the new phenomenon as well. The narrow altitude range and large horizontal extent of elves are similar to a singular Space Shuttle low-light video observation of lightning-associated airglow brightening reported in 1992 by Prof. William Boeck, Niagara University and his colleagues at NASA's Marshall Space Flight Center.

Since 1993 observations have documented the diversity of transient optical flashes occurring high above thunderstorms. Sprites, by far the most common of these events, and sometimes visible to the naked eye, can be routinely captured on special low-light video cameras. Sprites appear predominately red and last for only tens of thousandths of a second—the blink of an eye. Among the successes of SPRITES '95 were the numerous optical spectra of sprites obtained at Yucca Ridge by scientists from Lockheed Martin of Palo Alto, CA. Dr. Stephen Mende reported that "the red coloration of the sprites appears to derive from emissions of the nitrogen first positive band." This confirms independent spectral data taken during the summer of 1995 by the Geophysical Institute of the University of Alaska (Don Hampton and Matt Heavner, Gene Wescott, Dave Sentman). John Molitoris, Lawrence Livermore National Laboratory, successfully deployed a new, fast imaging system called IROCS, Infrared and Optical Camera System, designed to detect the direction of propagation of sprites and characterize their infrared signature.

In addition to the elves, Dr. Lyons for the first time captured on ground-based video another type of upper atmospheric fireworks, blue jets. These cone-shaped spurts of energy move upwards from thunderstorm tops to over 40 kilometers altitude at speeds approaching 100 kilometers a second. University of Alaska researchers using two aircraft in the summer of 1994 obtained the first color images of sprites and discovered the blue jets. That research is funded by NASA's Space Physics Division.

While the 1995 blue jet images were anticipated, the unambiguous identification of elves required a teaming of theoretical predictions and new instrumentation. Elves were actually detected during the SPRITES '94 campaign, said Lyons, "but since even video wasn't fast enough, we couldn't separate out the two phenomena. By combining our cameras with the high speed photometers from Tohoku, all the pieces began to fall into place." Sprites, of which more than a thousand have now been documented, often start tens of milliseconds after a cloud-to-ground (CG) lightning flash of positive polarity. Their optical emissions may in part be the result of electron impact excitation due to intensification of the upper atmosphere's electric field. This is due to rearrangements of the electrical charges within the thunderstorm far below as a result of the lightning event. Elves, on the other hand, may be the almost immediate result of lower ionosphere heating by the direct electromagnetic pulse (EMP) created by the

CG discharge itself. The elves first appear at altitudes around 80-95 km and spread outward and downward. While perhaps only reaching down to 60-70 km altitude, they are horizontally very broad, extending to several hundred kilometers across. Like sprites, elves appear to be related to the more powerful of the CG lightning flashes which lower positive charge to ground. Elves can appear by themselves, or sometimes occur just prior to a sprite.

The successful detection of elves resulted from an instrumentation design aided by theoretical predictions of diffuse optical emissions from ionospheric heating due to lightning EMP made by scientists from the STAR Laboratory of Stanford University. Dr. Yuri Taranenko, now at Los Alamos National Laboratory, has received the American Geophysical Union's F.L. Scarf Award for his 1993 Stanford Ph.D. thesis in the context of which these predictions were made. Prof. Umran Inan, Director of the STAR Laboratory, notes that "newer theoretical models appear to suggest that the elves' luminous disks may actually be in the shape of a rapidly expanding doughnut."

Sprites, elves and possibly blue jets may also play a role in the chemical makeup of the upper atmosphere as they engulf thousands of cubic kilometers of the stratosphere and mesosphere. Recent calculations performed by Dr. Russ Armstrong, Mission Research Corporation, Nashua, NH who obtained the first optical emissions confirming ionization in sprites and elves suggest "they can be a significant source of stratospheric oxides of nitrogen, one not previously considered in the many theoretical models attempting to predict global change processes from man-made pollutants."

NASA and KSC are interested in determining if the events present any type of risk for Space Shuttle launches or landings. Carl Lennon, a technical representative for information systems in the Shuttle Operations Directorate, said KSC is funding the sprite research as part of a Small Business Innovative Research grant. Although preliminary indications are that sprites and elves don't present a serious threat to the Shuttle, data obtained may contribute to selecting the types of materials used in the next generation of aerospace vehicles. There is also speculation that the comparatively rare but more energetic blue jets could pose a threat to aerospace operations in the 20-40 kilometer altitude range. The wealth of new data may also lead to an increased understanding of the Earth's electrical circuitry.

Lyons said that the program at Yucca Ridge this past summer helped dispel some of the mystery and provided theoreticians with hard data against which to test their various theories. Participants in SPRITES '95 also verified that sprites and elves are associated with perturbations in radio signals over a wide range of frequencies. Since optical systems are not suitable for sprite monitoring during the day or cloudy skies, newly discovered radio signatures could supplement the optical monitoring. "Now that we know they're there, we need to learn to detect and locate them automatically," Lyons said

HQ NASA

4/7/2003

SECTION 2

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Science Times

TUESDAY, DECEMBER 12, 1995

The New York Times

ewfound Elves (Not Santa's) Blaze at the Very Edge of Space

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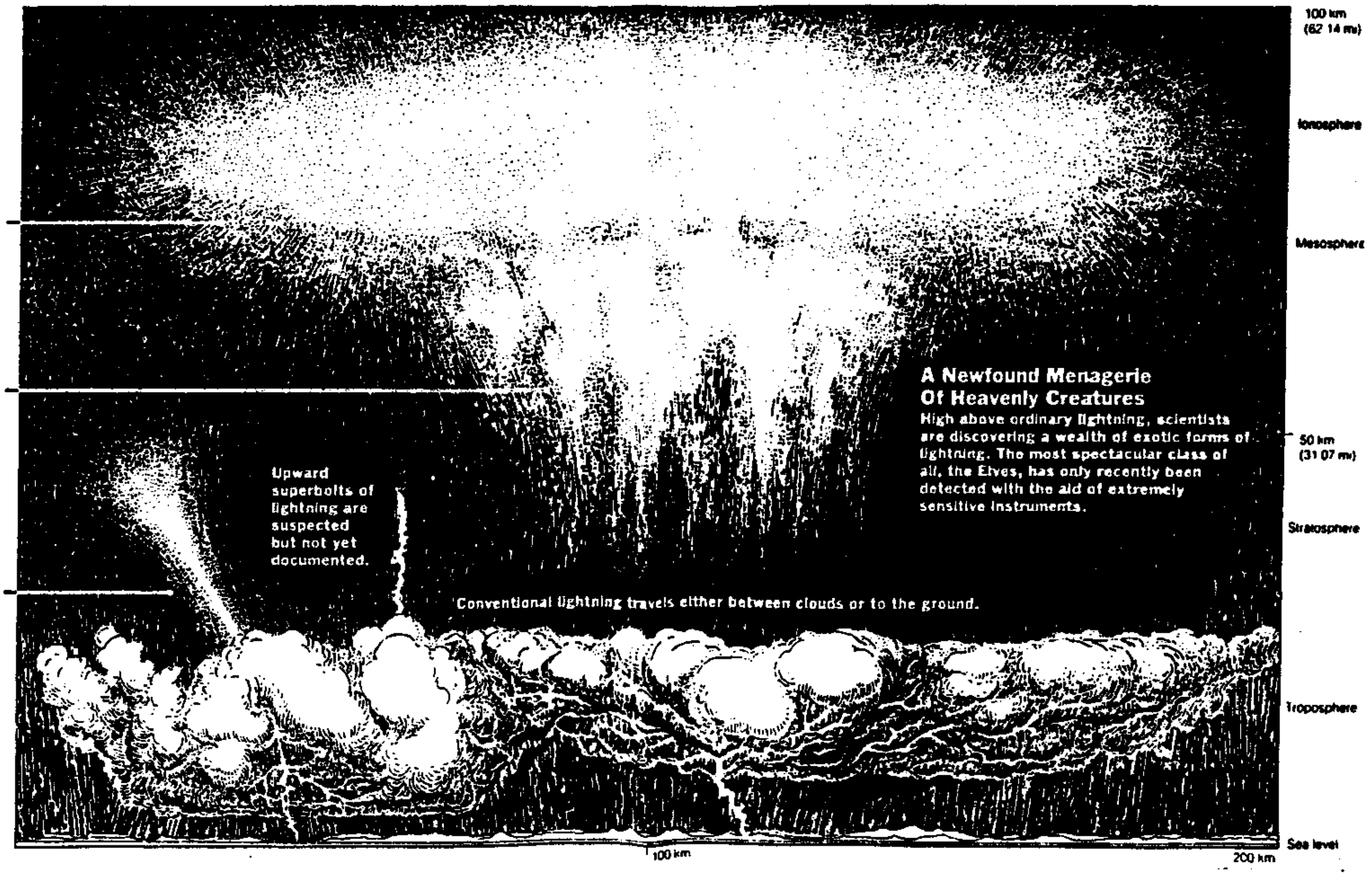

A Newfound Menagerie Of Heavenly Creatures

High above ordinary lightning, scientists are discovering a wealth of exotic forms of lightning. The most spectacular class of all, the Elves, has only recently been detected with the aid of extremely sensitive instruments.

Figure 1-18. Illustration from the New York Times (12 December 1995).

HQ NASA

4/7/2003

SECTION 7

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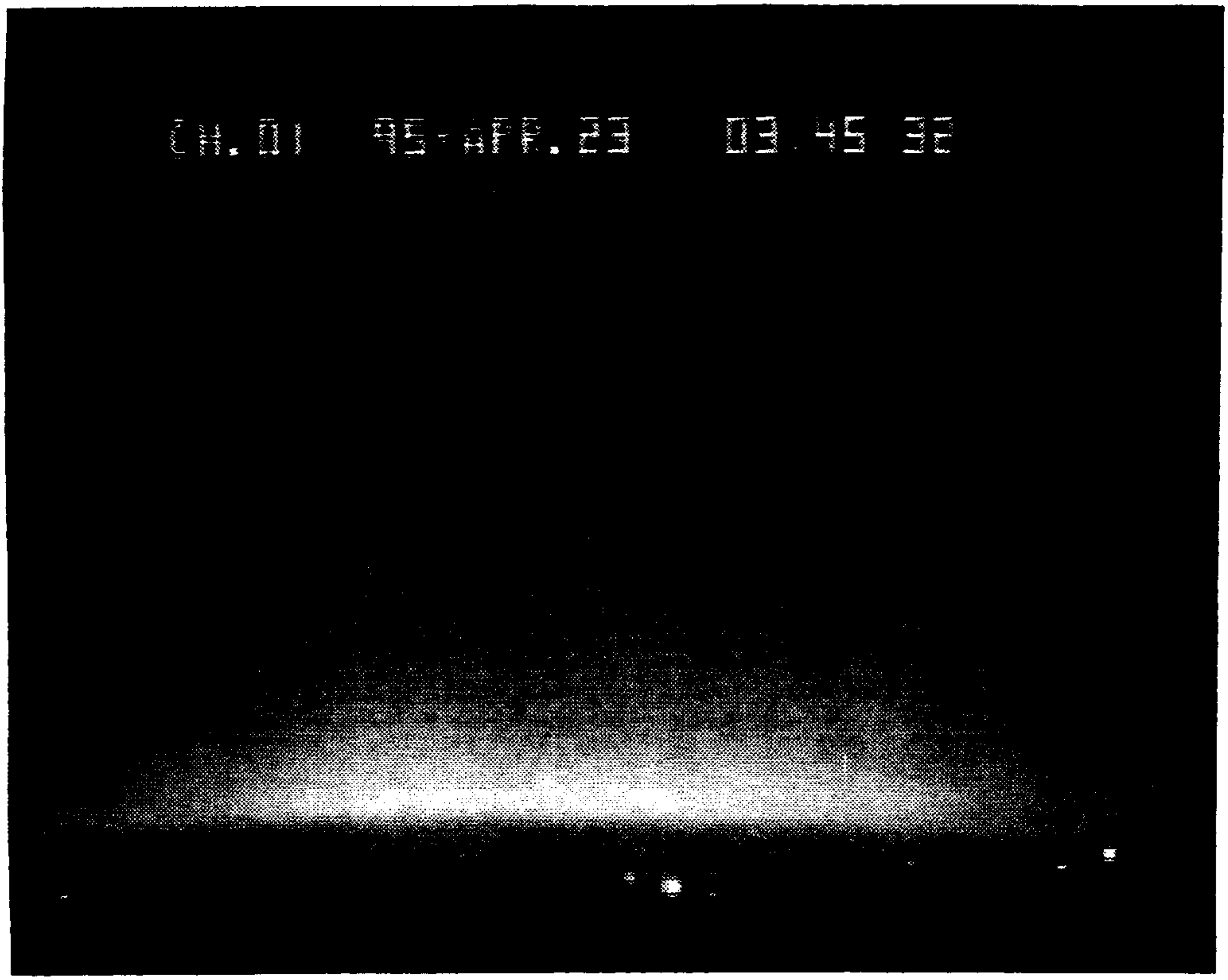
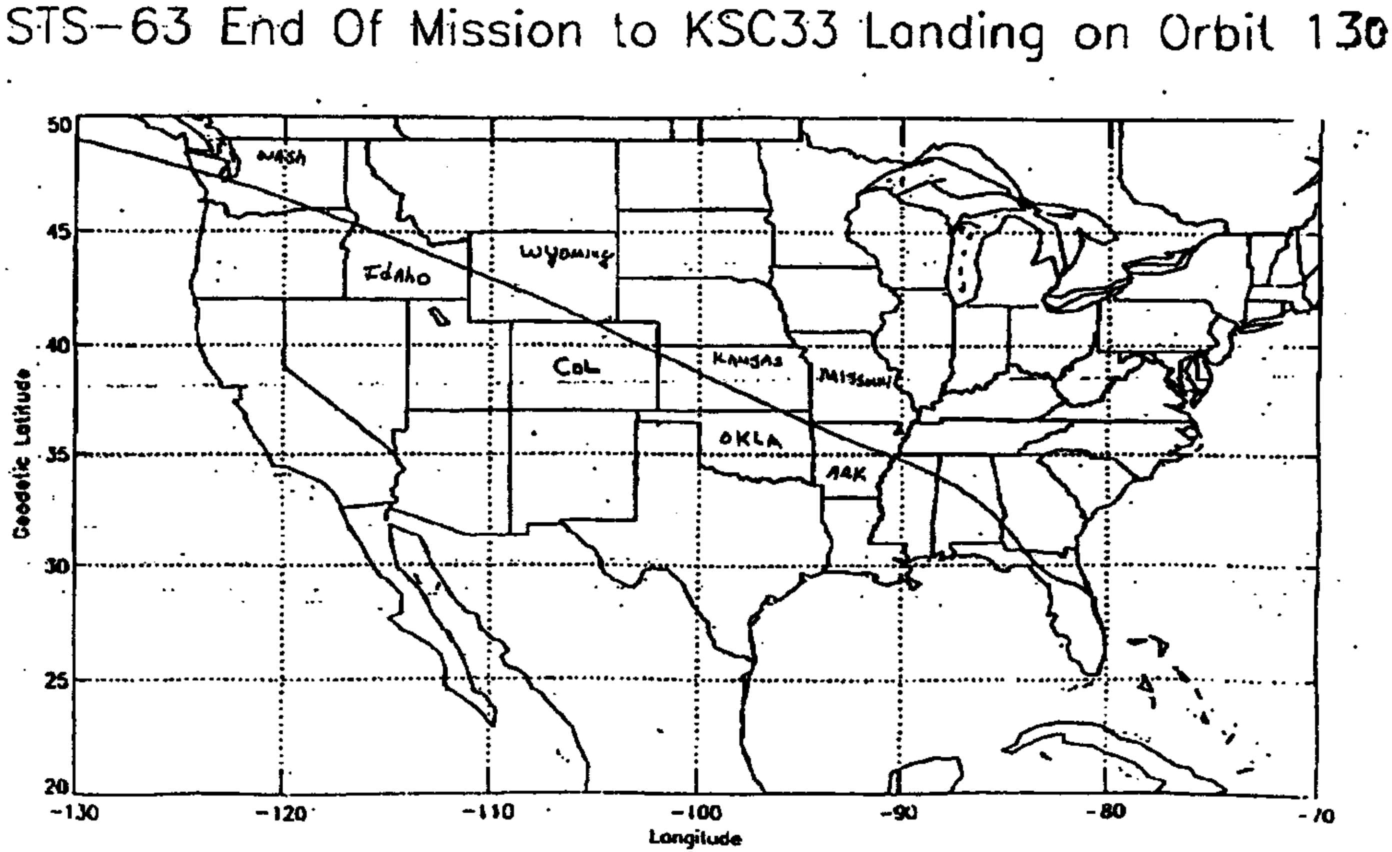


Figure 6-1. LLTV image of a broad auroral curtain over mid-latitude North America acquired using a XYBION system. Image courtesy of Prof. J.R. Winckler.



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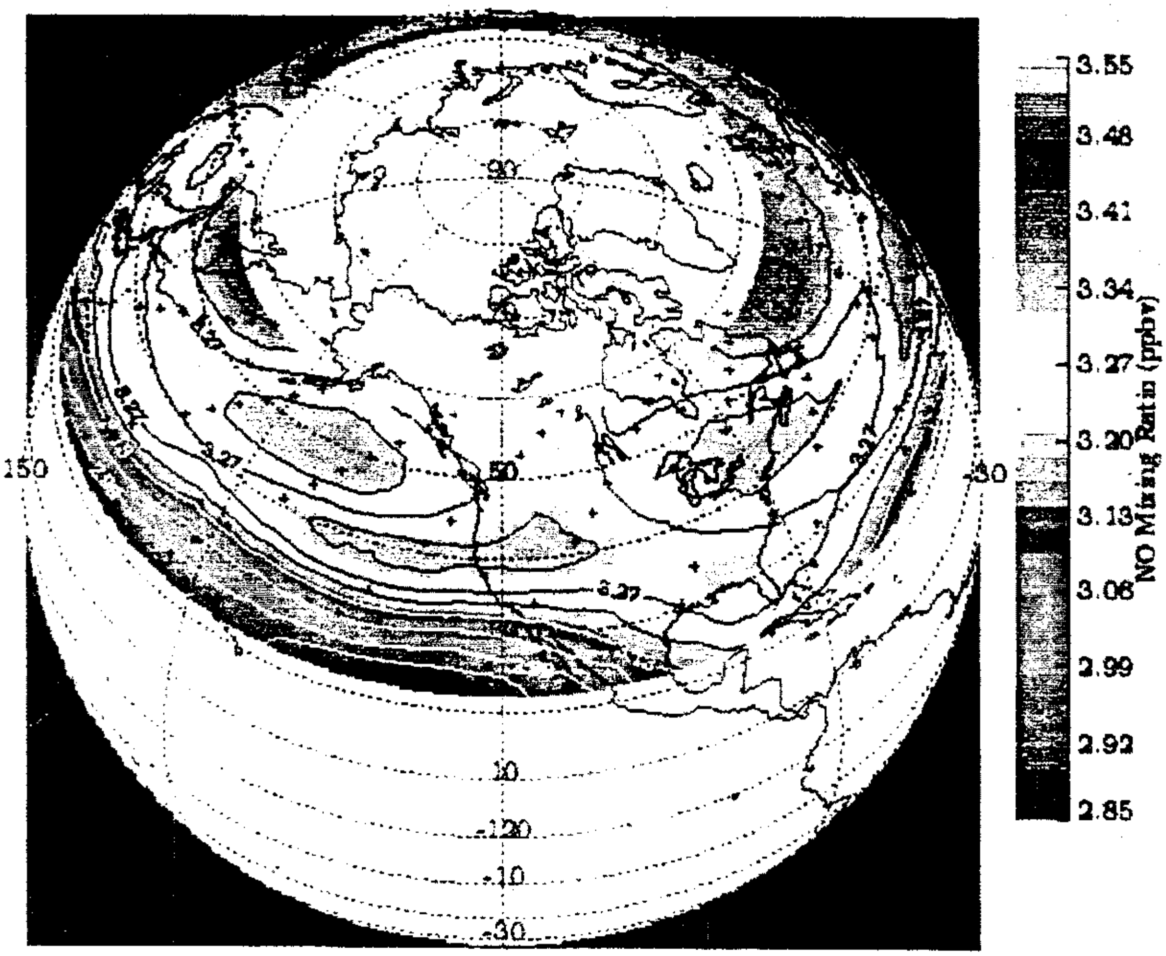
Expected: KSC Landing 05:50:31 CST
11 Feb 1995

Figure 6-2. End of mission trajectory for STS-63, which descends through the region having the highest known frequency of sprites and elves.

HALOE



HALOE NO 9.00 mb Surface Cross Section, Sunset on 01-JUL to 11-JUL-1994

Figure 6-3. Analysis of NO concentrations at 9 mb obtained by the HALOE satellite. Note the plume of NO drifting with the winds westward from the central U.S. This was during a period of active sprite production above the High Plains.

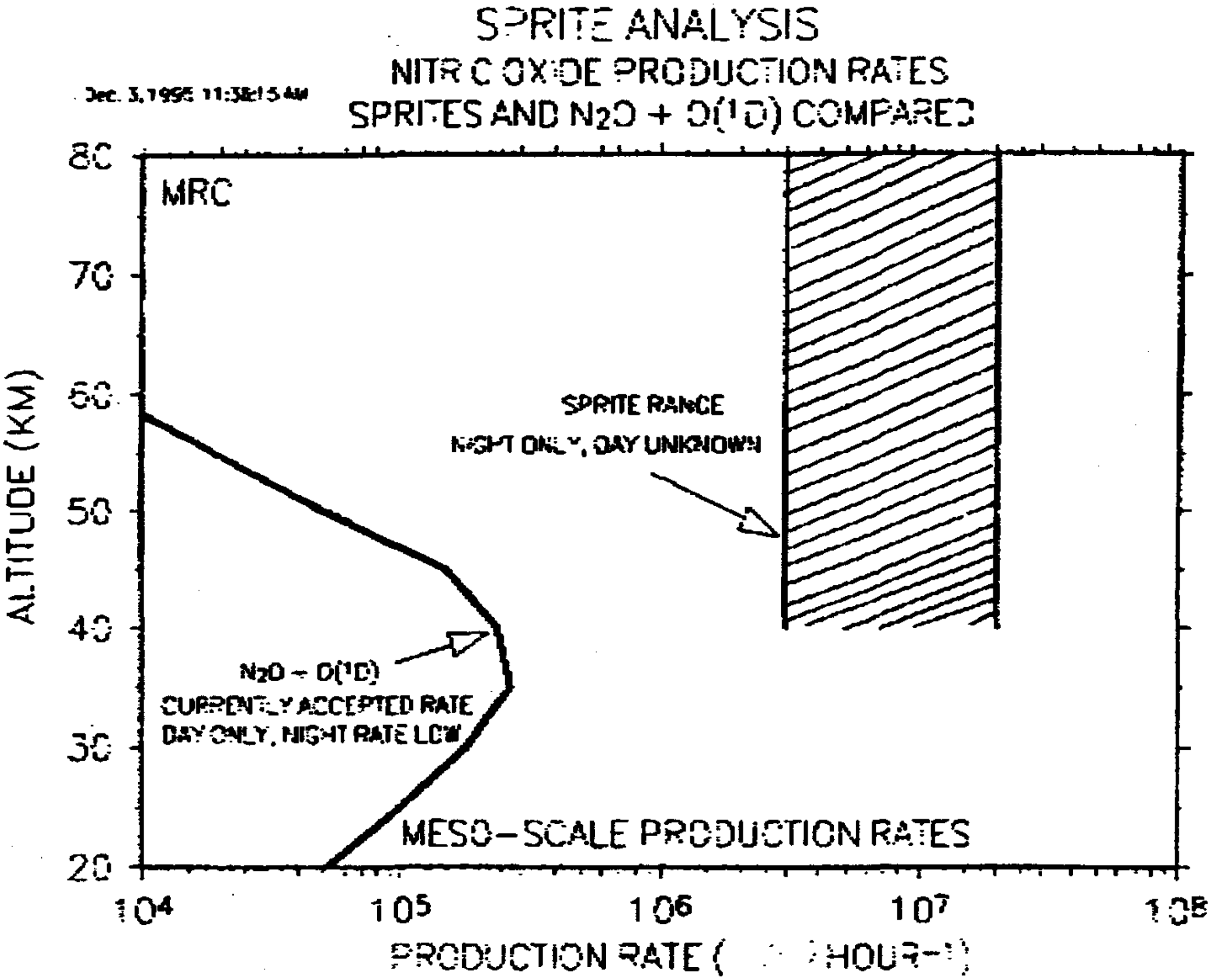


Figure 6-4. Initial analysis of the contribution of sprites to NO in the 40-80 km altitude range compared to known natural processes. From Armstrong et al. (1996).

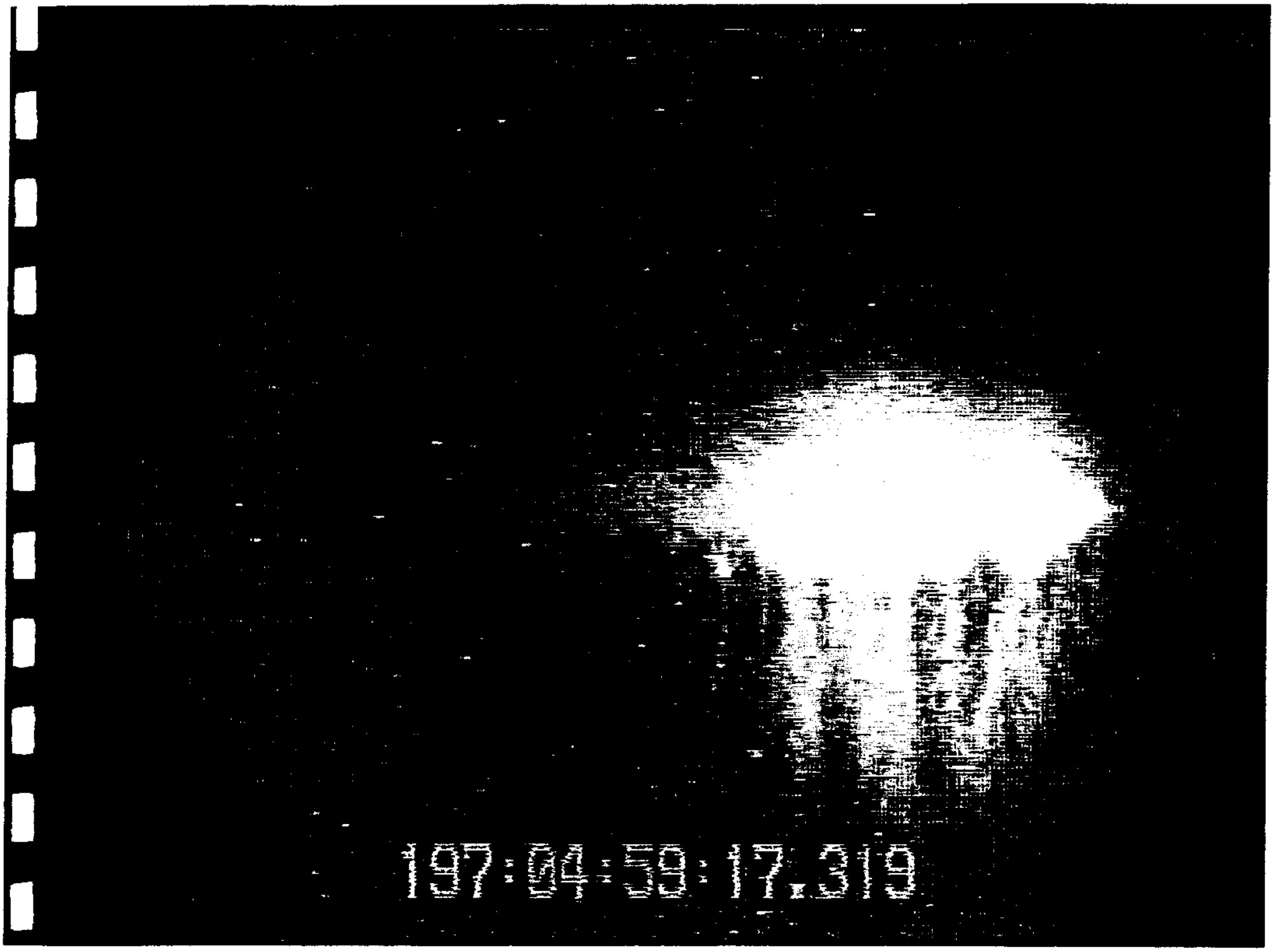


Figure 6-5. Close up of an elve and a sprite with well developed tendrils.

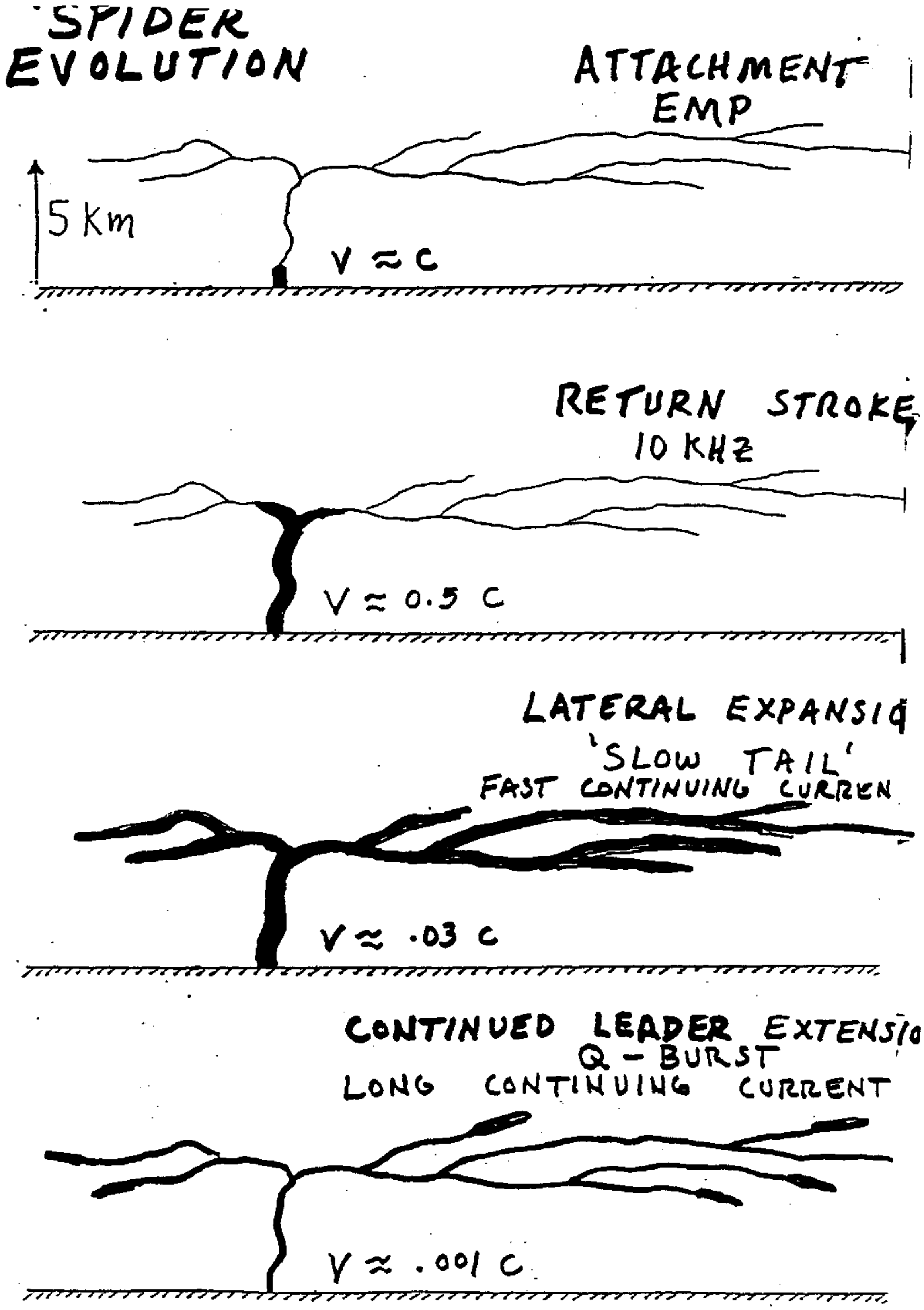


Figure 6-6. Sketch of the interrelationships between the +CG return stroke. the illumination of the dendritic "spider lightning" channels, the continuing currents and the slow tail and Q-burst generation. Courtesy Earle Williams.

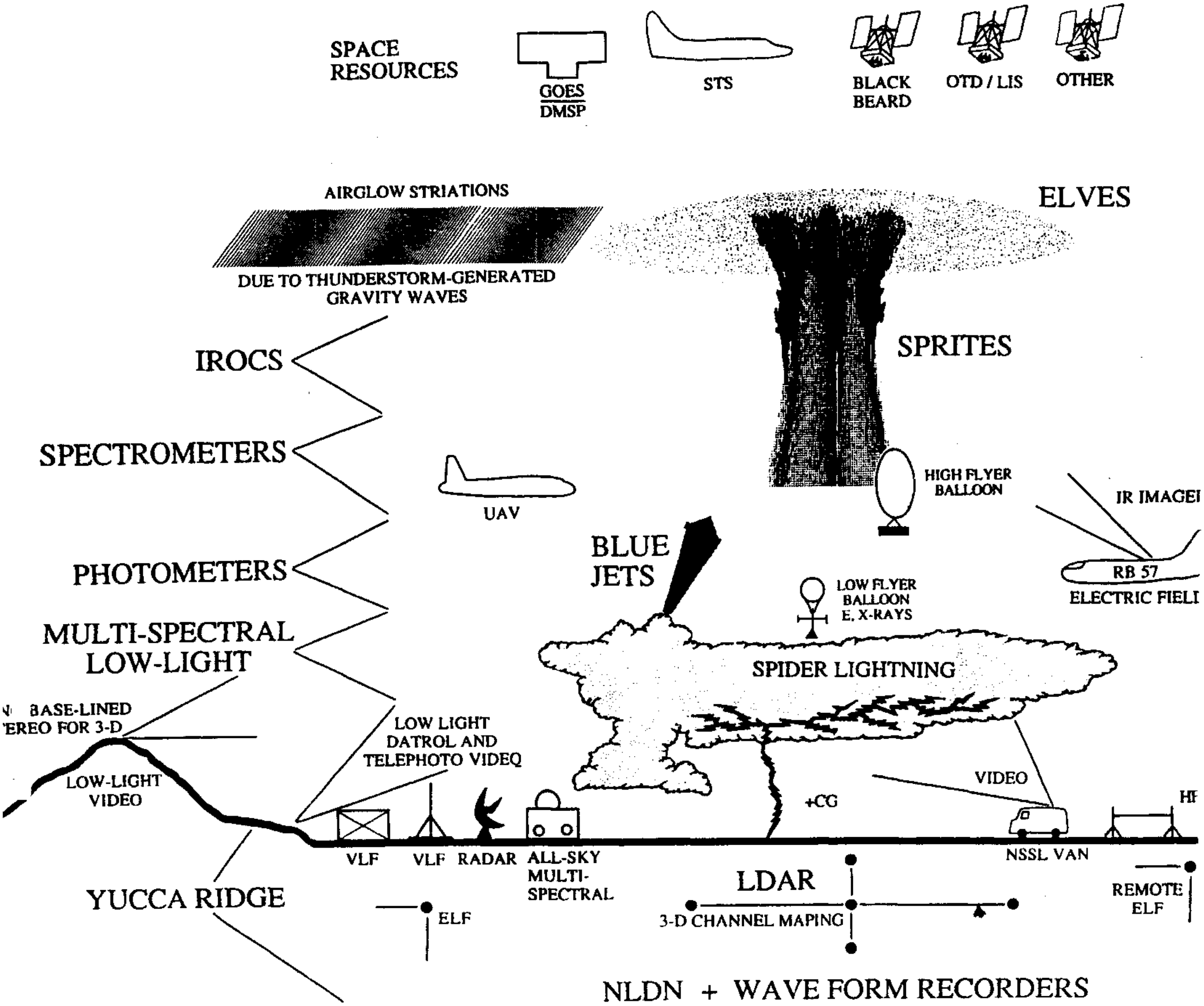


Figure 6-7. Schematics of a full-scale observational program to study TLEs.

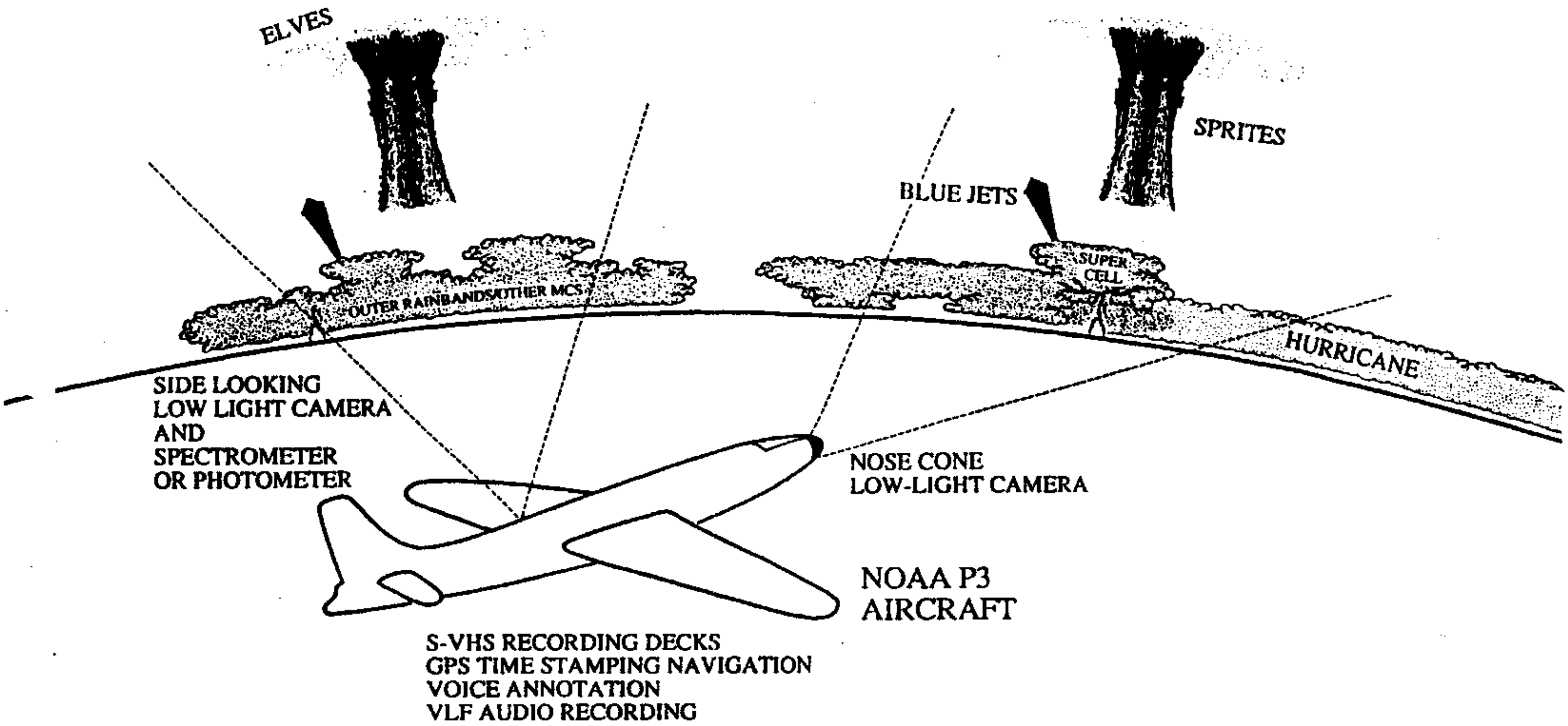


Figure 6-8. A proposal to mount LLTV systems on routine NOAA/HRD hurricane reconnaissance flights.

7.0 ACKNOWLEDGMENTS

This work was supported under an SBIR Phase II contract (NAS10-12113) from the NASA Kennedy Space Center. We acknowledge the contributions of many, including Carl Lennon, Launa Maier and Ron Bentti (NASA KSC) and O. H. Vaughan, Jr. (NASA MSFC). This work was a follow-on to a Phase I Small Business Innovation Research (SBIR) contract with the National Aeronatics and Space Administration, Kennedy Space Center (Contract NAS10-11974).

Several individuals were acting as key consultants to this project and their substantial contributions are greatefully ackowledged; Prof. John R. Winckler (University of Minnesota), Robert J. Nemzek (Los Alamos, NM), Perry R. Malcolm (U.S. Air Force Academy), Earle Williams (MIT) and Marek Uliasz (Ft. Collins, CO).

Particular attention is called to the efforts of Thomas E. Nelson (ASTeR) who most ably handled the complex equipment logistics during the data gathering phase and many aspects of data processing and analysis in the follow-on studies. Liv Nordem Lyons also made a valuable contribution in several key areas including facilitating participants planning, graphics and illustrations, techncial editing and administration.

The contributions of the many SPRITES'94 and '95 participants are acknowledged throughout this report. Among the many who participated and so freely shared their insight and information are: Dennis Boccippio (MIT/NASA MSFC), Bob Boldi and Charles Wong (MIT), William Sturz (Xybion Electronics Corp.), John Molitoris (Lawrence Livermore National Lab), Colin Price (Tel Aviv University), Russ Armstrong, Ian Baker and Jeff Shorter (Mission Research Corp.), Michael Taylor and Peter Mace (Utah State Univ.), Umran Inan, Bill Trabucco, Alex Slingeland and Steve Reising (STAR Lab, Stanford University), Y, Fukunishi, Y. Takahashi and M. Kubota (Tohoku University), Richard Dowden (University of Otago), Stephen Mende and Rick Rairden (Lockheed Martin), Les Hale (Pennsylvania State Univ.), Frank Djuth (GeoScience, Inc.), Roland Tsunoda (SRI International) and Dave Sentman and Gene Wescott (Geophysical Institute, University of Alaska).

We would like to acknowledge the valuable insights provided through discussions with many individuals including William Boeck (Niagara University), Bob Franz

(LANL), Dave Desrochers (USAF), James Kroll (ASOSR), Laila Jeong (Phillips Lab), Rick Howard (NASA), Bob Holzworth (University of Washington), Ken Cummins (GDS), D. Papadapolous (University of Maryland), Richard Goldberg (NASA GSFC), Dan Holden (LANL) and Jerry Fishman (NASA MSFC).

Special thanks also to Prof. Cecil S. Keen (Mankato State University) who provided animated GOES satellite loops covering the SPRITES'94 and '95 programs and to Dr. Noel Petit (Augsburg College) who converted the voluminous 8 mm NLDN data tapes into CD-ROMs.

8.0 REFERENCES AND EXTENDED BIBLIOGRAPHY

The following include the literature references cited in this report. It also contains an extended bibliography of papers and reports that are directly or indirectly relevant to the topics at hand.

These include papers on storm dynamics, atmospheric electricity, lightning physics, space physics and radio science. The compilation, while extensive, is not complete. The breadth of the interdisciplinary studies surrounding the study of ionospheric and mesospheric transient luminous events is so great as to preclude a complete treatment of all papers which may be relevant. We feel, however, this represents the most comprehensive compendium of resources currently available. We plant to update this listing on an ongoing basis.

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SECTION 6

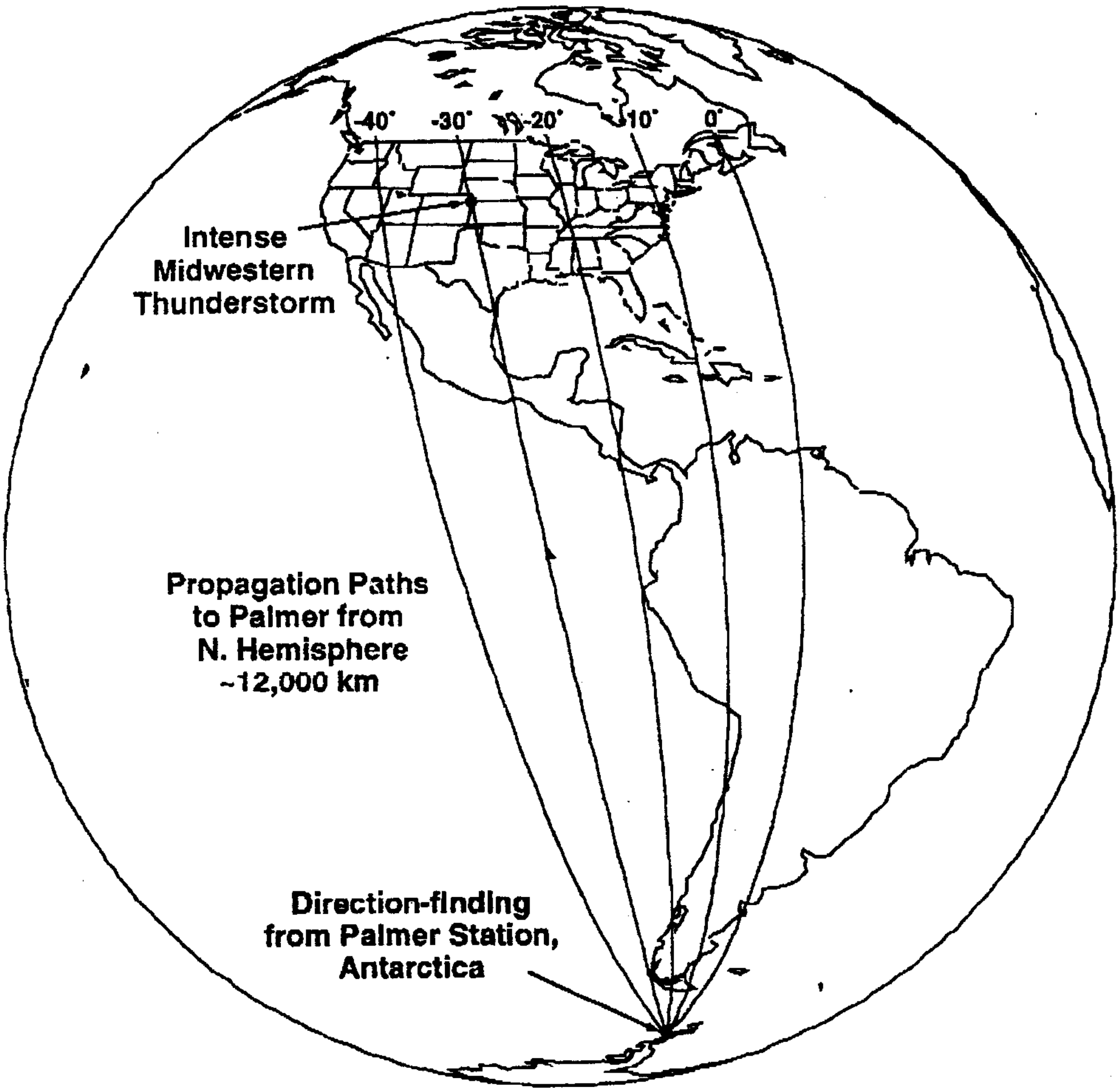


Figure 4-12. Source: Reising et al. (1996).

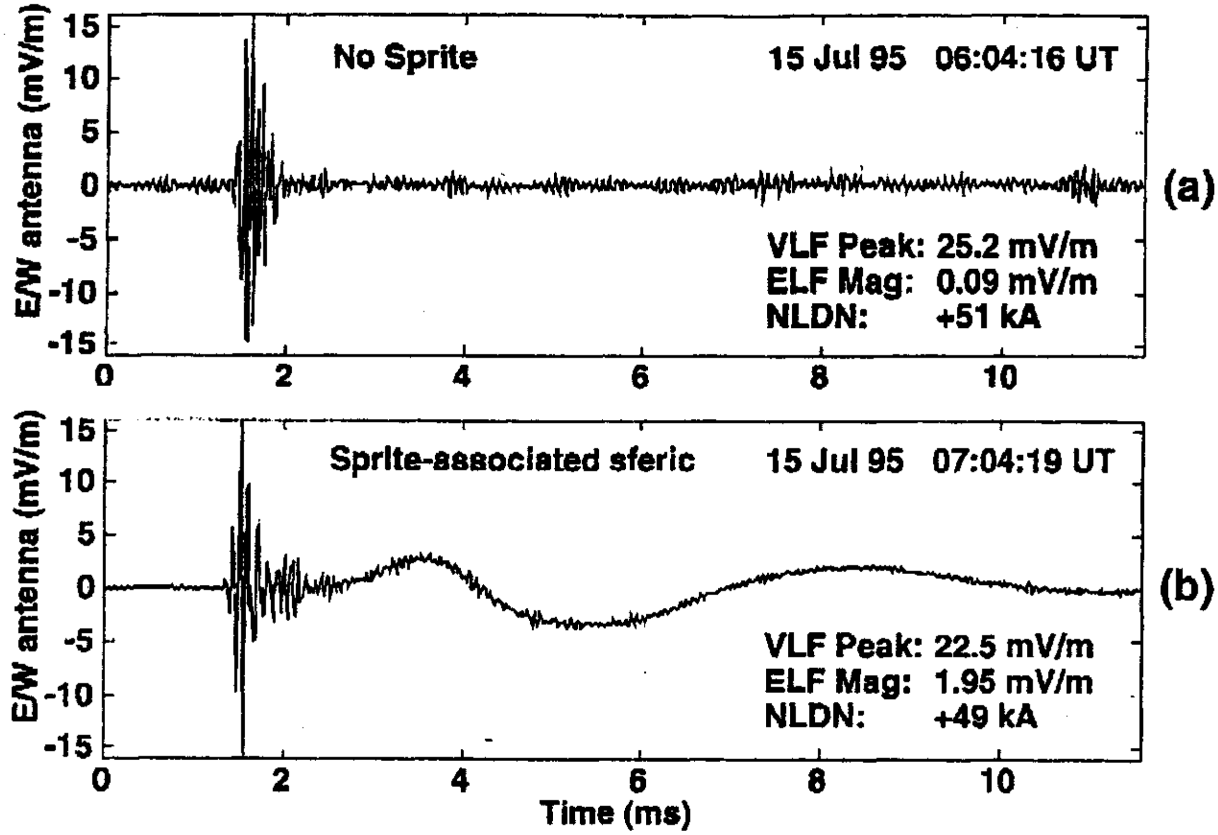
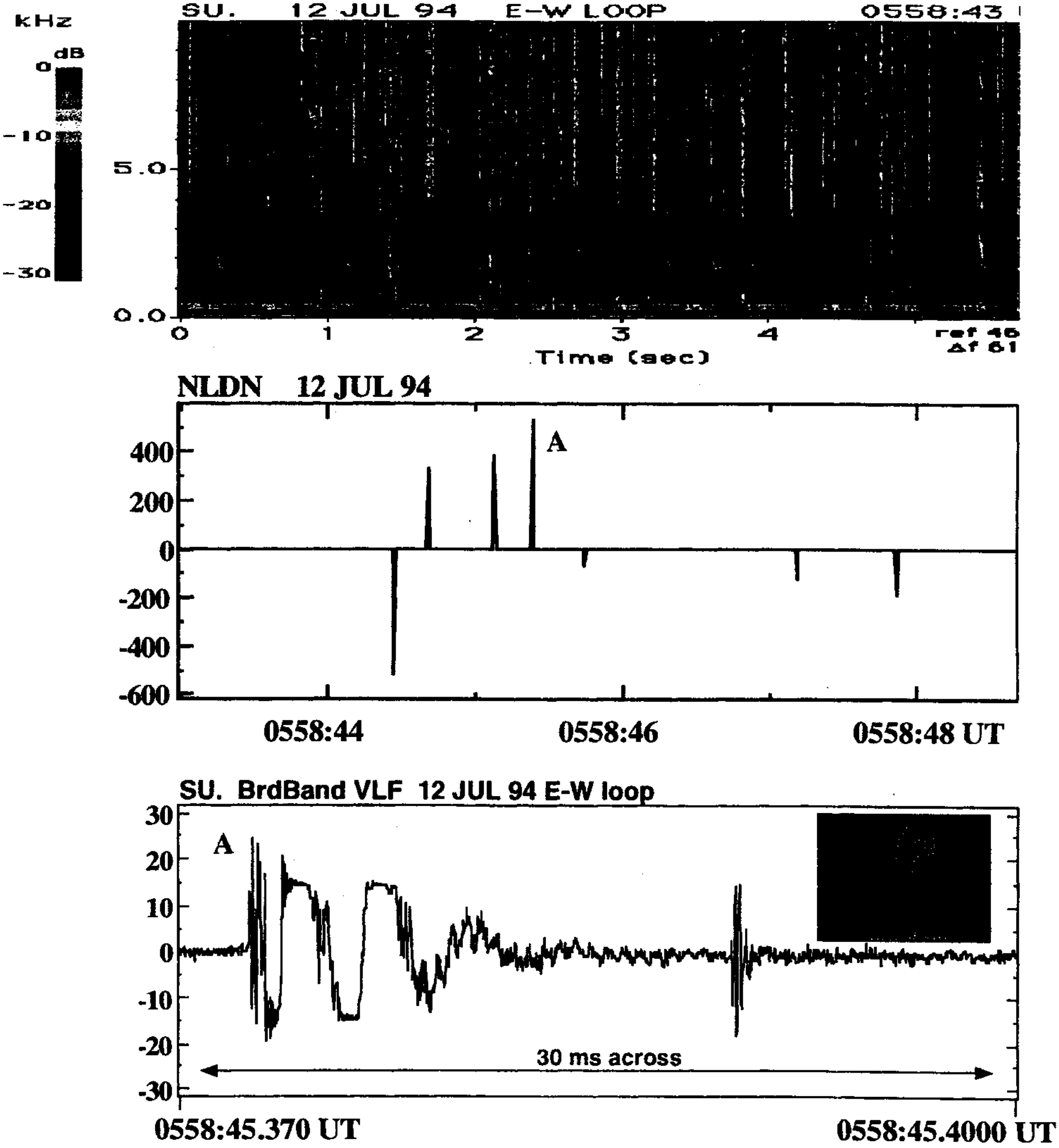
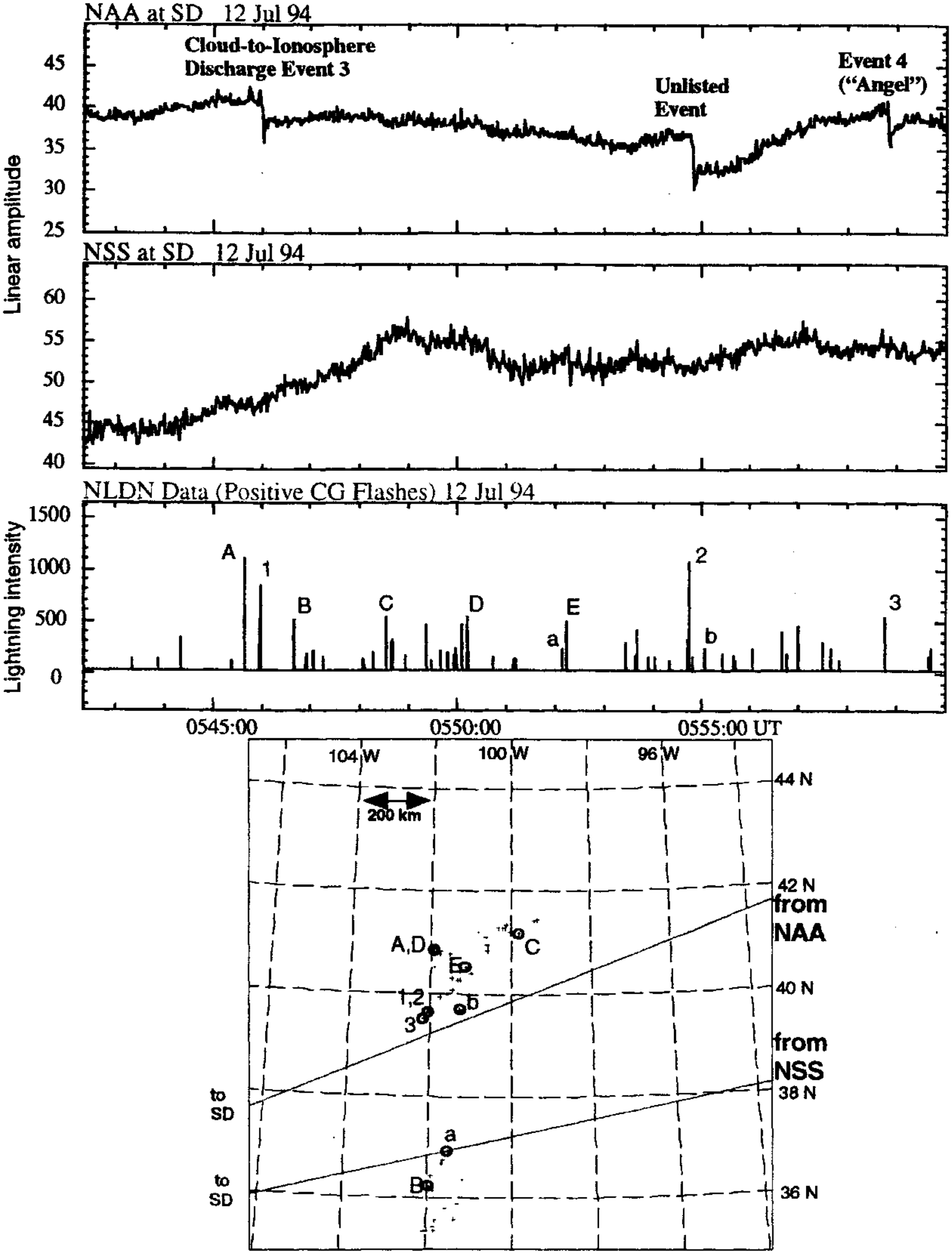


Figure 4-13: Source: Reising et al. (1996)



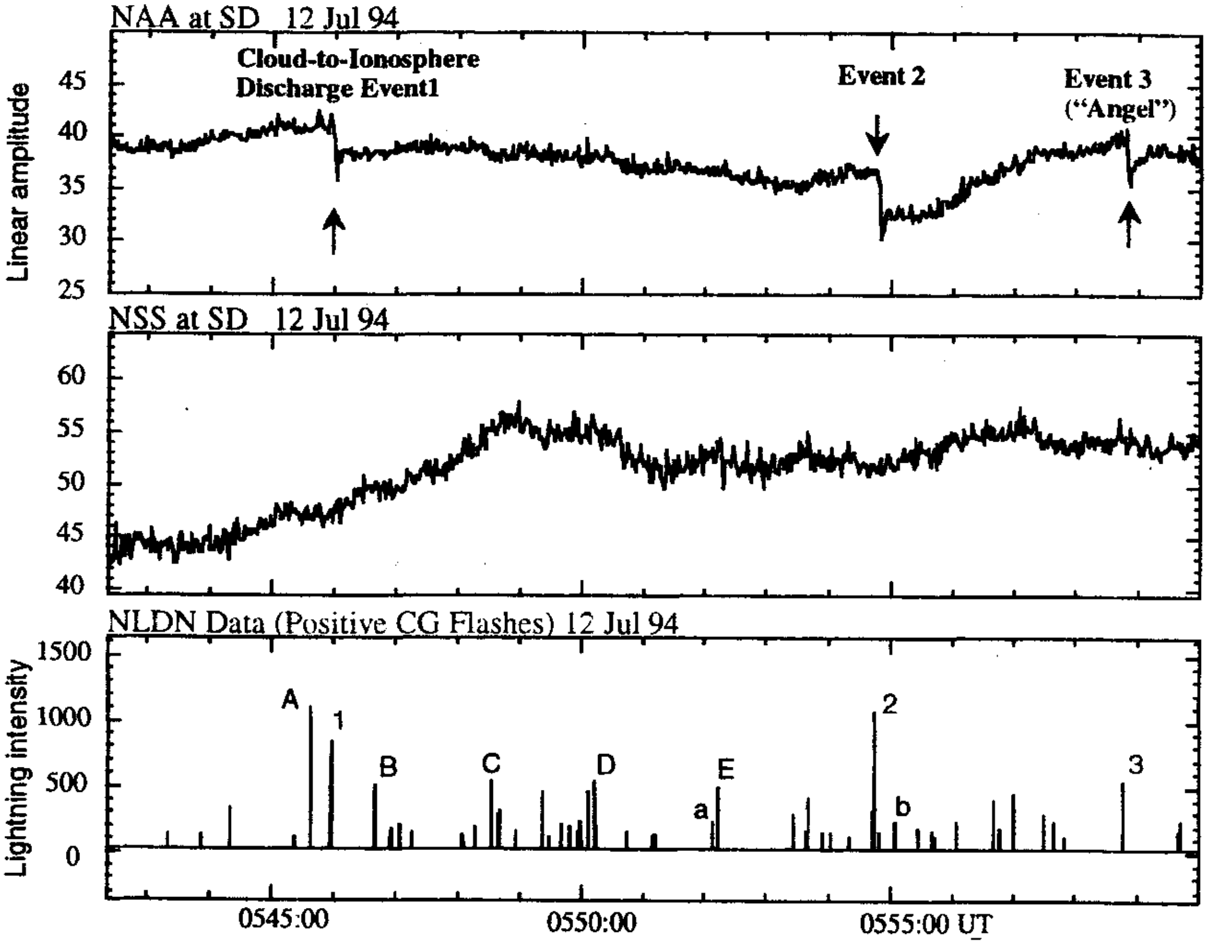
Broadband VLF spectra of the CG discharges which produced the Cloud-to-Ionosphere Discharge (Event 3: "Angel") and VLF Sprites as observed at Stanford University (SU). The radio atmospherics associated with the CG discharge A and the following burst of discharges are extremely intense, and have particularly strong low frequency (<3 kHz) components. The lowest panel shows the time waveform of the CG flash A; the saturation of the receiver in the first few milliseconds is clearly apparent.

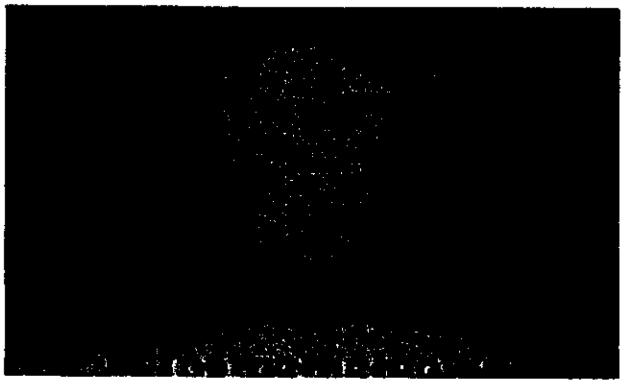
Figure 4-14: Courtesy Umran Inan, STAR Lab, Stanford University.



The three VLF perturbation events shown in the top panel were observed on the NAA-San Diego signal in time coincidence with Cloud-to-Ionosphere discharges (or Red Sprites) observed from the ground by the Winckler/Lyons group [Winckler et al., 1994; Fall AGU Meeting]. Detailed association of VLF events observed on the NAA-SD signal with CG lightning discharges. Top panel shows the amplitude of the NAA signal observed at San Diego showing three large amplitude perturbations. The nearby NSS-SD signal is shown in the second panel. In view of the extremely large CG flash rate in this storm, only positive CG flashes are shown. Intense lightning flashes are marked A - E, and flashes which are very close to the paths are marked a,b. The three CG flashes which are associated with the VLF perturbations are those large flashes closest to the paths. The implication is that the other similarly intense CG flashes (e.g. A - E) also produce ionization changes, which would have been measured if the VLF path was closer to these flashes. Flashes a, b which are similarly close to the path are not intense enough to produce an observable change.

Figure 4-15: Courtesy Umran Inan, STAR Lab, Stanford University.





05:45:56.188 UT C-I Event 1

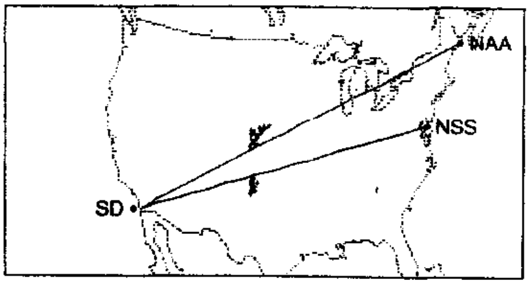


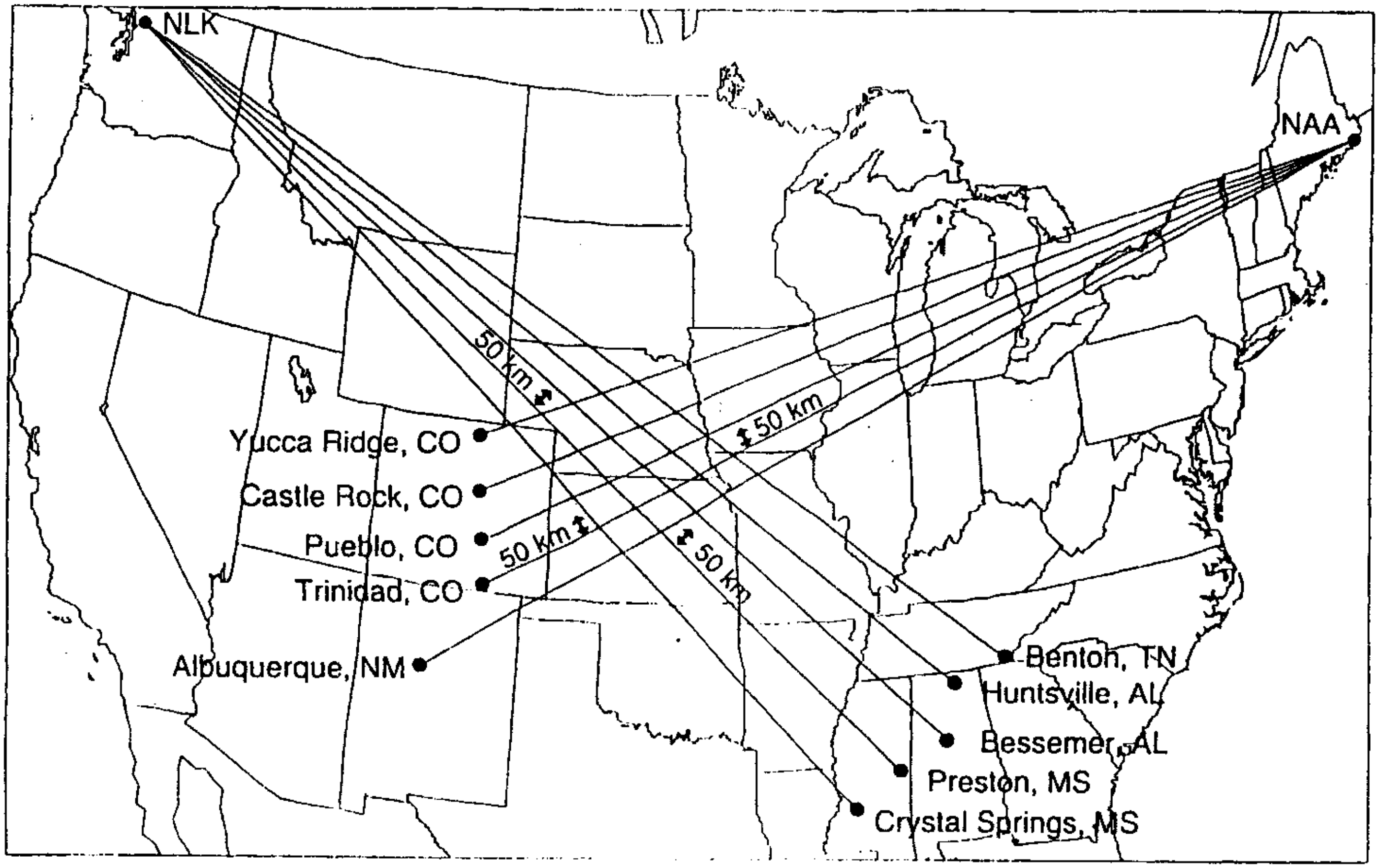
Image Data Courtesy of Dr. W. Lyons / ASTER Inc.

05:54:43.782 UT C-I Event 2

05:58:45.391 UT
C-I Event 3 "ANGEL"

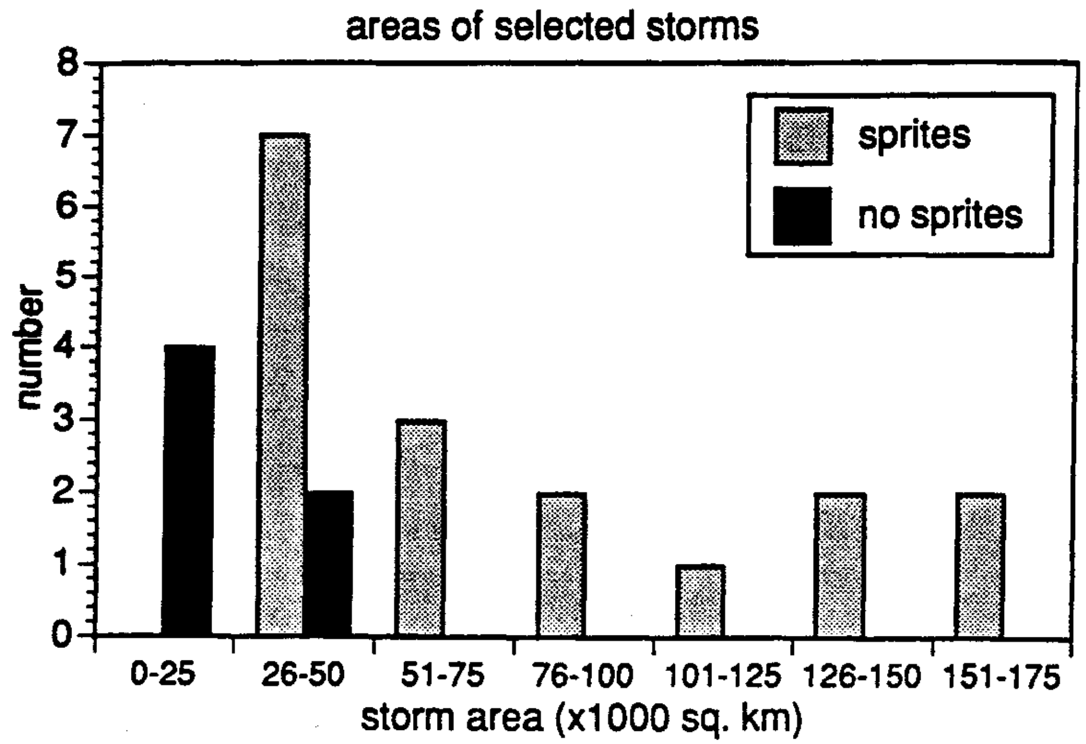
Figure 4-16: Courtesy Umran Inan, STAR Lab, Stanford University.

HAIL*



*Holographic Arrays for Ionospheric Lightning research

Figure 4-17: The proposed holographic arrays for ionospheric lightning research arrays that will be activated by Stanford during SPRITES'96. Courtesy Umran Inan.



Measured radar echoes areas associated with selected 1994 High Plains storms which both did and did not produce sprites detectable from YRFS.

Figure 4-18.

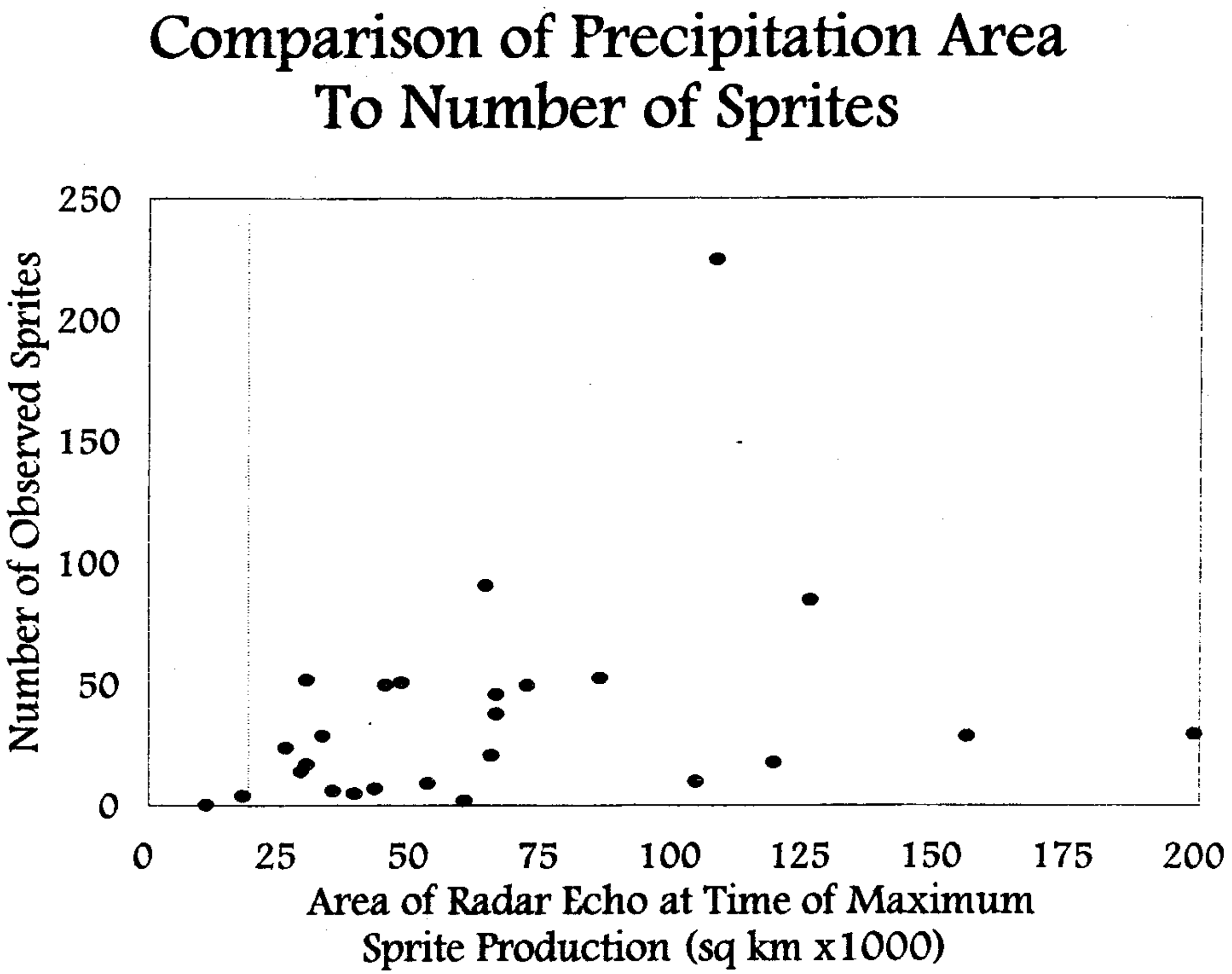


Figure 4-19: Area of radar echo for sprite producing storm at time of maximum sprite production versus total number of sprites observed from that storm for the 1995 season.

Sprite forecasts, 1994-1995 campaigns

OBSERVED

PREDICTED	NO	YES
NO	11	3
YES	2	51

VALIDATION

SKILL SCORES

Total forecasts:	67
Percent correct:	94%
Probability of detection: D/(B+D)	.94
False alarm rate: C/(A+C)	.08
Critical success index: D/(B+C+D)	.93
True skill score: POD-FAR	.86

Figure 4-20.

Figure 4-21. Typical supercell which results in localized hail storms along the Front Range. These cells are often prolific lightning producers, including many +CGs. Their size, however, rarely meets the sprite-generating criteria of 20,000 km^2. Additional monitoring of such storms is warranted. They may also be a source of blue jets.

5.0 CLIMATOLOGY

When, how often and under what circumstances do sprites, elves and blue jets occur, not just over the United States, but worldwide? Figure 1-2, based on the limited sample from literature references, gives credence to the notion that TLEs may be globally distributed. The distribution of sprite generating storms, based on those monitored by the LLTV systems at YRFS in 1994 and 1995 (Figure 5-1), suggests that while common throughout the 400,000 km^2 effective monitoring region, one can also detect a tendency for more sprite-bearing storms to be located from Kansas northwards.

During three summers of sprite monitoring from YRFS, it was noted that storms located east through north of the camera site often were more likely to provide sprite images. This was initially interpreted as the result of the most favorable viewing conditions for the LLTV systems being in that quadrant. But the finding that sprites and elves are uniquely a product of +CG flashes suggested that a more detailed climatological investigation of the NLDN data, stratified by polarity and peak current might be in order.

Several unpublished climatologies of CGs from the NLDN have shown that +CG events represent a higher percentage of the CG flash population over the northern High Plains than elsewhere in the nation. Following this lead we plotted those +CGs with >75 kA peak current during July-August, 1993 and June-July-August, 1994 and 1995, from 0300-0900 UTC (Figure 5-2). A clear concentration of large +CGs is evident in a broad belt stretching northeastward from eastern Colorado into Minnesota. This is the area in which most of the sprite observations from Yucca Ridge have been made. A blow up of this region in which we have plotted only +CG of > 100 kA peak currents from 0300 to 0900 UTC (Figure 5-3) reveals an interesting clustering of large +CG events imposed upon the corridor of high flash densities. The clusters are also apparent on a monthly time scale such as for July 1993 (Figure 5-4). This clustering might be related to some sort of "sprite generating cell" present within the large MCS stratiform regions. Similar +CG clusters in tall, hail-producing supercell storms on the High Plains have been previously noted by Stolzenburg (1994). These clusters typically occur in storms much smaller than sprite storms and often occur prior to 0300 UTC. They therefore may represent a different phenomenon from that suggested here.

A much more extensive climatological analysis of the NLDN database has recently been completed by the contractor. The raw NLDN data were obtained from GDS, Inc., originally on 8 mm tape, subsequently converted to CD-ROM for ease of manipulation. The data were for the months of June (1991, 1994, 1995), July and August (1991, 1993, 1994, 1995) and September (1991, 1994, 1995 [last 19 days only]). Over nearly 14 summer months, almost 59 million CG flashes were reported. This averages 4.4 million flashes per summer month, with the peak being 7.1 million in July 1993.

Once on CD-ROM, we sorted the NLDN data and prepared files of only CG flashes having reported peak currents of >75 kA. There has been some speculation that the NLDN network calibrations for flashes of >60 kA is not entirely representative (Idone et al., 1993). For this study, we will take the peak current values as reported by NLDN. We have used the signal strength to peak current multiplier of 0.20 rather than the more recently suggested value of 0.185.

Figures 5-5 and 5-6 show hourly tabulations of the distribution of large peak current positive and negative CGs, including the maximum value observed for both the entire NLDN and the "sprite region" of the central U.S. (see Figure 5-19). The number of large peak current CGs is 1.39 million for the U.S. as a whole, with 13.7% of these being +CGs. In the central part of the country, there were 450 thousand large peak current CGs, but there a much larger fraction, 29.5%, were of positive polarity. A monthly break down of large peak current CGs of both polarities is included in Figure 5-7. The month of July typically has the most flashes of any magnitude including those > 75 kA.

The distribution of large peak current CGs in the central U.S. by polarity is shown in Figure 5-8. Events of larger than 200 kA are comparatively rare, although over 2900 were recorded. If one assume that +CGs with peak currents >75 kA are likely candidates to produce sprites and elves, than 132,794 represents an approximate upper limit for the number of sprites and elves in this region over a 14 summer month period. This places the frequency of sprites and elves at around 10^4 per month or 14 per hour in this region. Note: many sprites have also been detected with +CGs having peak currents of less than 75 kA. However since the percentage of +CG producing sprites is not well known, these two factors probably tend to cancel each other out.

The temporal distribution of large amplitude central U.S. CGs of both polarities is shown in Figure 5-9. It should be noted that for all amplitude categories, there are more negative than positive CGs. While the percentage of +CGs with larger peak currents is higher, the shear number of -CGs assures that at all sizes they dominate. We note, however, that during the early evening hours in the central U.S., the large amplitude positives come very close to outnumbering the large amplitude negatives. This several hour long period roughly coincides with the peak sprite producing times for storms monitored from YRFS.

An ongoing task underlying this project has been to assess the potential for TLEs near the Kennedy Space Center and also along the launch and descent corridors of the Space Shuttle. A nationwide large peak current CG density was constructed. For all 14 months, the number of flashes stratified by polarity and peak current were summed into squares 47 km on a side (the MDR coordinate system that has been used in a number of previous lightning climatologies). Figure 5-10 shows the distribution of CGs of both polarities with >75 kA peak current. One is immediately struck by the very high number along the Gulf and southeastern Atlantic coastlines, and especially over the open waters. The network detection efficiency begins to fall off rapidly more than 200-300 km offshore (Cummins et al., 1995) as evidenced by the declining densities further from land. There are also small peaks evident in both the upper midwest and northwest Mexico. When these data are separated by polarity (Figures 5-11 and 5-12) a rather startling difference emerges. Due to their predominance in the overall sample, the -CG density map looks similar to the pervious figure. The +CG distribution, however, is radically different, with a pronounced maximum in large peak current +CGs stretching from eastern Colorado north-northeast in a broad belt into Minnesota. This area closely corresponds to the region of maximum nocturnal MCS activity in the U.S. and closely matches the favored sprite-viewing regions from YRFS. The smaller pocket in northwestern Mexico is apparently related to a region of preferred development of very large MCSs due to sea breeze/terrain interactions. Note that there are relatively few large peak current +CGs in or around the Florida peninsula.

The diurnal distribution of the large peak current CGs was studied by breaking up the data into three time periods: 1100-1900, 1900-0300, and 0300-1100 UTC, the last corresponding to peak sprite observation times from YRFS. Large amplitude +CGs tend to cluster in the High Plains and upper Midwest during all time periods, but are most numerous during the late afternoon and on into the nighttime hours. The distribution of large amplitude -CGs reaches a maximum along the Gulf coast and over Florida (most likely from sea breezes) during the late afternoon. During the night there are comparatively few large -CGs over Florida, but many continue over the surrounding ocean. The over-water maxima are puzzling. Since these data represent summer periods, the warmth of the Gulf Stream would not appear to be a significant factor. The high concentration of large amplitude -CGs around the New Orleans area is also not easily explained.

Figures 5-19 and 5-20 are plots over the central U.S of the largest of CG flashes, those exceeding 200 kA. The -CG map shows a hint of a minimum in the "sprite alley" region from Colorado to Minnesota. The cluster in Texas is suspected to be related to the 1995 Dallas hail disaster, but this remains to be verified. A somewhat higher density of large -CGs is also evident over the Rocky Mountains. The map for largest +CGs reflects the general pattern, with a corridor stretching from Kansas into the upper Midwest. The peculiar arc shaped cluster in Texas can not be explained at this time. A somewhat similar pattern can be found for the very largest CGs (>300 kA) shown in Figure 5-21. The negatives tend to be clustered in the southeast, especially over the Gulf and Atlantic whereas as the positives are more prevalent in the High Plains and Minnesota.

The +CG destiny charts may very well represent a very crude distribution of sprites and elves for the United States. Whether blue jets can be expected to be preferentially found in the regions of elevated large amplitude -CG frequencies is an open but intriguing question.

While on a national scale sprites may be most commonly found above the U.S. High Plains, according to Lyons and Williams (1993), sprite-like phenomena have been reported by observers worldwide. This would imply that storms with characteristics different from High Plains nocturnal MCS might produce sprites. In the 1995 South American airborne campaign (Sentman, personal communication, 1995), sprites were detected above somewhat smaller convective storms, though many were more than 150 km on a side. Yet it is suspected that the CG discharges resulting in those sprites were among the larger, both in peak current and horizontal in-cloud branching. Tropical thunderstorms in which large positive discharges accompany the end of storm oscillation (EOSO) during the system's decaying stages has been noted by Mazur et al. (1995). Thus we suspect that while sprites do occur over larger tropical systems (though somewhat smaller than midwestern MCSs), they are less frequent on a per storm basis. On the other hand there are many more potential storms from which sprites could be generated.

And, importantly, it should also be noted that MCS-class storms are not relegated to the interior of North America. They occur over South America (Velasco and Fritsch, 1987), the Indian Subcontinent (Laing and Fritsch, 1993a) and Africa (Laing and Fritsch, 1993b) to cite just a few of the available studies. Figure 5-22 shows a one year distribution of the largest convective systems on the planet, the mesoscale convection complex (MCC) derived from satellite data from 1986-1987. MCCs are clearly not relegated to mid-latitude northern hemisphere summers. Intense lightning is also present during certain stages of tropical storm intensification (Lyons and Keen, 1994) and may likewise represent a tropical sprite source region.

Do sprites and elves occur in Florida? Two summer campaigns were unsuccessful in obtaining images of TLEs but this was the result of unusually storm free periods or alternately heavy cloud cover associated with tropical storms. Based upon the CG climatology, it would appear that the frequency of sprites is clearly lower than over the midwest, but sprites can still occur. During the summer months it is not uncommon for east and west coast sea breezes to merge in the interior of the peninsula with resulting deep convection covering areas substantially in excess of 20,000 km^2. The LDAR system has reported occasional 100+ km long horizontal discharges and the KSC monitoring cameras themselves have recorded large spider lightning events (Figure 5-23). If there is a relationship between blue jets and large peak current -CGs, then their numbers in the KSC region would appear to be far higher than in the YRFS region.

The meteorological conditions associated with sprites and elves over the High Plains are portrayed in summary form in Figure 5-25. While the MCS may have a relatively small (≈20 km) intense core in which large -CG flash rates and high radar reflectivity are found, the bulk of the system is comprised of a massive stratiform precipitation region. This may either be leading or trailing the convective core, depending upon the troposphere wind profile. These massive anvil clouds, which have been noted to extend to up to 700 km in length, have been found to possess multi-layered charge structures with vast horizontal pools of positive charge (Marshall et al., 1995). While it once was thought that the anvil charge was the result of horizontal advection from the convective core, it now appears more likely that a substantial fraction results from in situ charging due to ice-ice mechanisms (Rutledge and Petersen, 1994; Rutledge et al., 1993). These storms often have the typical bi-polar pattern described by Orville et al. (1988). In the stratiform region they generally have relatively low densities of CG flashes with a high proportion of +CGs. When a leader generates a positive return stroke, this emits a strong VLF signal detected by the NLDN. It appears that many of these +CG continue to re-illuminate the vast network of horizontal channels within the anvil, resulting in a continuing current and further draining vast quantities of positive charge. This removal of such large amounts of charge (perhaps up to 600 C according to Earle Williams, personal communication) over such a large area creates transient electrical fields above the storm greatly stressing the mesosphere to the point of dielectric breakdown.

A parallel question involves the percentage of lightning flashes which generate sprites, elves or blue jets. Boeck et al. (1991), based on very preliminary imagery from the Space Shuttle, concluded that the frequency of occurrence for TLEs was on the order of 1 per observed 5000 CG/IC discharges and thus could be termed "unusual", but not rare. If one notes the range of annualized planetary lightning rates (Brooks, 1925; Orville and Spencer, 1979; Liaw et al., 1990; and Kotaki et al., 1981), Boeck's ratio implies between 0.6 and 2.5×10^6 events per year (every 12.5 to 50 seconds). For selected storms studied by YRFS, the local ratio was at times found to be almost two orders of magnitude lower. How this translates to a global ratio for all storms remains unclear.

In summary, over the U.S. High Plains the initial evidence suggests that a necessary, though maybe not sufficient condition for sprites is an MCS with >20,000 km^2 radar echo area having a large stratiform precipitation region containing numerous +CG flashes having continuing currents. The sprites are a quasi-electrostatic response to +CG events having continuing currents drawing from complex horizontal electrical discharges within the MCS anvil that are part of the +CG discharge process. Such horizontal anvil discharges are known to extend for over 100 km. On a number of occasions sprites have been noted "dancing" in sync with cloud flashes propagating within extensive anvil canopies.

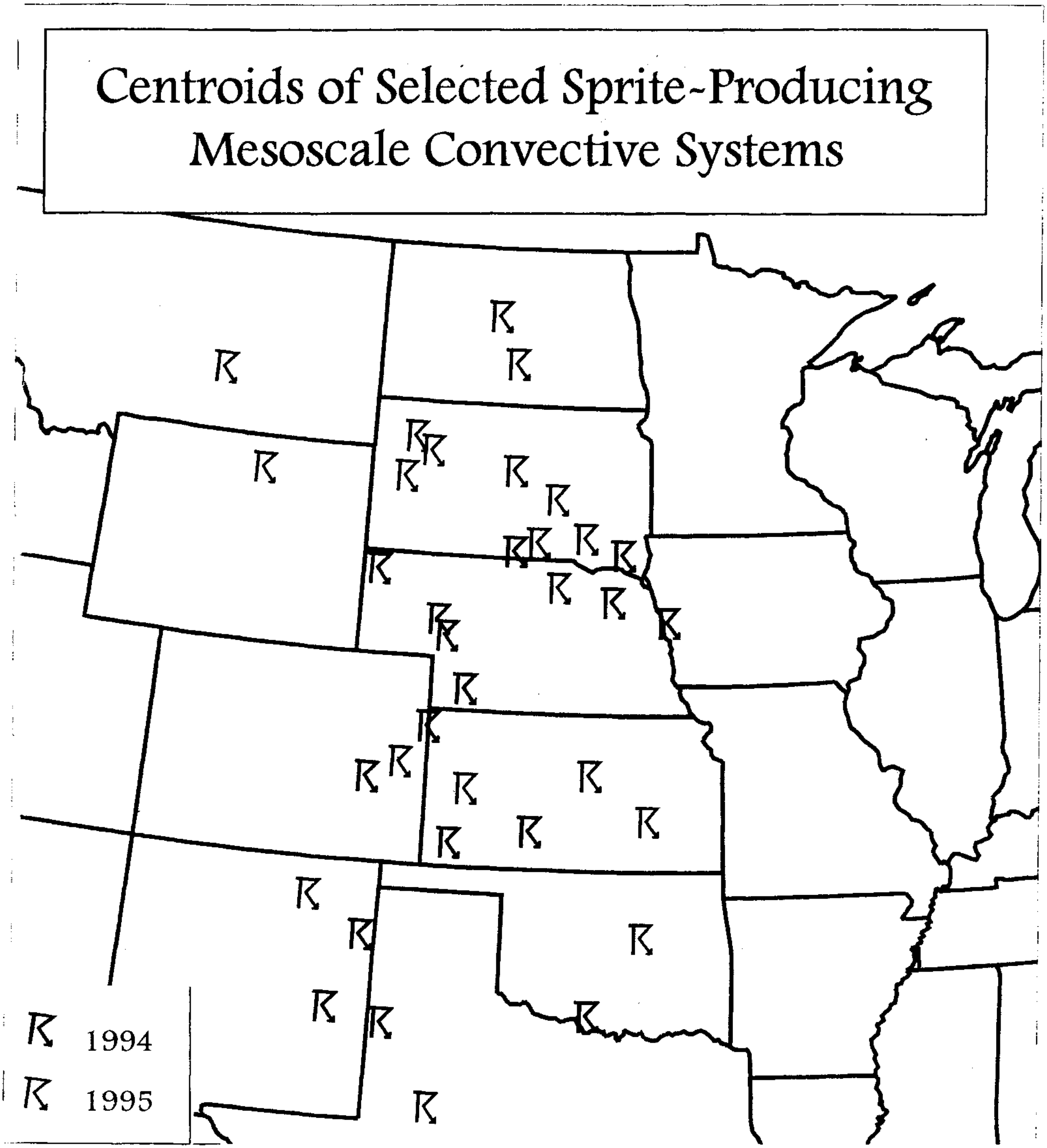
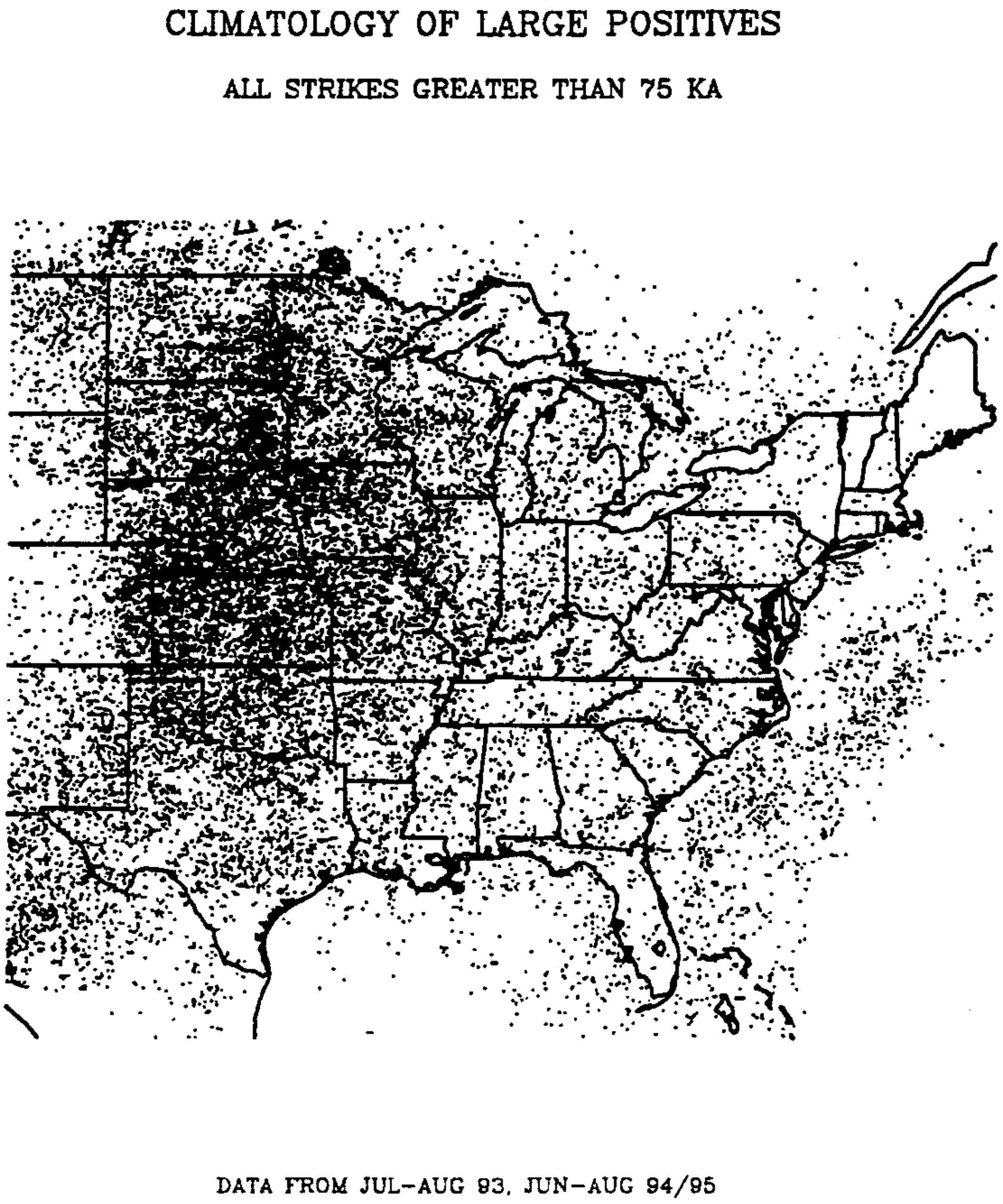


Figure 5-1. Location of major sprite producing storms viewed from YRFS in 1994-95.

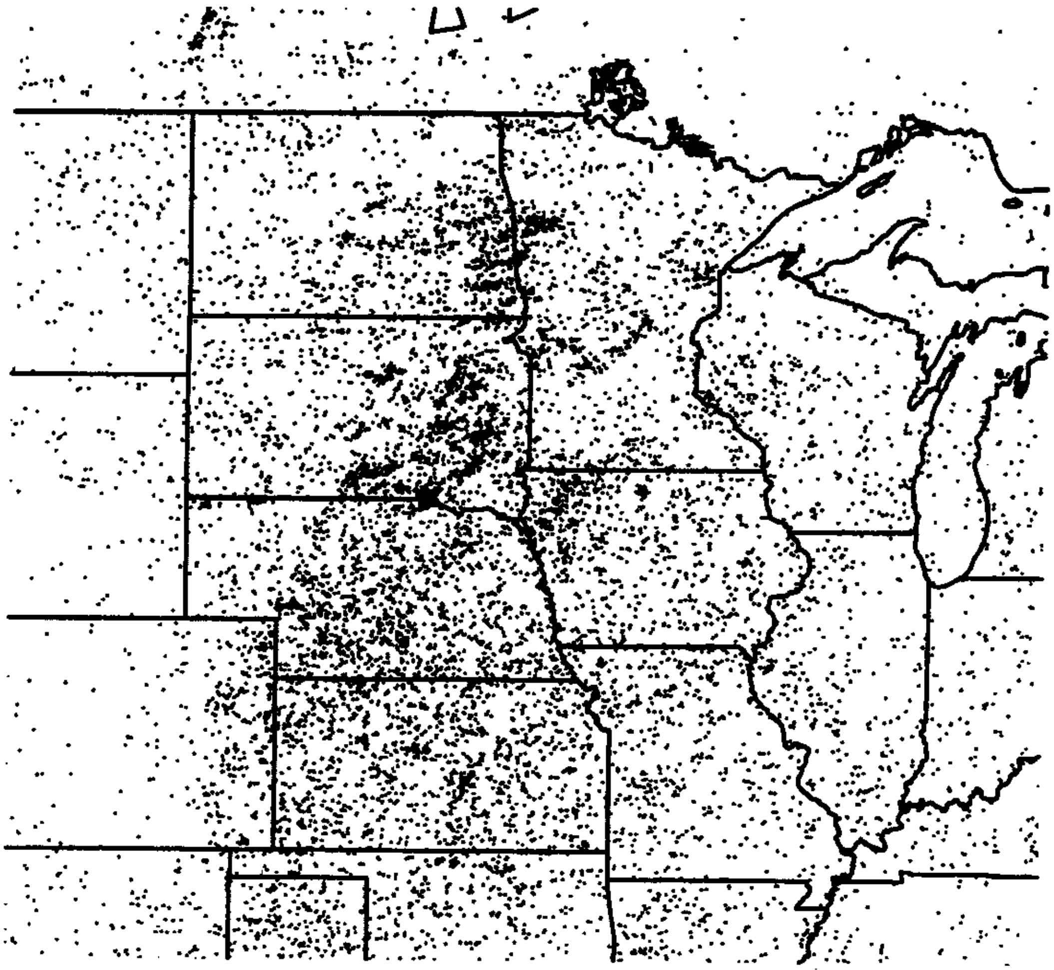


Plot of all +CGs with peak currents >75 kA during the July-August, 1993 and June-July-August, 1994 - 1995 period between 0300-0900 UTC, the times when sprites are most likely to be observed over the central U.S.

Figure 5-2.

CLIMATOLOGY OF LARGE POSITIVES

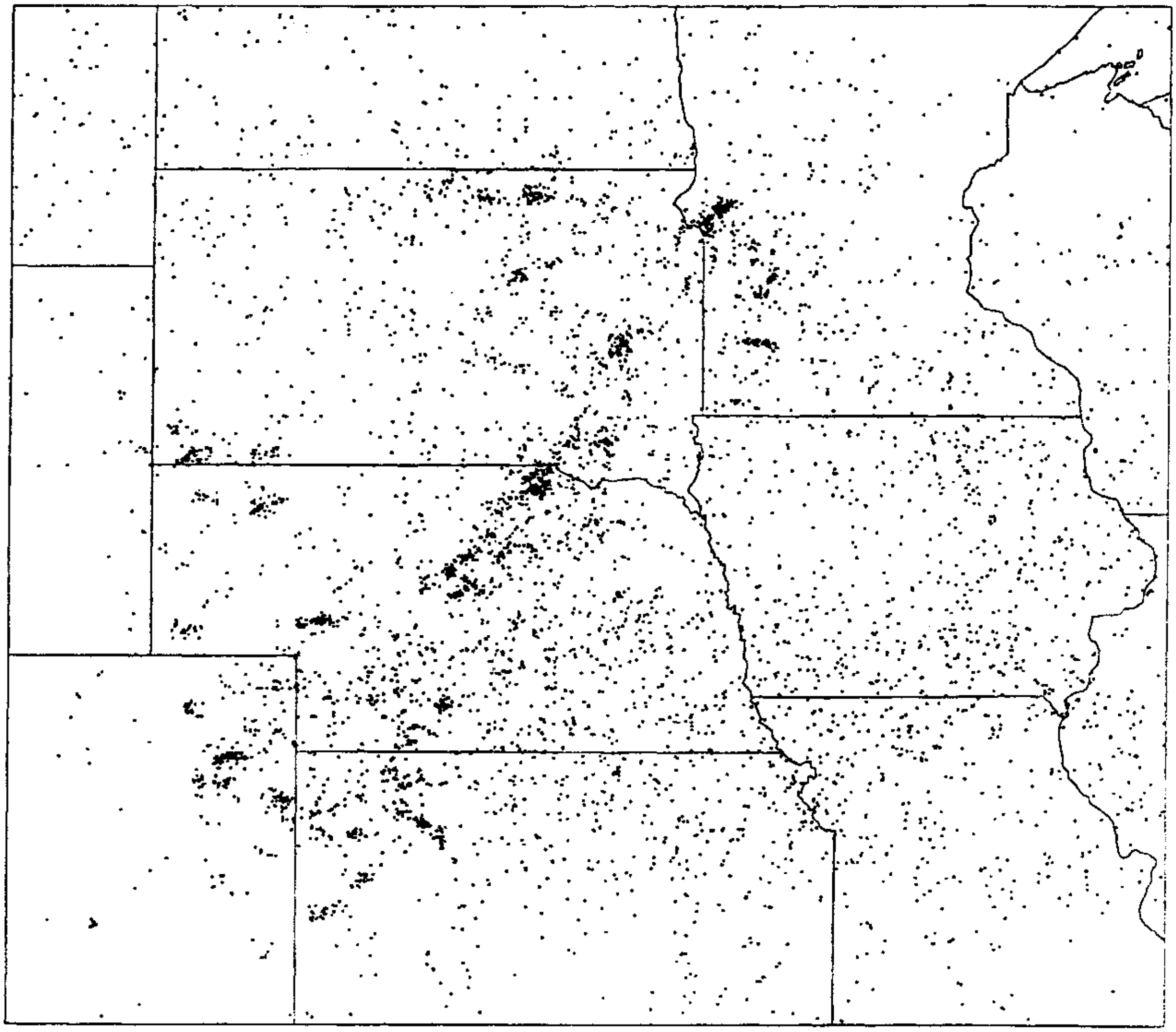
ALL STRIKES GREATER THAN 100 KA



DATA FROM JUL–AUG 93, JUN–AUG 94/95

Figure 5-3. Plot of all +CGs with peak currents > 100 kA between July-August 1993 and June-August 1994 and 1995 between the hours of 0300 - 0900 UTC.

CLIMATOLOGY OF LARGE POSTIVES



JULY 1993
All strikes larger than 100kA

Figure 5-4. Plot of +CGs >100 kA for the month of July 1993.

T	MAX		75-100		100-200		200-300		300-400		>400		>75	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-
1	378	486	10234	36873	5535	14807	120	278	6	24	0	5	15895	51987
2	333	511	10297	30912	5599	12539	117	282	4	12	0	3	16017	43748
3	384	957	9121	25777	4988	10663	119	260	4	14	0	3	14232	36717
4	434	468	7883	23534	4354	9701	115	230	5	15	2	1	12359	33481
5	341	465	6735	22671	3789	10112	83	216	5	12	0	3	10612	33014
6	509	392	5807	22908	3162	10243	76	230	2	6	1	0	9048	33387
7	439	547	5528	23602	3268	10946	60	219	0	6	2	1	8858	34774
8	487	387	4810	24507	2741	11729	70	246	1	14	2	0	7624	36496
9	344	461	4381	26162	2613	13107	90	306	2	22	0	2	7086	39599
10	580	471	3714	28467	2123	14576	70	334	0	14	1	3	5908	43394
11	386	416	3567	31465	2042	16643	88	418	2	15	0	2	5699	48543
12	372	422	3283	34895	1961	18840	76	468	3	17	0	2	5323	54222
13	397	446	3083	35191	1993	19598	62	456	2	21	0	3	5140	55269
14	300	445	3004	35043	1768	19116	52	447	1	26	0	2	4825	54634
15	293	568	2747	33773	1715	18180	63	418	0	15	0	3	4525	52389
16	374	472	2441	33318	1560	17850	39	382	3	18	0	2	4043	51570
17	404	446	2195	33190	1368	17305	28	381	0	15	1	3	3592	50894
18	295	466	2131	36728	1299	17664	40	362	0	13	0	3	3470	54770
19	399	410	2334	41988	1478	18428	43	338	1	15	0	1	3856	60770
20	404	584	2872	48128	1764	19277	42	359	3	20	1	4	4682	67788
21	576	502	3791	51549	2115	19663	44	349	2	15	1	2	5953	71578
22	400	470	5398	51688	3030	19327	77	339	4	23	1	1	8510	71378
23	393	574	7168	49188	3949	18507	58	351	2	18	0	3	11177	68067
24	352	387	8633	43842	4898	16773	110	338	2	17	0	0	13643	60970
0	580	957	121157	825399	69112	375594	1742	8007	54	387	12	52	192077	1209439

Figure 5-5. Hourly (UTC) distribution of positive and negative CGs above indicated peak currents (kiloamps) for the entire NLDN domain over 14 summer months.

T	MAX		75-100		100-200		200-300		300-400		>400		>75	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-
1	378	486	7424	12851	3891	4708	77	96	5	8	0	2	11397	17665
2	333	359	7603	10667	3921	3818	68	82	4	3	0	0	11596	14570
3	313	957	6800	8634	3632	3029	87	82	2	6	0	2	10521	11753
4	383	468	6034	7832	3183	2677	86	62	3	5	0	1	9306	10577
5	331	403	5168	7569	2845	2624	58	48	4	1	0	1	8075	10243
6	509	366	4323	7605	2260	2699	44	46	1	2	1	0	6629	10352
7	426	272	4322	7781	2508	2716	38	34	0	0	1	0	6869	10531
8	312	386	3758	7755	2137	2831	52	45	1	3	0	0	5948	10634
9	301	386	3343	7843	2028	2945	66	45	1	3	0	0	5438	10836
0	283	404	2759	7835	1560	3057	53	52	0	3	0	1	4372	10948
1	306	314	2550	8172	1454	3363	68	59	1	2	0	0	4073	11596
2	341	324	2176	8233	1308	3515	62	68	2	3	0	0	3548	11819
3	331	446	2014	7831	1277	3456	48	52	1	2	0	1	3340	11342
4	300	445	1820	7057	1060	3430	35	67	1	2	0	2	2916	10558
5	290	440	1643	6463	1010	2977	39	66	0	4	0	1	2692	9511
6	286	323	1329	6130	827	2065	25	48	0	4	0	0	2181	9047
7	255	418	1119	5987	690	2697	17	63	0	6	0	2	1826	8755
8	259	380	1034	7267	634	3108	20	69	0	1	0	0	1688	10445
9	270	372	1218	9569	809	3792	31	62	0	3	0	0	2058	13426
0	404	353	1518	13203	976	4983	22	78	0	7	1	0	2517	18271
1	309	502	2144	15420	1178	5515	24	96	1	4	0	1	3347	21036
2	400	358	3341	16306	1886	5846	37	105	1	7	1	0	5266	22264
3	344	574	4938	15958	2655	5693	29	102	1	4	0	1	7623	21758
4	293	387	6064	14541	3438	5342	66	91	0	8	0	0	9568	19982
0	509	957	84442	228509	47167	87686	1152	1618	29	91	4	15	132794	317919

Figure 5-6. Hourly (UTC) distribution of positive and negative CGs above indicated peak currents (kiloamps) for the central U.S. over a 14 summer month period.

Large Amplitude CGs (>75 kA)

Source: NLDN (1991, 1993, 1995) Domain: Entire Network

July 1995	155,585
July 1991	138,538
July 1994	175,838
July 1993	121,900
June 1994	115,913
August 1995	105,493
August 1991	104,362
August 1993	102,018
August 1994	97,357
June 1995	93,406
June 1991	85,418
September 1991	69,970
September 1994	58,802
September 1995	35,318

Figure 5-7. Monthly distribution of large amplitude 9>75 kA of both polarities for the entire NLDN network.

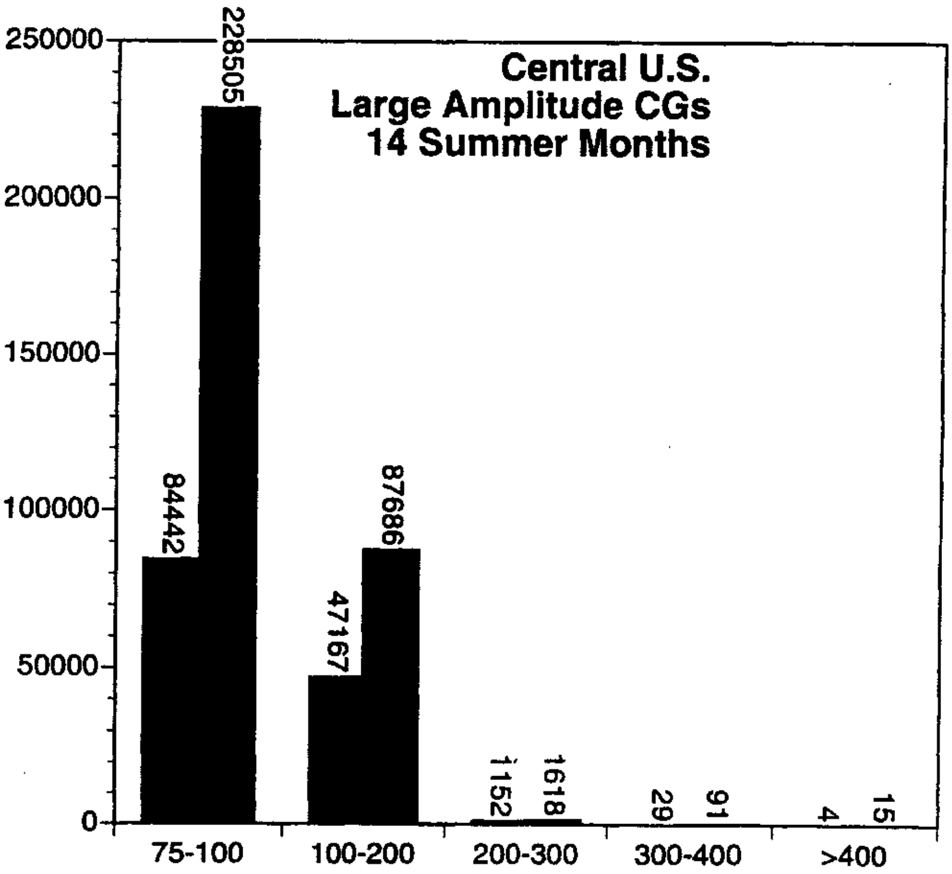


Figure 5-8. Distribution of large amplitude negative and positive CGs for 14 summer months in the central U.S.

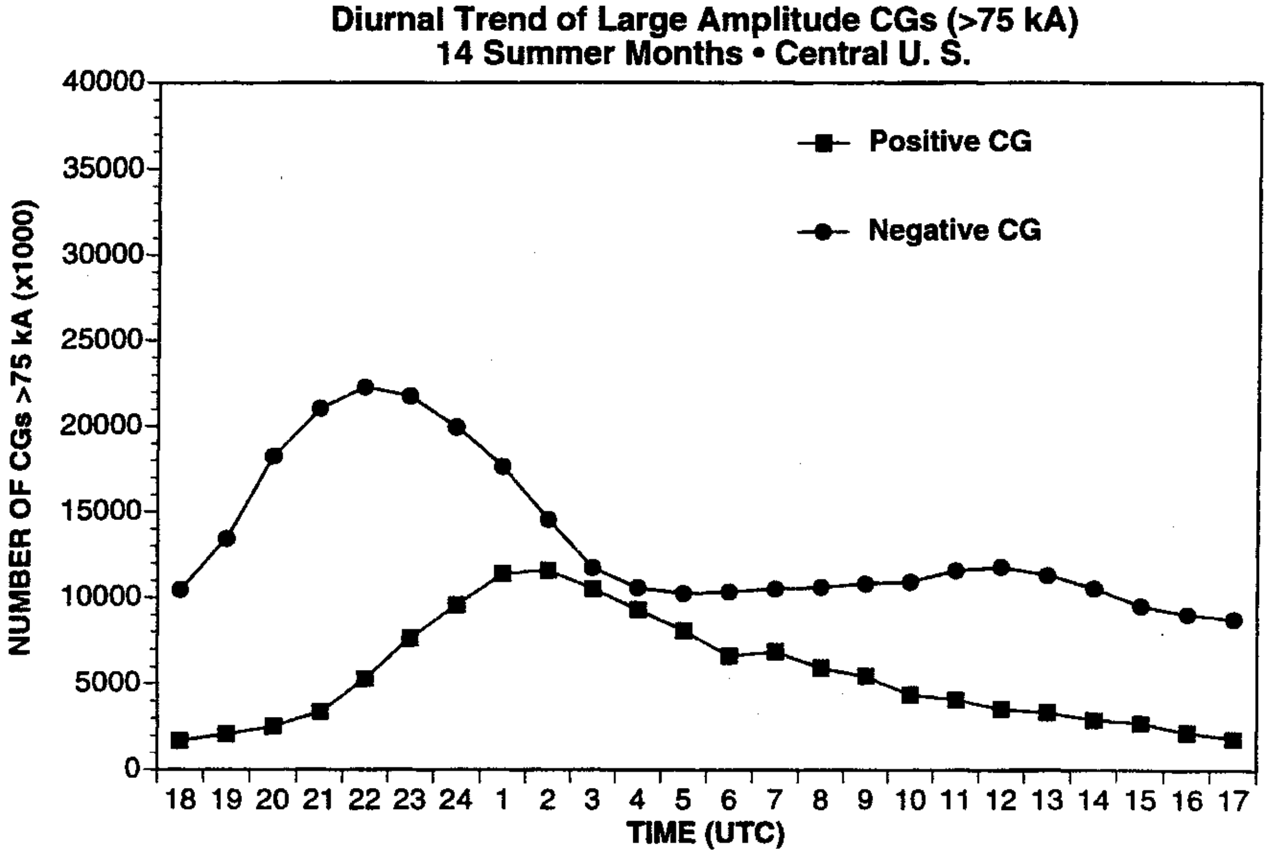


Figure 5-9. Hourly distribution of the number of large amplitude (>75 kA) negative and positive CGs over a 14 summer month period in the central U.S.

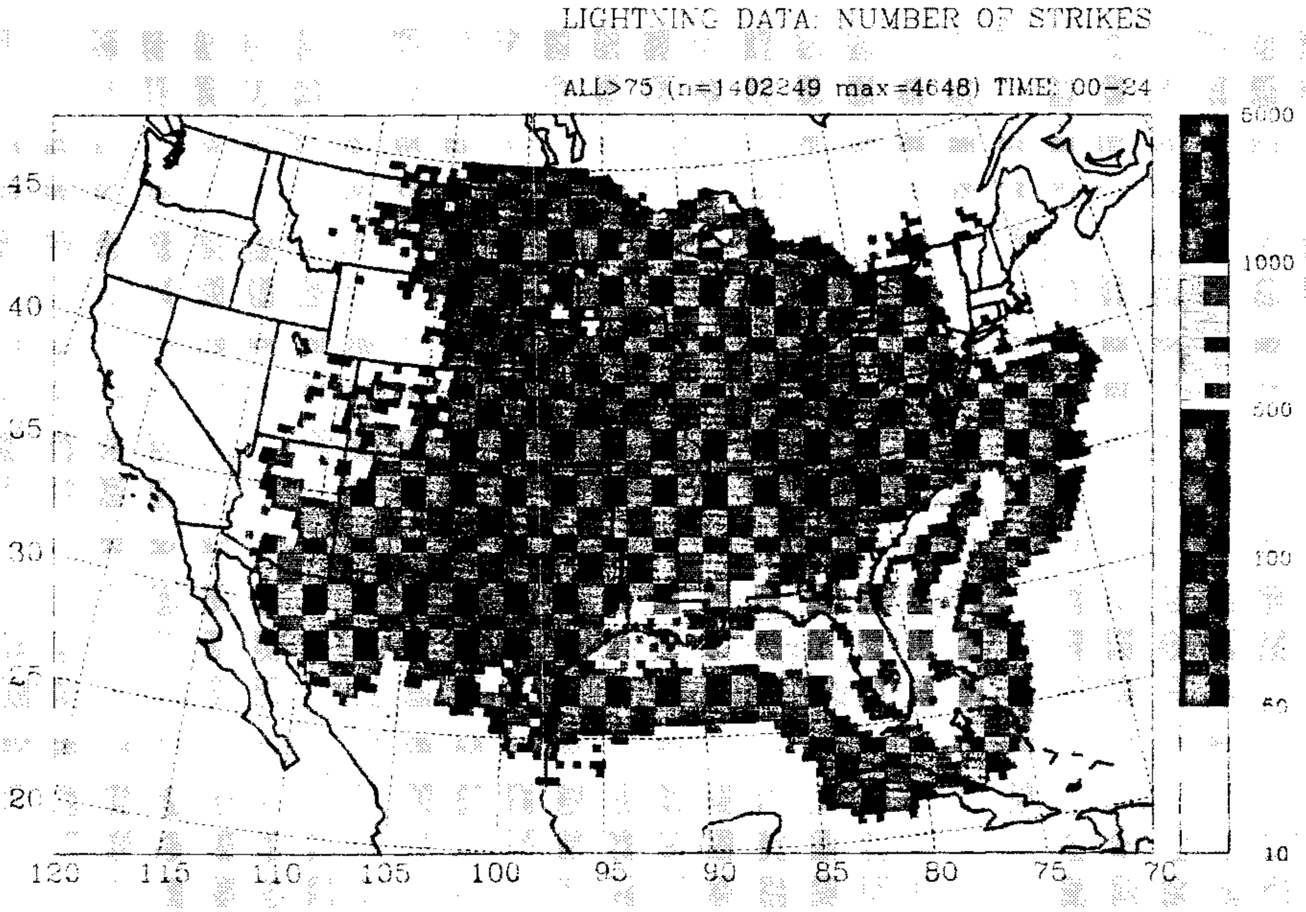


Figure 5-10. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for both polarities, for a 14 summer month sampling period, for all hours.

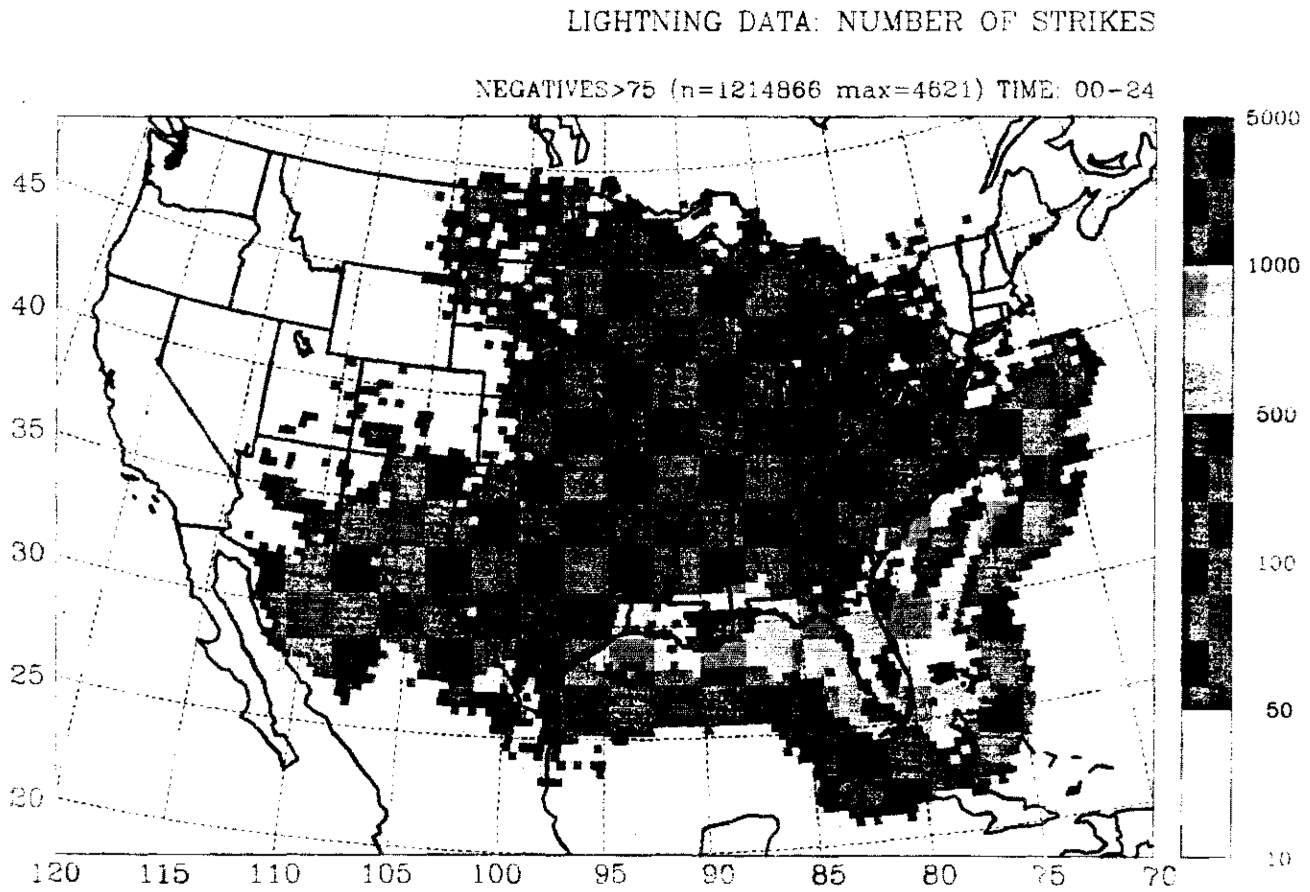


Figure 5-11. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for negative polarities, over a 14 summer month sampling period, for all hours.

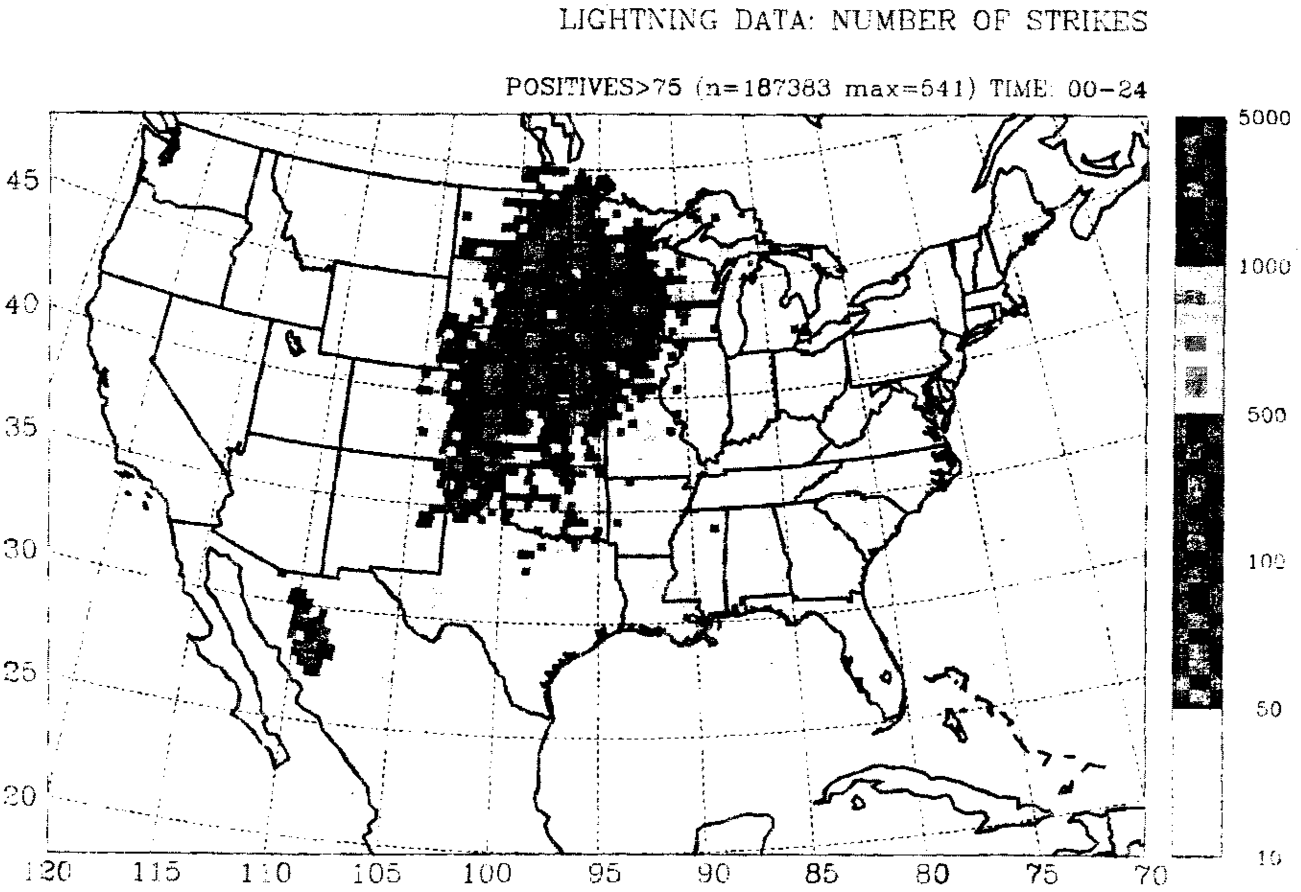


Figure 5-12. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for positive polarities, for a 14 summer month sampling period, for all hours.

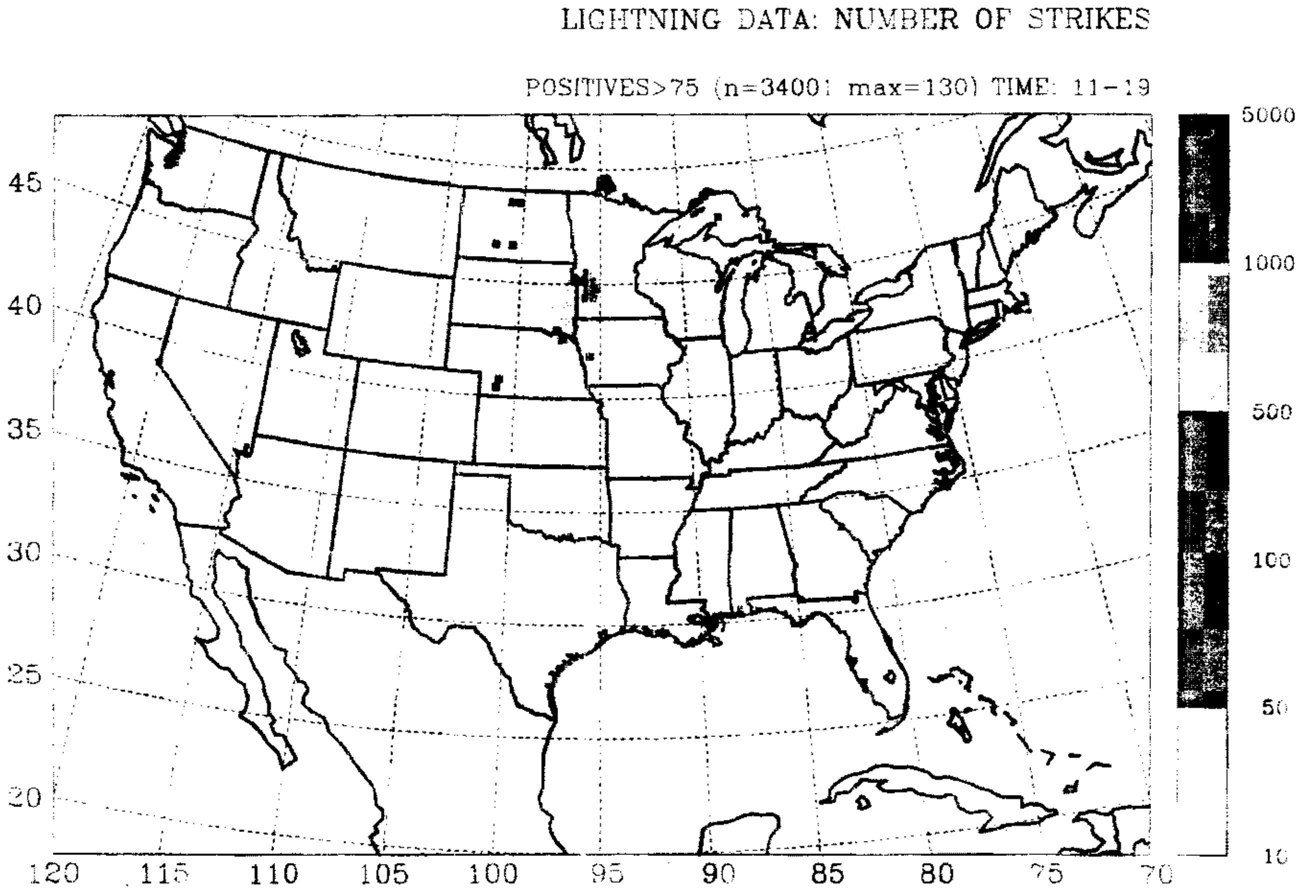


Figure 5-13. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for positive polarities, for a 14 summer month sampling period, for time period from 1100-1900 UTC.

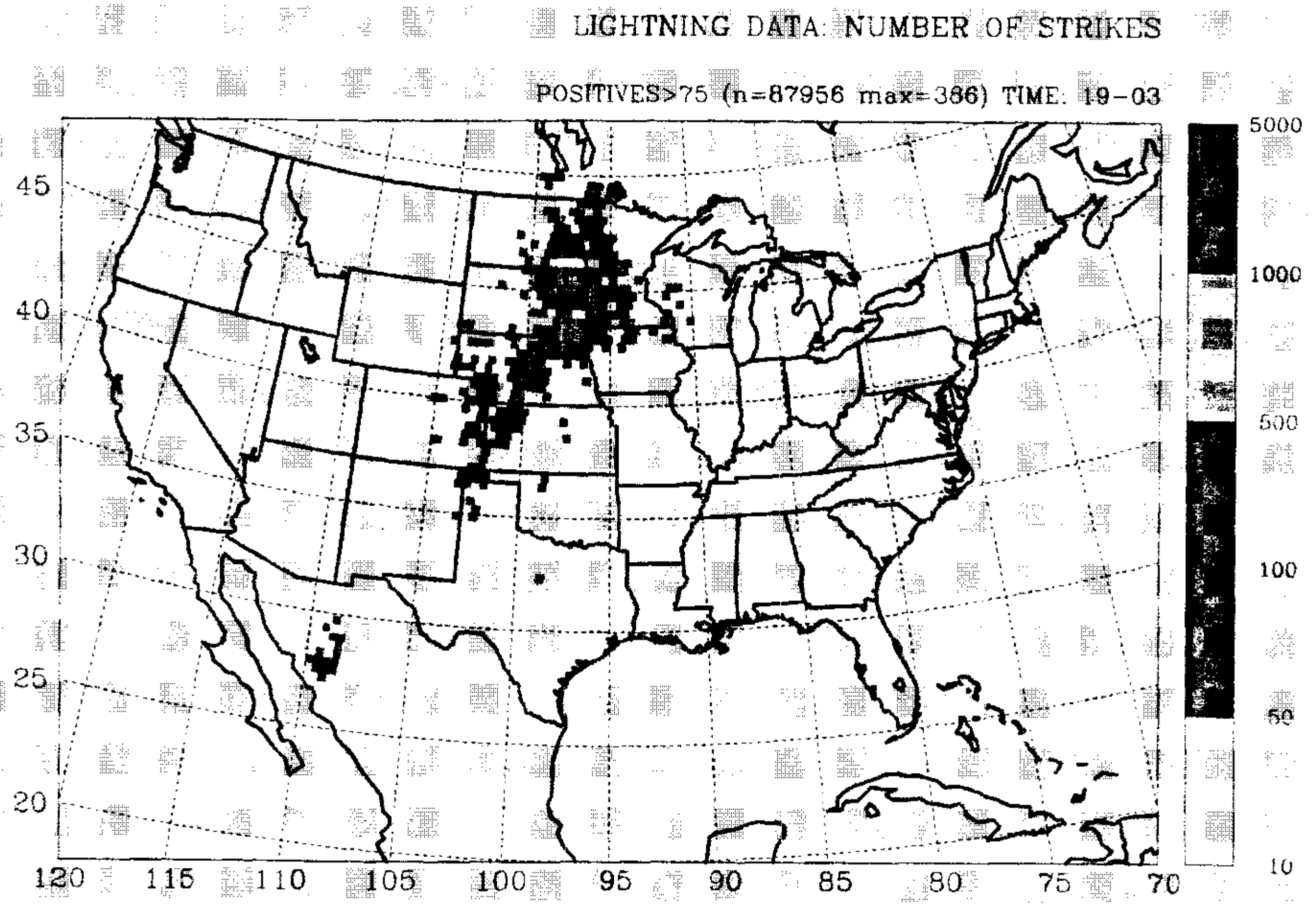


Figure 5-14. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for positive polarities, for a 14 summer month sampling period, for time period from 1900-0300 UTC.

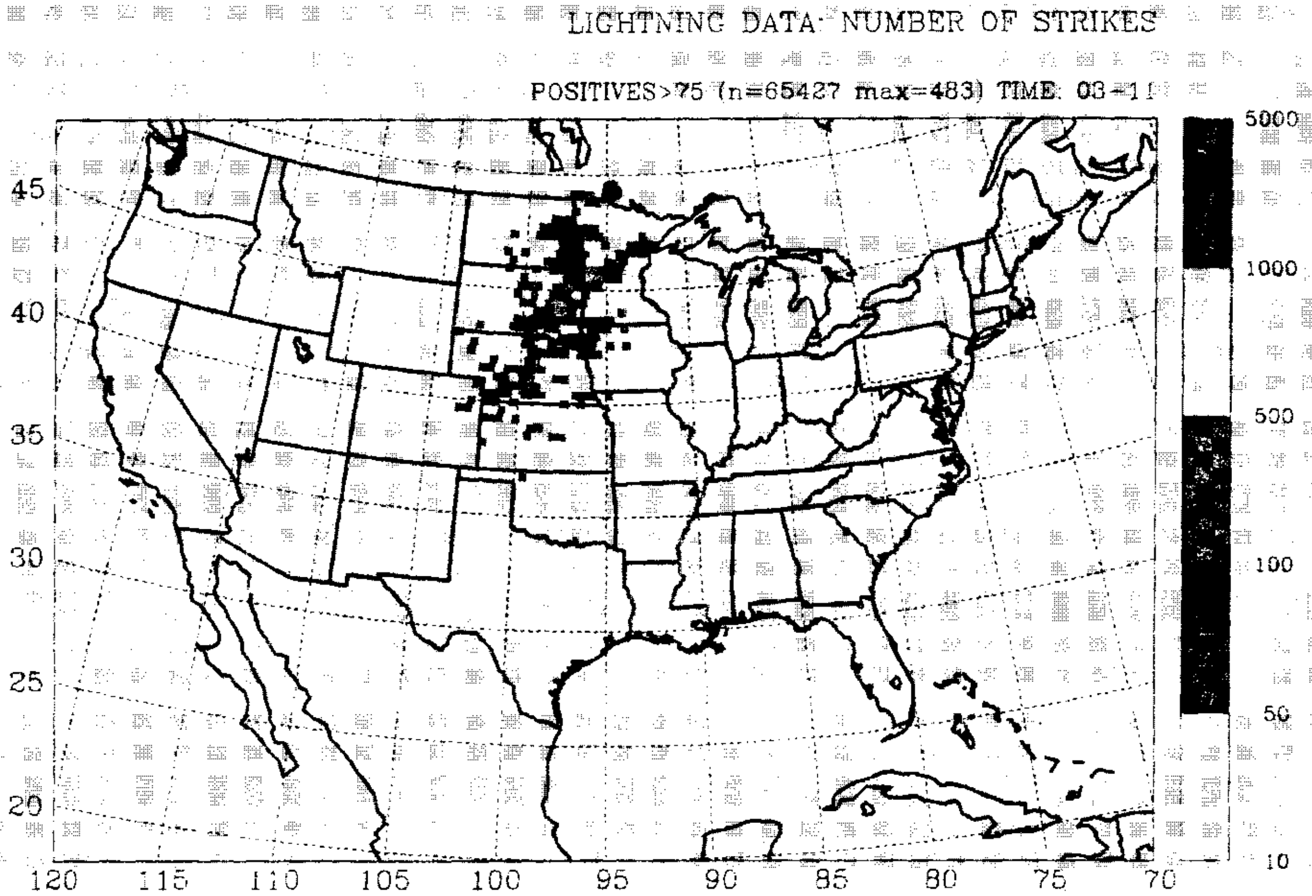


Figure 5-15. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for positive polarities, for a 14 summer month sampling period, for time period 0300-1100 UTC.

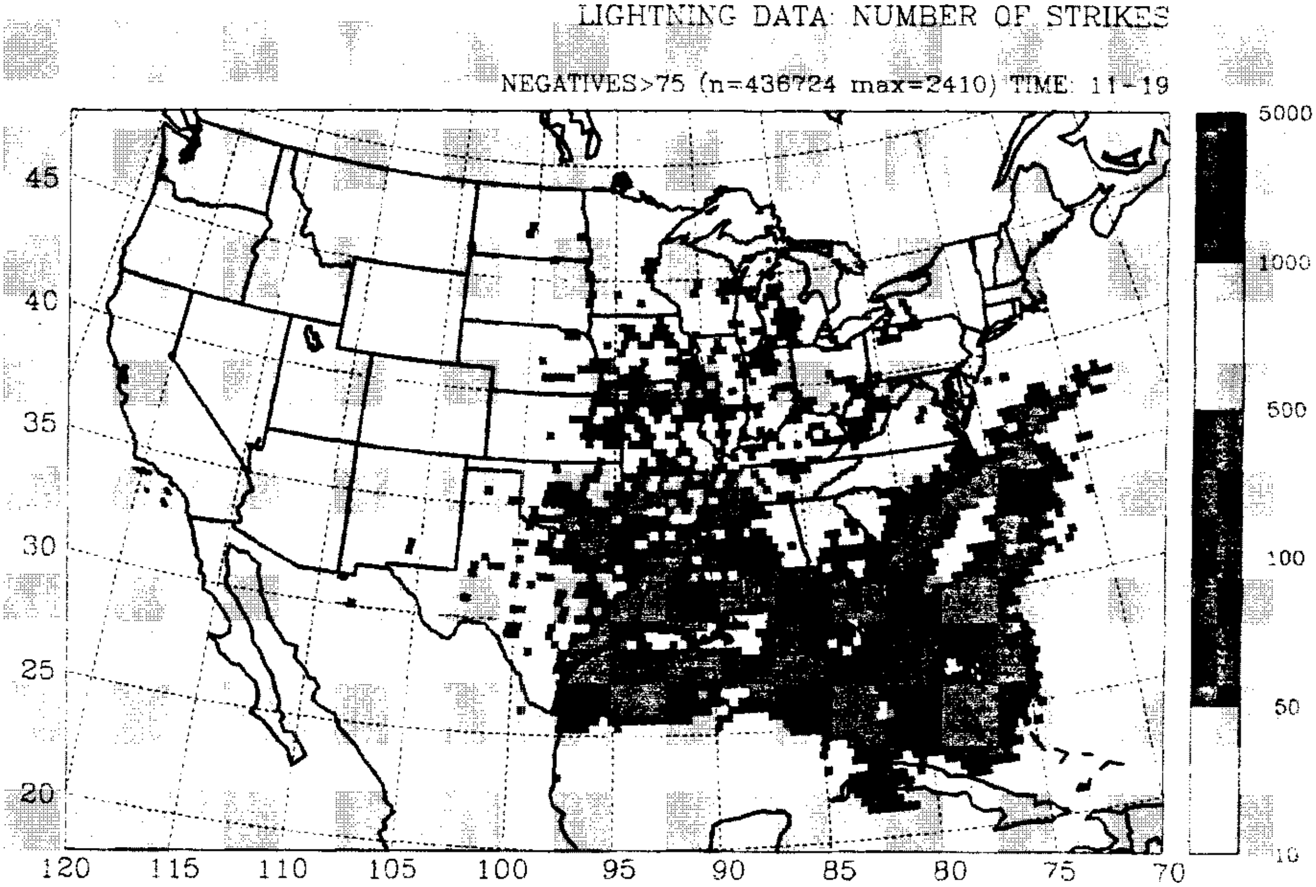


Figure 5-16. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for negative polarities, for a 14 summer month sampling period, for time period 1100-1900 UTC.

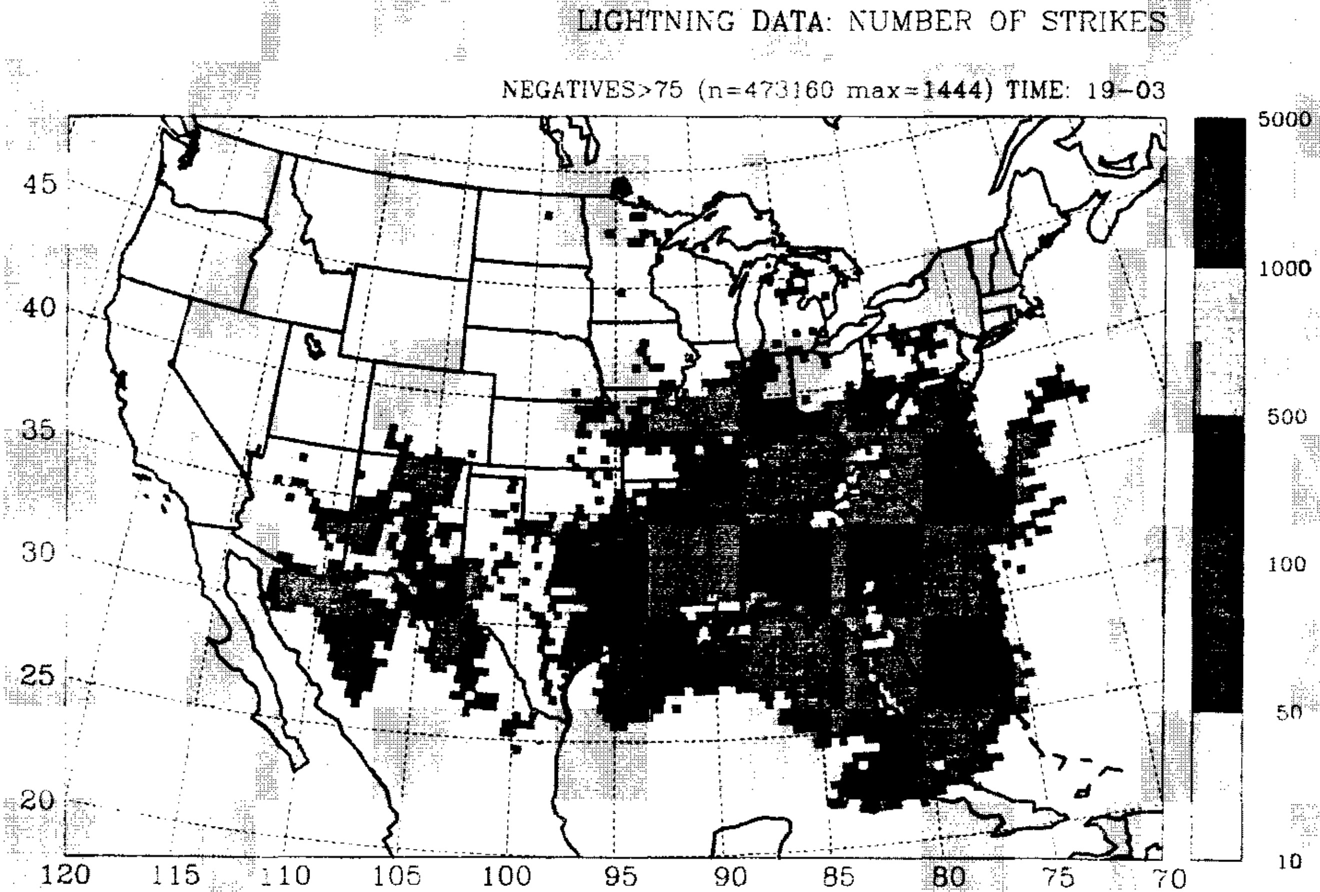


Figure 5-17. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for negative polarities, for a 14 summer month sampling period, for time period 1900-0300 UTC.

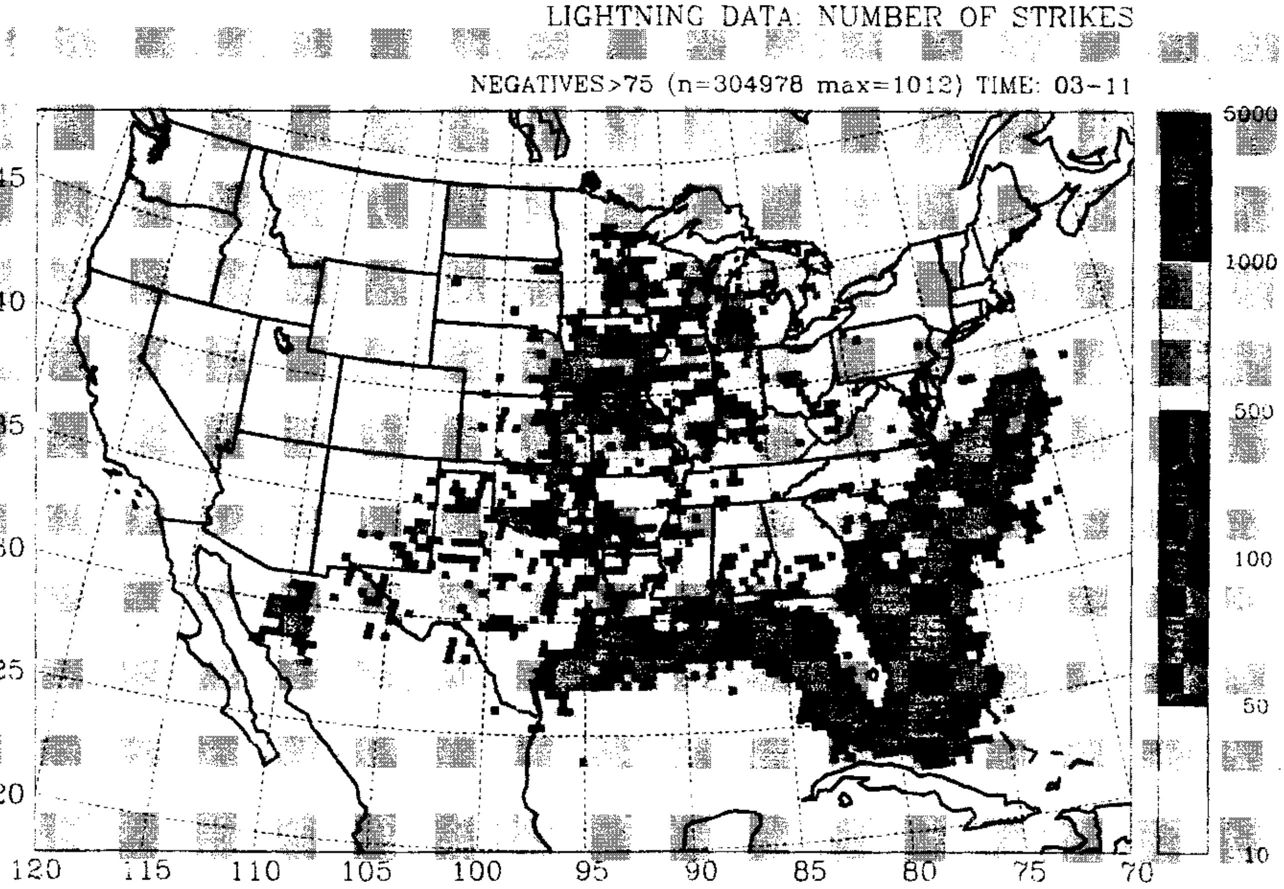


Figure 5-18. Density of CG flashes >75 kA peak current detected by the NLDN, in 47x47 km squares, for negative polarities, for a 14 summer month sampling period, for time period 0300-1100 UTC.

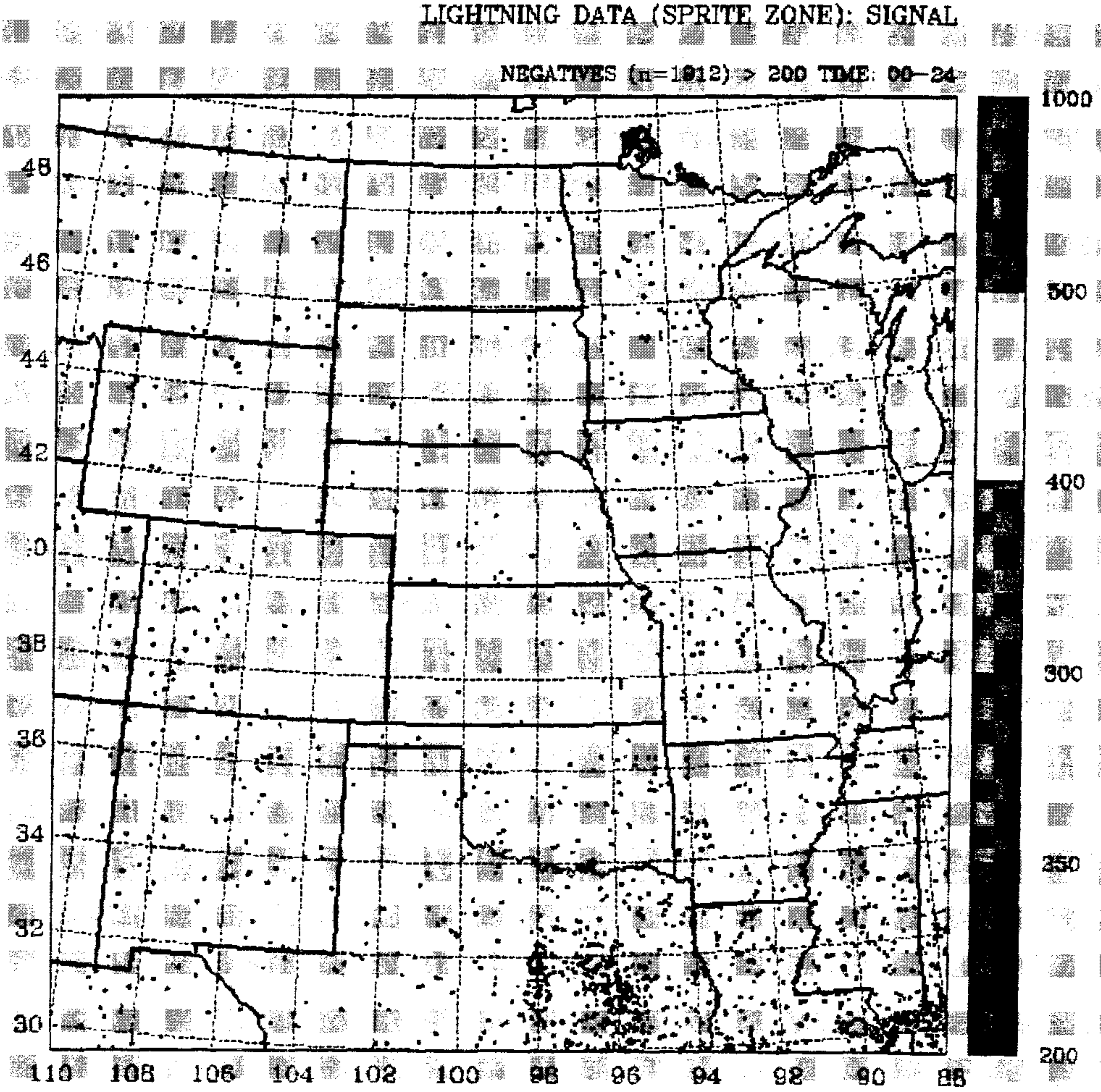


Figure 5-19. Plot of negative CGs having peak currents >200 kA over central U.S. for a 14 summer month period.

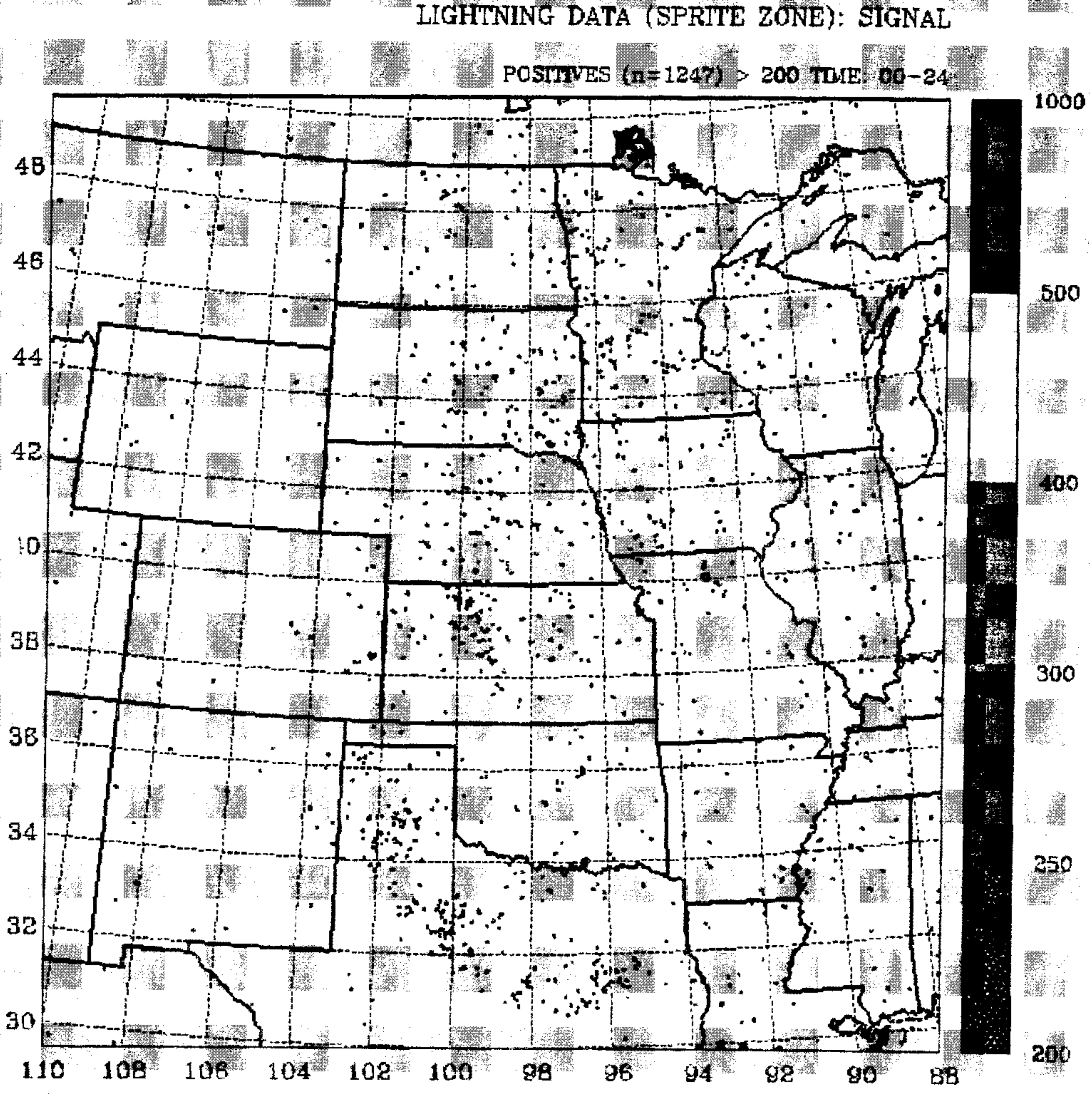
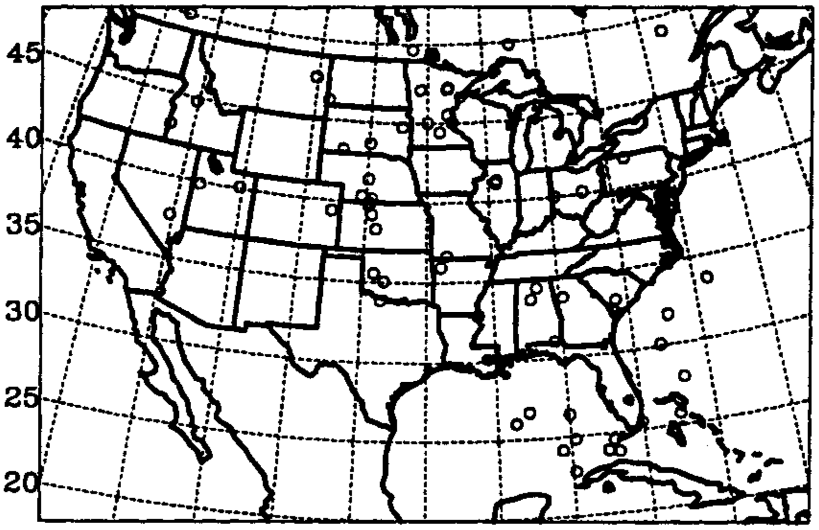


Figure 5-20. Plot of positive CGs having peak currents >200 kA over central U.S. for a 14 summer month period.

LIGHTNING DATA: NUMBER OF STRIKES

POSITIVES (circles n=65) > 300 TIME: 00-24



NEGATIVES (crosses n=438) > 300 TIME: 00-24

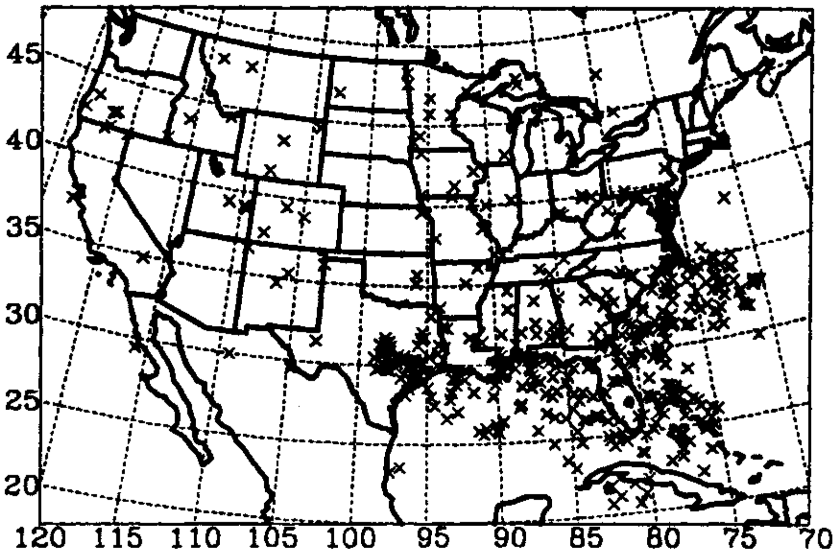
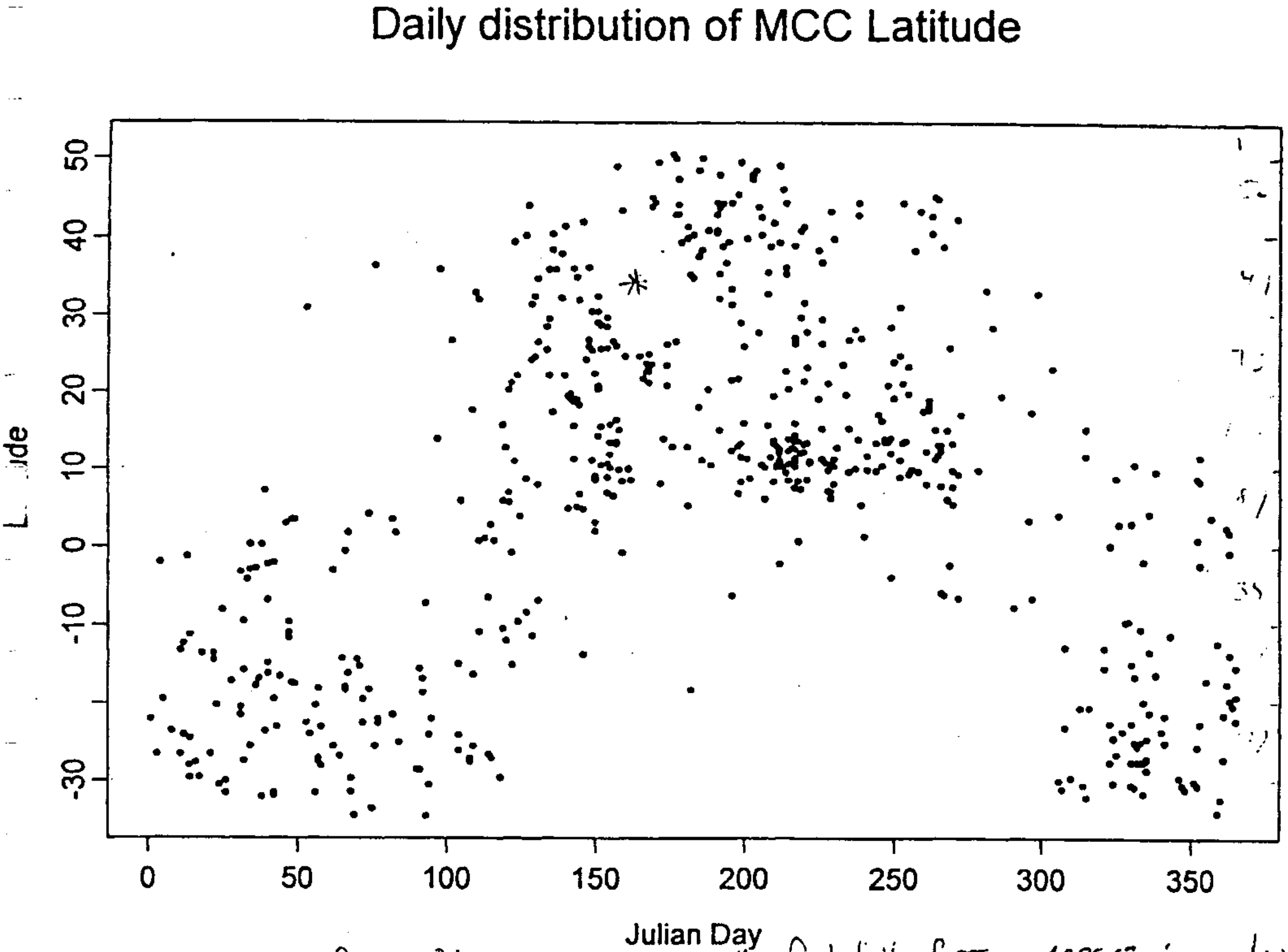


Figure 5-21. Plot of positive CGs (top) and negative CGs (bottom) with peak currents >300 kA over U.S. for a 14 summer month period.



No MCCs occurred from late May through the first half of June 1986 87; a time period when MCCs are typically numerous.

Figure 5-22. Location of satellite observed mesoscale convective systems (MCCs) as a function of latitude of the course of a year long period beginning in June 1986. There was an uncharacteristic dearth of MCCs in the central U.S. during May and June. Courtesy Mike Fritsch.

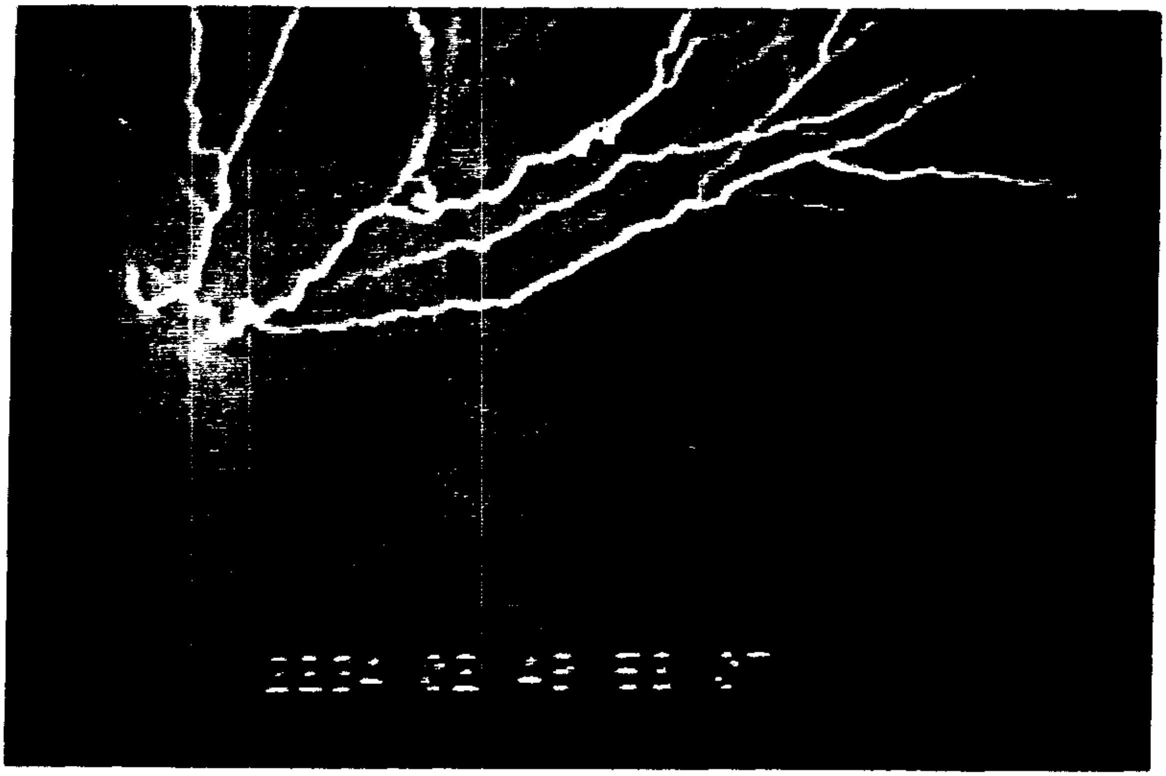


Figure 5-23. An example of spider lightning over the Kennedy Space Center suggesting that while large amplitude +CGs associated with spider lightning events are less common over central Florida compared to the central U.S., they do indeed occur.

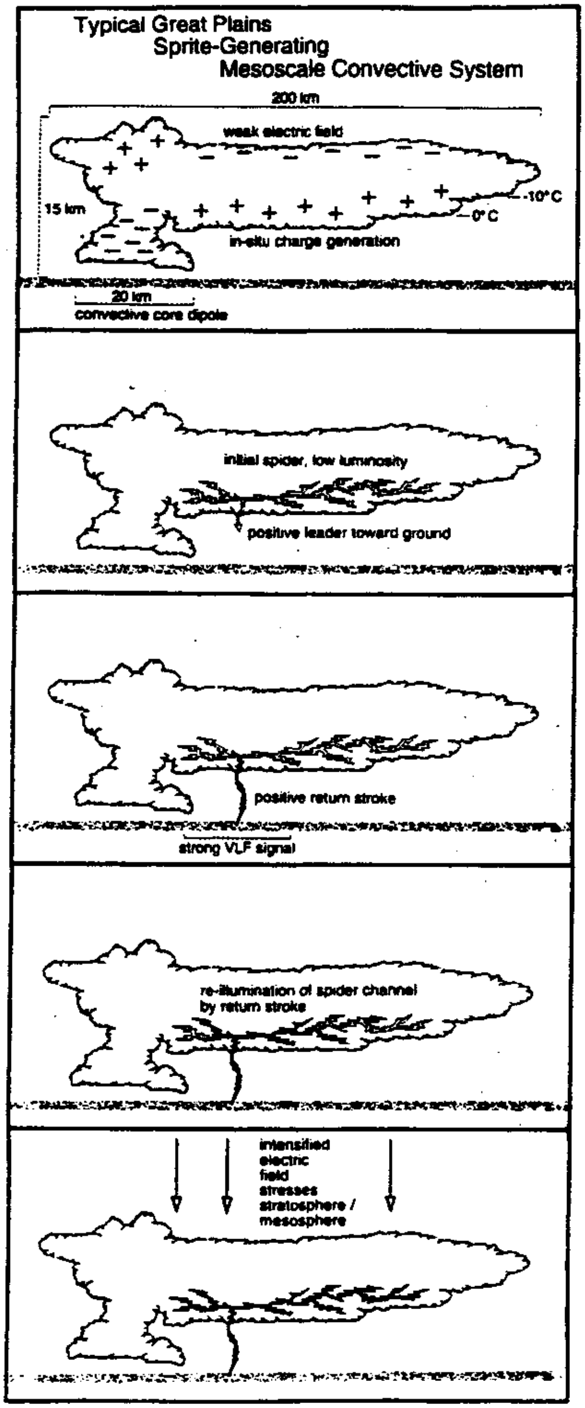


Figure 5-24. Schematic of the meteorological and lightning processes involved in the quasi-electrostatic generation of mesospheric sprites above mesoscale convective systems.

6.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Implications

During the last three years there have been significant advances in our understanding of the physical characteristics, frequency and distribution (at least on a national scale) of transient luminous events. Three distinct phenomena have been described and at least partially explained. Additional phenomena may await to be recognized.

Taking the broader view, what are the implications of these findings? What impacts might sprites, elves and blue jets have upon aerospace operations above 20 km? How might atmospheric chemical processes in the stratosphere and mesosphere be influenced by sources never previously considered in global chemical models? How might these events influence the atmospheric electrical environment, the global electrical circuit and perhaps even the near-space environment? Probably far more questions have arisen since 1993 than have been answered. But there are at least some clarifications beginning to emerge.

Do spites, elves and blue jets pose a threat to aerospace operations, especially the Space Shuttle? Sprites and elves can involve vast volumes of the atmosphere, tens to hundreds of thousands of cubic kilometers. Their optical emissions are primarily the products of electron impact excitations, which in and of themselves do not appear to be sufficiently energetic to result in direct influences upon vehicles. Above 50 or 60 km altitude sprites and elves appear to have energy densities comparable to that of the aurora. The Shuttle routinely flies through the auroral zone, shown imaged using a XYBION camera (Figure 6-1) on a night when a broad auroral curtain was visible from mid-altitudes over the U.S.

Given the considerable uncertainties, however, with regards to the energetics of certain features of the sprite (i.e., the tendrils) and their potential association with upward avalanching runaway electron streams and the further generation of gamma-ray bursts, the issue of aerospace vehicle safety is not yet closed.

The detection of the influences of the sprite generation processes over such a wide spectrum of frequencies must be considered. There are clear indications that RF signals in at least in the ELF and VLF, and probably much higher frequencies, could in some way be influenced. The possible influences on telemetry should be considered in more detail by communications engineers. The luminous portions of sprites and elves do not extend much above 100 km altitude, but there is no evidence that strong electrical fields related to the parent tropospheric electrical discharges may not be present to much greater heights.

It is likely that the Space Shuttle sooner or later will be directly involved within a sprite or elve. If we use the end of mission descent trajectory for STS-63 (Figure 6-2) as a model, one can see that it passes directly over the region of suspected maximum sprite and elve occurrences. Between 105°W and 85°W, the Shuttle is descending from about 68 km to 51 km, which is near the layer of the most energetic sprite processes. Passage through this layer takes approximately 384 seconds. If we use the +CG climatology as a guide, we can estimate that during the summer months, sprites and elves are occurring over and area of 1.5 million square kilometers at the rate of 15 per hour. Further assuming that the radius of influence for each sprite is about 50 km, then each sprite covers about 7850 km^2. Thus approximately 117,750 km^2 (or 7.8%) of the sprite region is impacted each hour. The probability of a Shuttle descending through this region being involved in a sprite is on the order 1%, or one out of hundred missions (in summer). On any given flight, the probability is either zero (winter or storm free period) or considerably higher if an active sprite producing mesoscale complex were beneath the flight path. The probability of direct Space Shuttle involvement in a sprite or elve is many orders of magnitude higher than the chances of being struck by lightning during the launch phase (Mach, 1989).

The issue of blue jets is a bit more problematic. They appear to posses substantially higher energy densities (Wescott, personal communication). There are some indications that a blue jet may involve energies on the order of 10^{16} ergs, or approximate 300 kilowatt hours. Given the maximum altitude for blue jet luminosity of 50 km, it would be only on the final portion of a decent, which for STS-63 was the Alabama to KSC leg, where interactions with a blue jet were possible. But we note this region has a high frequency of powerful -CGs which may be related to blue jet production. The phenomena is rare, but the one storm that has been studied in detail produced over 50 blue jets in a short period of time.

Thus while there is no compelling evidence to suggest a clear and well formulated threat to aerospace operations, especially when considering blue jets, extreme caution and avoidance still would appear to be the prudent course of action.

What are the implications of the existence of relatively frequent sprites and elves upon stratospheric and mesospheric NOx production? Armstrong et al. (1996) have attempted to address this issue using the limited data available at this time. Sprites and elves may well represent an unidentified source of NOx in the middle and upper atmosphere. Whatever effects they may have are not included in any current atmospheric chemical model. This omission could influence predictions concerning global climate change and in assessing the environmental impacts of the next generation aircraft fleet.

There has been no direct measurement of NO produced in sprites. Recently, however, Beaver (personal communication) has analyzed HALOE data which indicates a westward-going "plume" of NO above the western US (Figure 6-3) in early July 1994 after a period of unusually high sprite activity (Lyons, 1994). Though certainly not conclusive, this finding, along with other evidence, is suggestive of production of NO by sprites. If the amount of NO produced is significant and transported to critical atmospheric regions, it could have substantial impact upon atmospheric chemical processes. Since NO is a known major constituent in the ozone cycle, sprites could be an important mechanism in determining ozone levels in the middle atmosphere. Current data support the notion that the electrodynamic energy in sprites is sufficient to induce significant chemical dynamic perturbations in the ambient atmosphere over mesoscale regions. Recent photometer measurements of the 427.8 nm band in sprites yielded direct information on the energy deposition and ionization rate and established the minimum energy of the electrons (Armstrong et al., 1996). Nitric oxide production in sprites results primarily from ionization and dissociative recombination processes that are not necessarily a result of thermodynamic equilibrium processes. The question is whether the primary electrons have sufficient energy to initiate the process. The electron energy threshold for initiating the process is about 30 eV. The dominant red emission in sprites originates from the N_2 1P bands, so we know that electrons of at least 10 eV are present. The observations of 427.8 nm emissions in sprites suggest the 30 eV threshold is exceeded. The high ionization rates implied by the radar measurements reported by Roussel-Dupre and Blanc (1996) are also supportive of this contention. Initial calculations yield approximately 10^{6} to 10^{7} NO per cm^3 per hour within several active sprite clusters occurring worldwide. As shown in Figure 6-4 the mesoscale production rate of NO from sprite activities is estimated to be two orders of magnitude greater than from other natural sources. On a global basis, sprite contributions are at least 1% of other identified sources, and this number could rise if higher energy levels within sprites can be verified. Sprites are likely to be clustered in mid-latitude and tropical regions. This region is where observed NOx/O_3 ratios deviate by more than 80% from current models. This deviation is not fully understood and has been blamed on incorrect modeling of transport processes. It may well be that mesoscale sources of sprite-generated NOx may account for much of the poor performance of atmospheric chemical models in the tropical stratosphere and mesosphere.

The influence of TLEs above 100 km remains an open question. Studies by Hays and Roble (1979) indicated that electric fields from large thunderstorms can penetrate to the altitude of low earth satellites and are detectable as perturbations to the background ionospheric conditions. The apparent upper limit of luminosity is about 100 km, yet lightning induced transient electric fields at much higher altitudes have been reported by Holzworth et al. (1985), Kelley et al. (1985) and Burke et al. (1992). Is there any connection between sprites, elves and whistlers? What role could TLEs play in maintaining the global circuit? These are among the many questions beginning to arise in the radio and space science communities.

6.2 What Has Been Learned to Date

Some of the mystery surrounding transient luminous events has begun to be lifted, though with each month new discoveries reveal how very complicated are the electrical processes within the earth's middle atmosphere and their linkage to tropospheric lightning. Substantial advances have been made in the theoretical understanding and numerical simulation of sprites, elves and blue jets. Some small progress has been made in beginning to quantify some of the geophysical impacts of these phenomena.

We have identified as separate entities at least three classes of TLEs. Figure 6-5 is a close up view of a classic elve and sprite, with pronounced tendrils. There is still considerable question about the origin of the tendrils in sprites and the energetics of the processes involved. While there is some circumstantial evidence we do not yet know if the elve/sprite mechanism is the source of the mysterious gamma ray burst being monitored from orbit.

It is clear that elves and sprites are the product of EMP and quasi-electrostatic processes generated by positive cloud-to-ground lightning flashes generally having larger than average peak currents, especially in the case of elves. Sprites and elves can occur together in a sequence, but also separately. The radar echo size criteria (>20,000 km^2) has proven to be a rather robust predictor for sprite and elve formation, at least in the U.S. High Plains. It is likely that the large stratiform precipitation regions are needed to generate the horizontally extensive layers of positive charge upon which the +CG flash draws the continuing current which also appears to be a necessary condition for (at least) sprite formation.

While the NLDN has provided valuable information on sprite-generating CG discharges, it is clear that we do not yet understand the details of the three-dimensional time-dependent electrical discharge within the parent thunderstorm. Figure 6-6 is a sketch, made by consultant Earle Williams, and presented at the recent AFOSR SPRITES'96 Workshop. Diagrams such as this are being drawn and re-drawn on almost a monthly basis, yet some closure on the essential issues is emerging. The role of the continuing current and the visible "spider lightning' discharge are believed to be important to the sprite formation processes, but hard data remain to be acquired. As for elves, while they appear to require large amplitude +CG flashes, the other defining characteristics of their parent lightning remain to be determined.

Sprites and elves can be routinely monitored using LLTV systems and photometers. It now appears reasonable to assume that Schumann resonance transients, known as Q-bursts, serve as an excellent diagnostic for +CG events which have a high likelihood of generating sprites. SR transients can be detected, and their source approximately located, using both single and multi-station sensors. The range of such systems could provide nearly global coverage using just several sites. Promising techniques for sprite identification and location are also being developed using VLF receivers. There is some evidence that active remote sensing of sprites (using radar) may be feasible.

The most important discriminant of storms with sprite potential appears to be the presence of large peak current +CG flashes. Phase II conducted the first known climatology of large peak current CGs for the US. It became immediately clear that there is a strong spatial disparity between those regions having relatively high frequencies of large amplitude positive and large amplitude negative CGs. The correspondence between the high peak current +CG corridor and a documented high rate of sprite occurrence is striking. Whether or not the regions with high frequencies of large peak current -CGs in the southeastern U.S., including the KSC area, indicate a relatively high rate of blue jets is still problematic.

We note that large mesoscale convective systems of the type which generate sprites and elves in the central US occur over many parts of the world. It now remains to be seen whether combinations of regional lightning detection network data, ELF transient measurements, and satellite observations can begin to converge on a better understanding of the global frequency and distribution of sprites and elves.

Initial studies of NO production by sprites suggest that at the minimum they can produce high levels of NO on a regional basis. Better understanding of global sprite climatology would help extend this effort, as would clarification the energy levels in sprites (especially the tendrils).

It is unclear whether sprites and elves pose a direct threat to the Space Shuttle. What is fairly certain, however, is that the chance of the spacecraft being involved in a sprite is vastly higher than that of a direct lightning strike. Using the descent path of STS-63 as a model, we estimate that the Shuttle would be directly involved within the volume of a sprite or elve on about one in a hundred missions during summer.

6.3 Recommendations for Future Studies

The characteristics of MCS anvils and electrical discharges (both large positive and negative CGs) that do and do not produce sprites and elves must be further examined. Future key measurements should include mapping the entire lightning discharge on the mesoscale using a 3-D time-of-arrival (TOA) system such as LDAR. Coordinated measurements should include the suite of optical and RF measurement deployed at YRFS in 1995 (Lyons, 1996) supplemented by balloon-borne electrical field sensors flown above the MCS tops as described by Marshall et al. (1995). High altitude balloons, equipped to monitor gamma ray bursts would be most valuable. Alternately, UAVs equipped with electric field, LLTV, gamma ray and perhaps chemical monitors could station keep over an active MCS for many hours. Figure 6-7 summarizes the potential assets that could be deployed in a full scale monitoring program. Many aspects of this plan are expected to be included in the upcoming SPRITES'96 and SPRITES'97 efforts funded by the U.S. Air Force Office of Scientific Research.

Many other small scale projects can be envisioned. For instance, the issue of whether blue jets might be more likely to occur in storms having frequent large peak current -CGs remains open. Each summer and fall, research aircraft from NOAA's Hurricane Research Division fly many tens of hours in the vicinity of deep tropical convection, including tropical storms. By including available LLTV systems in the compliment of sensors, a census of tropical TLEs could be readily and inexpensively assembled (Figure 6-8).

The potential for continuously and automatically monitoring Q-bursts using existing ELF equipment and software was described above. Even a single station can provide some information on the global distribution, albeit geographically coarse, of the lightning likely to be sprite producers. A three station ELF system in the U.S., (at the MIT Rhode Island site, KSC and YRFS) could locate with useful accuracy discharges likely to be sprite producers over North America and beyond. This would include coverage of the KSC area. The equipment to do this is largely in place at this time.

In the longer term, planning is underway by the contractor and scientists at the Goddard Space Flight Center to prepare the initial design for an orbiting platform. SpriteSat could include LLTV, gamma ray and electric field measurements to provide the first coordinated low-earth orbit view the emissions from sprites, elves and blue jets.

More exotic experiments can be envisioned. It is now possible to launch on balloons or small rockets small linear accelerators (linacs) which can generate up to 5 MeV election beams (Neubert et al., 1996). The notion of potentially being able to trigger a sprite or blue jet is intriguing. Success, or failure, in the attempt would help further understanding of the complex physical processes involved.

The Phase I and Phase II projects collected massive amounts of data, only small portions of which have been analyzed so far. Further efforts to extract information from the data already on hand would be warranted.

The search for additional TLEs. including the true upward lightning superbolt, should be extended.

The following are just some of the many extant questions that can be considered for follow on studies:

- How are sprites, elves and jets different from each other? What are the complete spectral characteristics of each phenomena [UV-visible-IR] ?
- What other phenomena may be present above thunderstorms?
- Why don't large negative CGs apparently produce sprites and elves?
- Why do only some large positive CGs produce sprites and elves?
- What type of large amplitude +CG causes elves but not sprites?
- What actually triggers a sprite, blue jet or elve?
- What is the cause of the fine structure, especially tendrils, in sprites?
- do sprites illuminate pre-existing atmospheric structure?
- What role, if any, do storm-generated gravity waves play in sprite structure?
- What is the direction of propagation for sprites and elves?
- Why do some mature storms meeting criteria wait several hours before generating sprites?
- Why do sprites tend to cluster above relatively small portions of the MCS stratiform region?
- What accounts for the long periods of highly regular sprite production as well as the sudden interruptions and lulls that can occur for no apparent reason?
- Do sprites, jet and elves also occur during the day? Do other phenomena occur in their place, such as large upward superbolts?
- What is the structure of the entire 3-D lightning discharge that produces sprites?
- What are the relationship of TLEs to X-rays, gamma rays and TIPPS/SIPPS?
- Are whistlers generated by sprite or elve processes?
- Can sprites generate acoustic waves that can be monitored at the surface?

- What are the electric fields above the parent thunderstorms?
- Can TLEs induce strong electric field transients at heights well above 100 km altitude? Can these interfere with aerospace operations?
- Can we use ELF/VLF measurements for global detection and location? what would be the detection rate and false alarm rates for sprites? Can elves be discriminated using ELF transients?
- What are the roles of TLEs in the global circuit?
- What is the global temporal and spatial climatology of sprites, blue jets and elves?
- What are the atmospheric chemistry impacts of sprites, elves and blue jets?
- What, if any, changes in operational procedures should NASA make in light of the new information on TLEs?
- Should KSC consider establishing an operational system to monitor the presence of sprites, elves and blue jets?

HQ NASA

4/7/2003

SECTION 5

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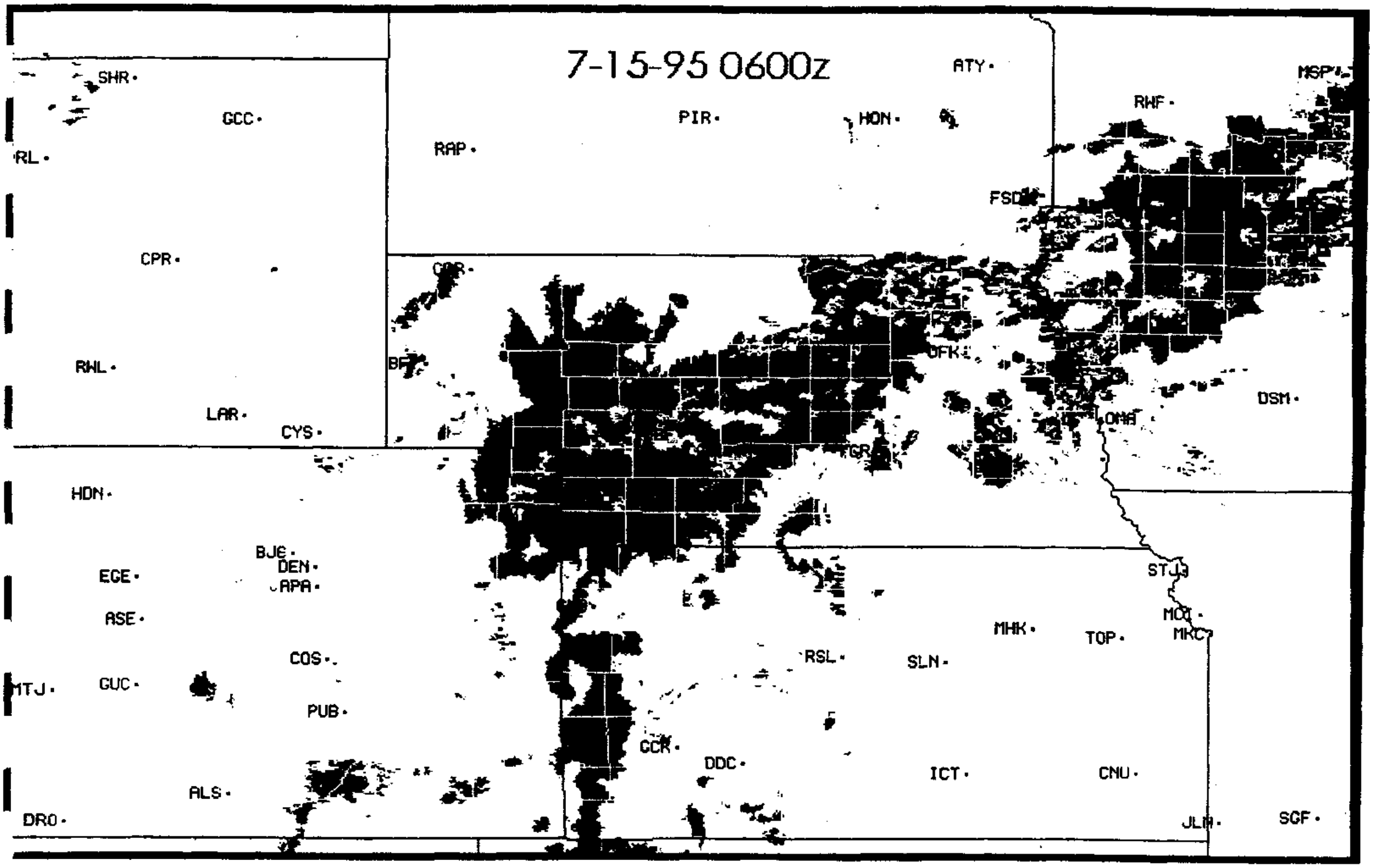


Figure 3-68. Regional radar reflectivity mosaic at 0600 UTC 15 July 1995.

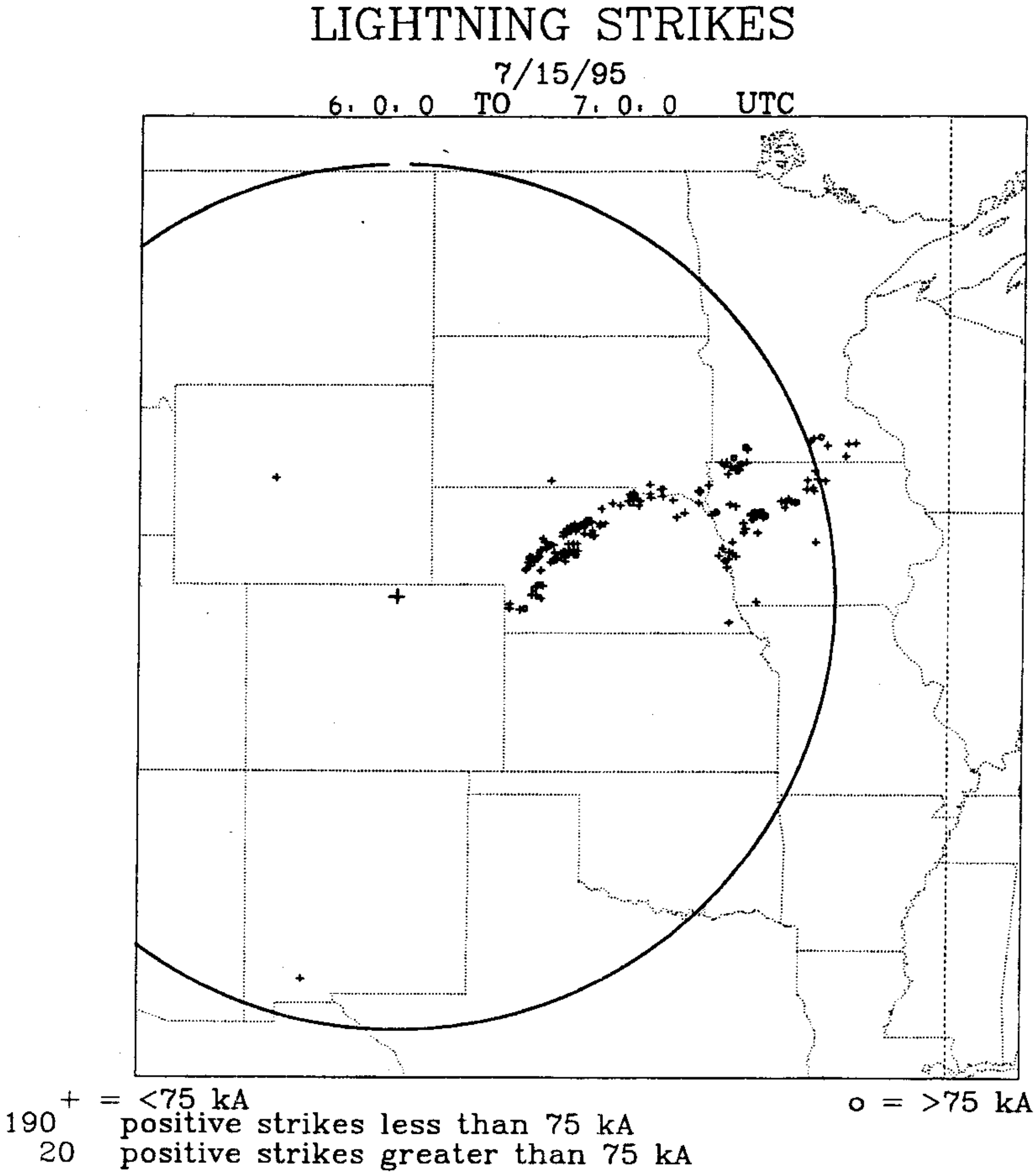
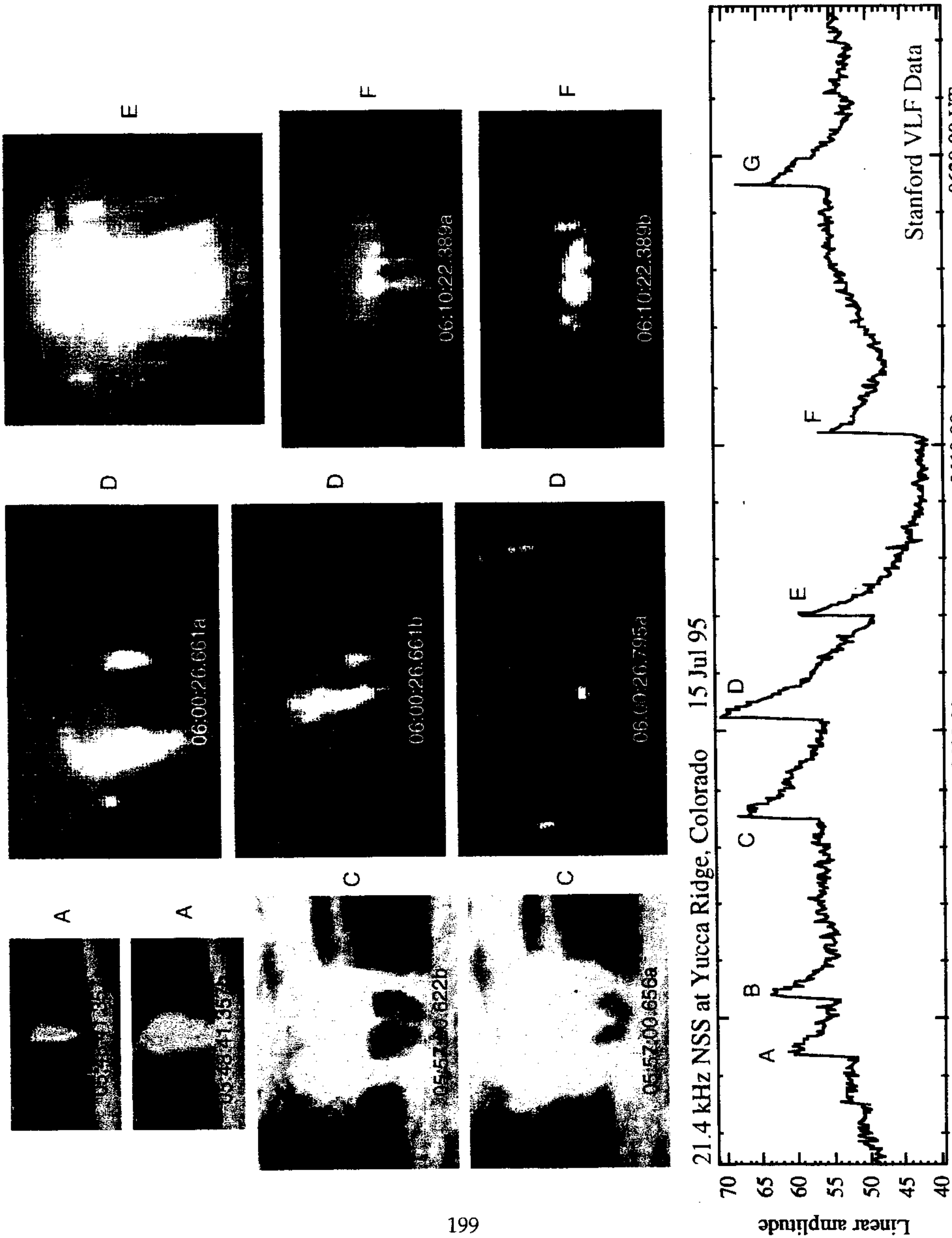


Figure 3-69. Plot of +CG flashes from NLDN between 0600 and 0700 UTC 15 July 1995 during peak of TLE episode.

Figure 3-70. Amplitude perturbations on the 21.4 kHz NSS signal associated with individual sprites (letters) imaged at YRFS on 15 July 1995. Courtesy: Umran Inan, STAR Lab.



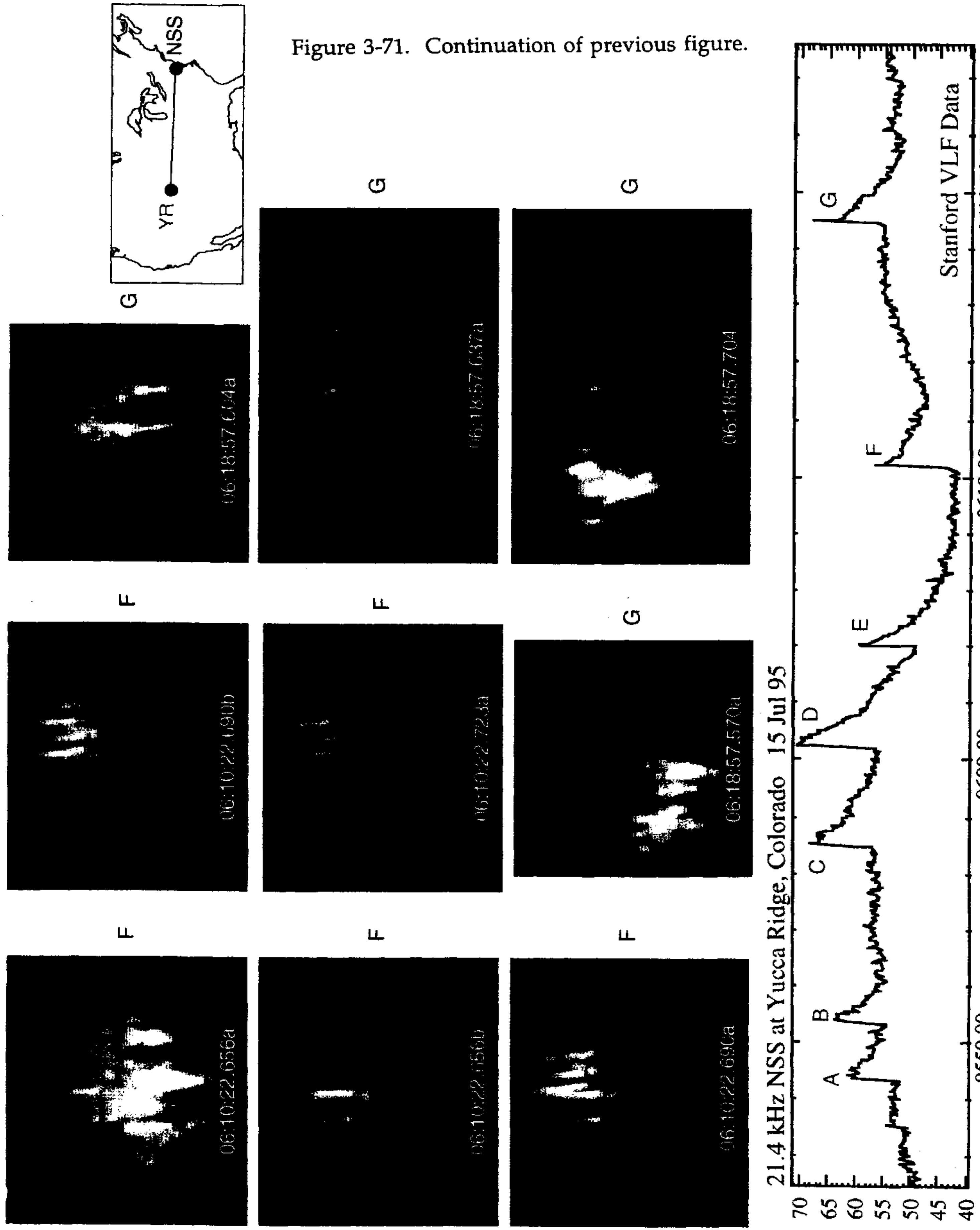


Figure 3-71. Continuation of previous figure.

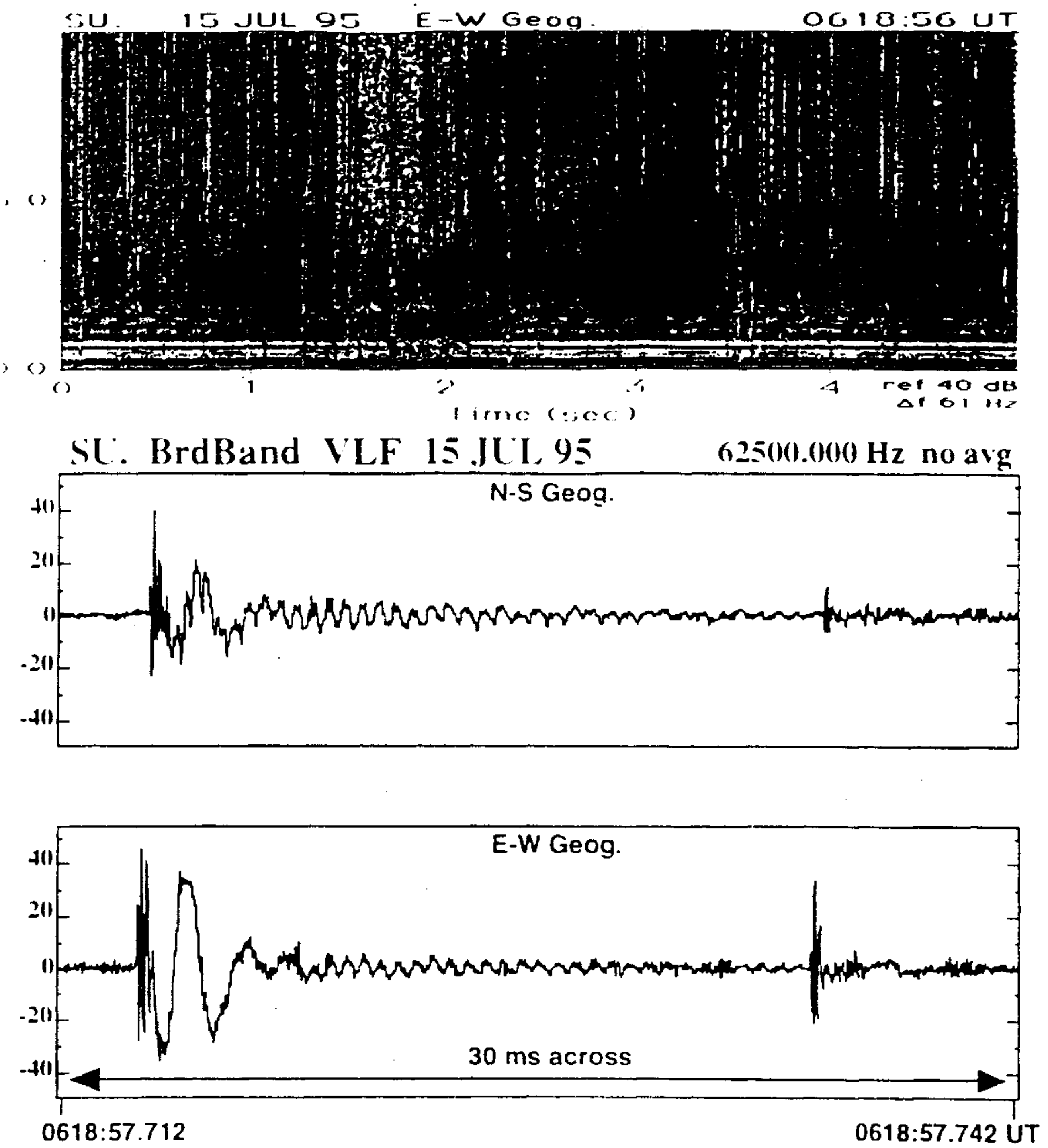


Figure 3-72. The E-W and N-S components of the broad band VLF sferics recorded by STAR Lab at YRFS for the sprite labeled as "G" in the previous figure. Courtesy: Umran Inan.

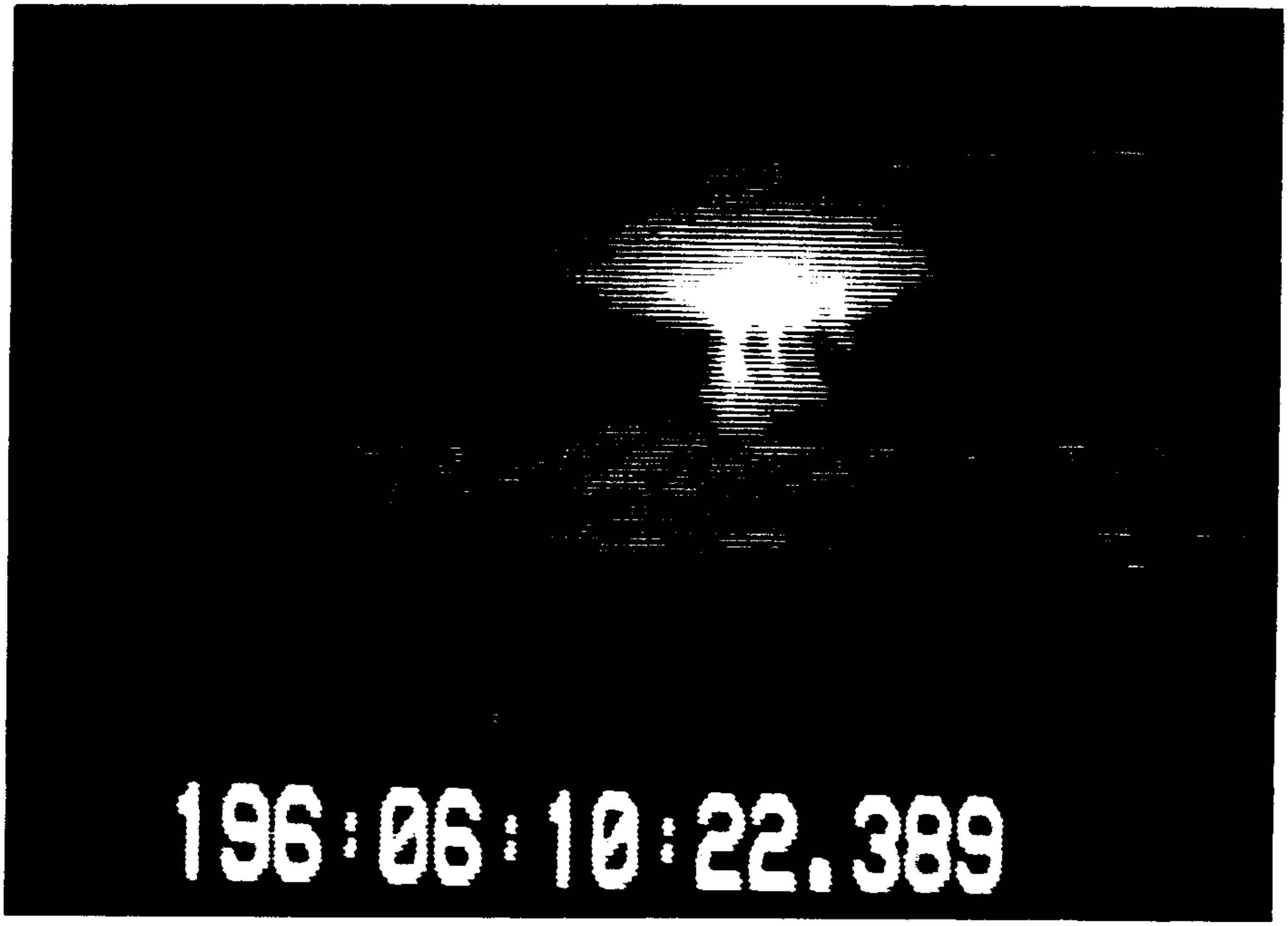


Figure 3-73. A single field of video which contains both a well defined elve and a multi-columned sprite with tendrils. At 0610.22 UTC 15 July 1995.

Figure 3-74. Six video field sequence showing the ascent of a possible blue (or red?) jet from behind a cloud bank (counterclockwise starting upper left). In field 5, the jet reaches its brightest and is briefly surrounded by what appears to be a ring of four or five sprites. 0608.26 UTC 15 July 1995.

Figure 3-75. Close up of blue (or red) jet (lowest elements) surrounded by a "ring" of small sprites. If the jet were at the same range as the sprites, it was computed to be ascending at around 140 km/sec and reached a final altitude of about 50 km.

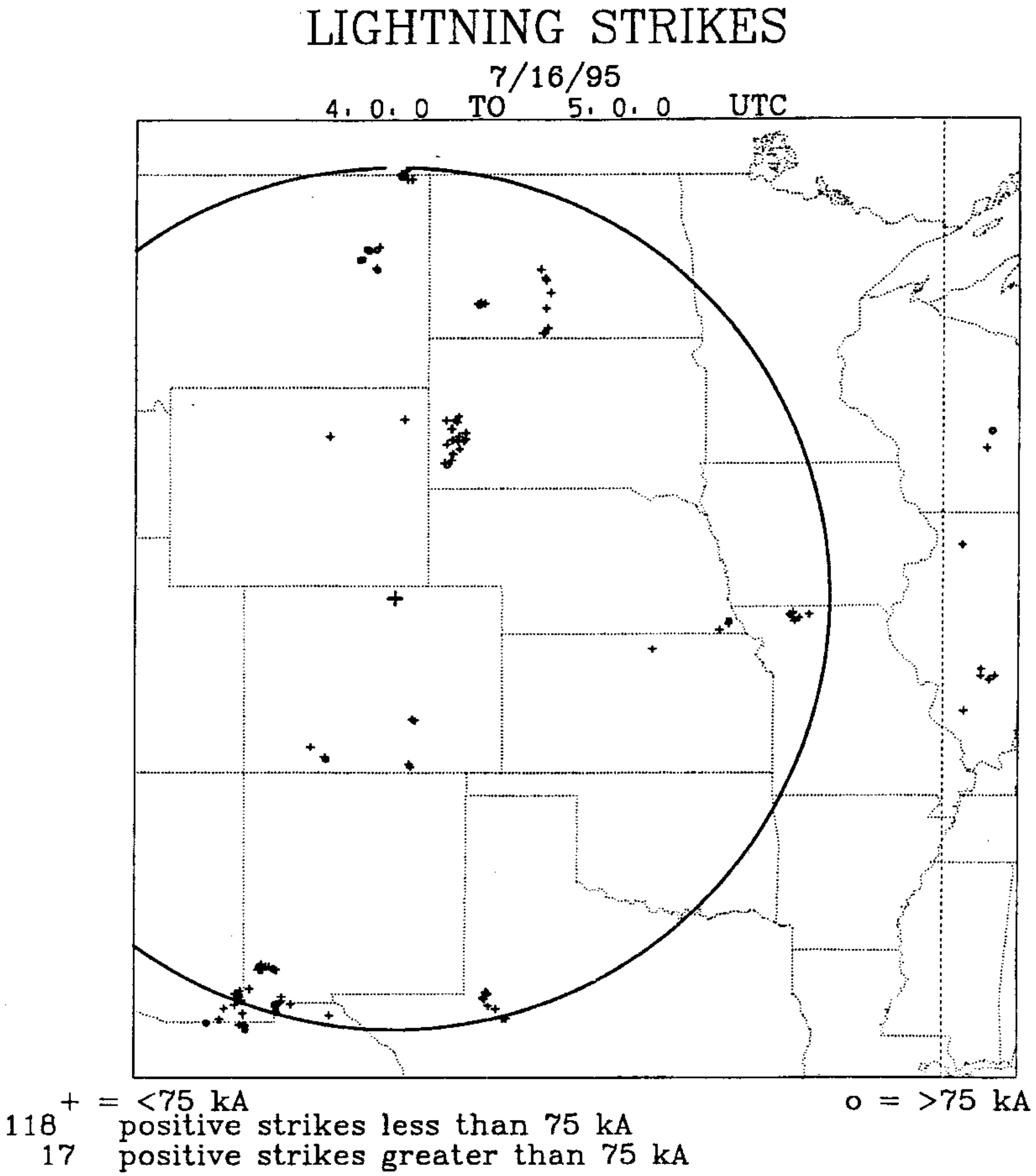
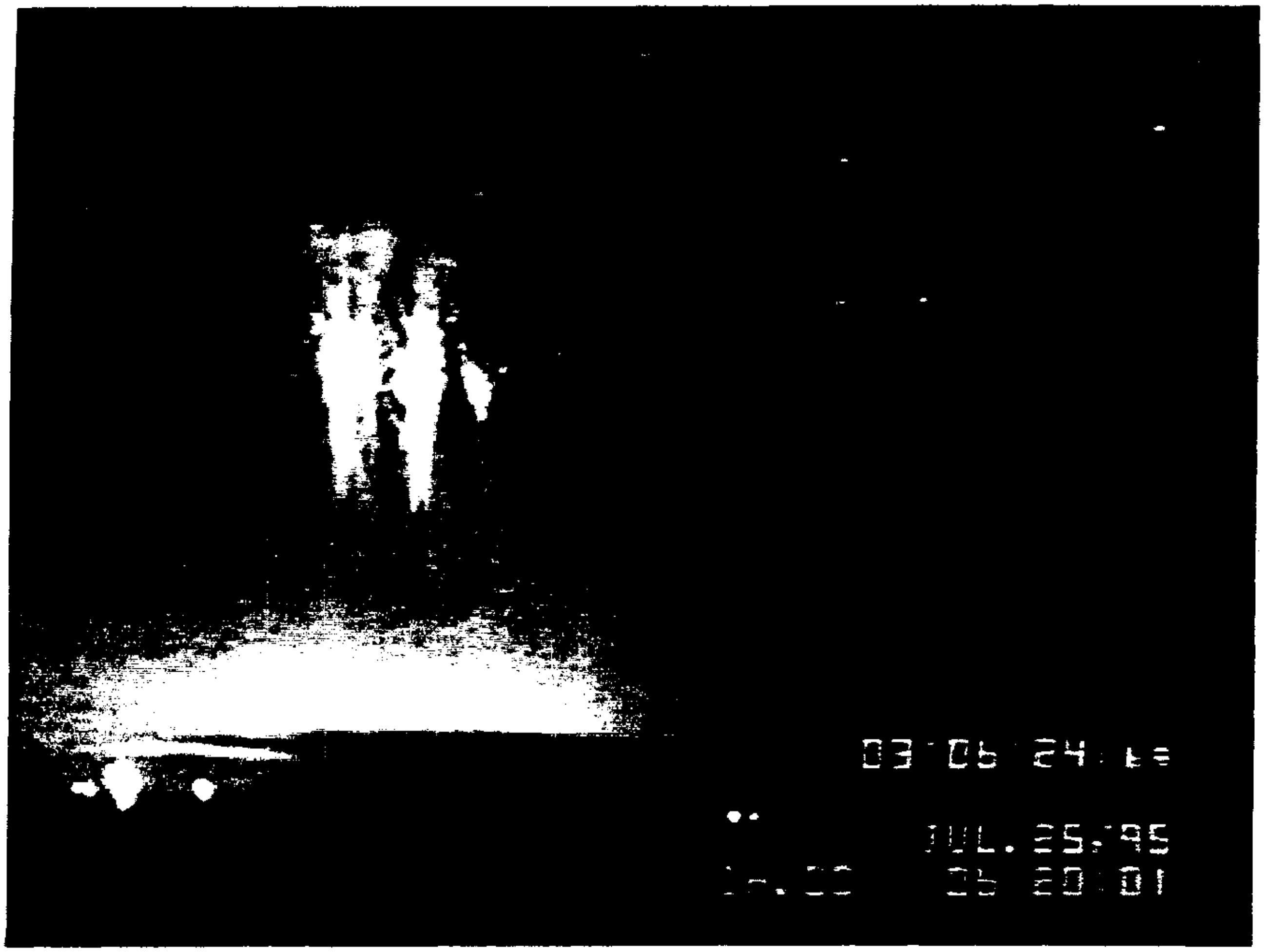


Figure 3-76. Plot of +CG flashes from NLDN between 0400 and 0500 UTC 16 July 1995. Note small cluster of flashes in western South Dakota that were under surveillance.



Sprites north of Fort Collins, Colorado
photo by S. B. Mende and R. L Rairden

Figure 3-77. One of many excellent sprite images obtained on the night of 16 July 1995. View looking north-northeast from Yucca Ridge. Note MCS anvil cloud outline by the glow from the in-cloud discharge associated with the sprite. Image Courtesy of Steve Mende and Rick Rairden.

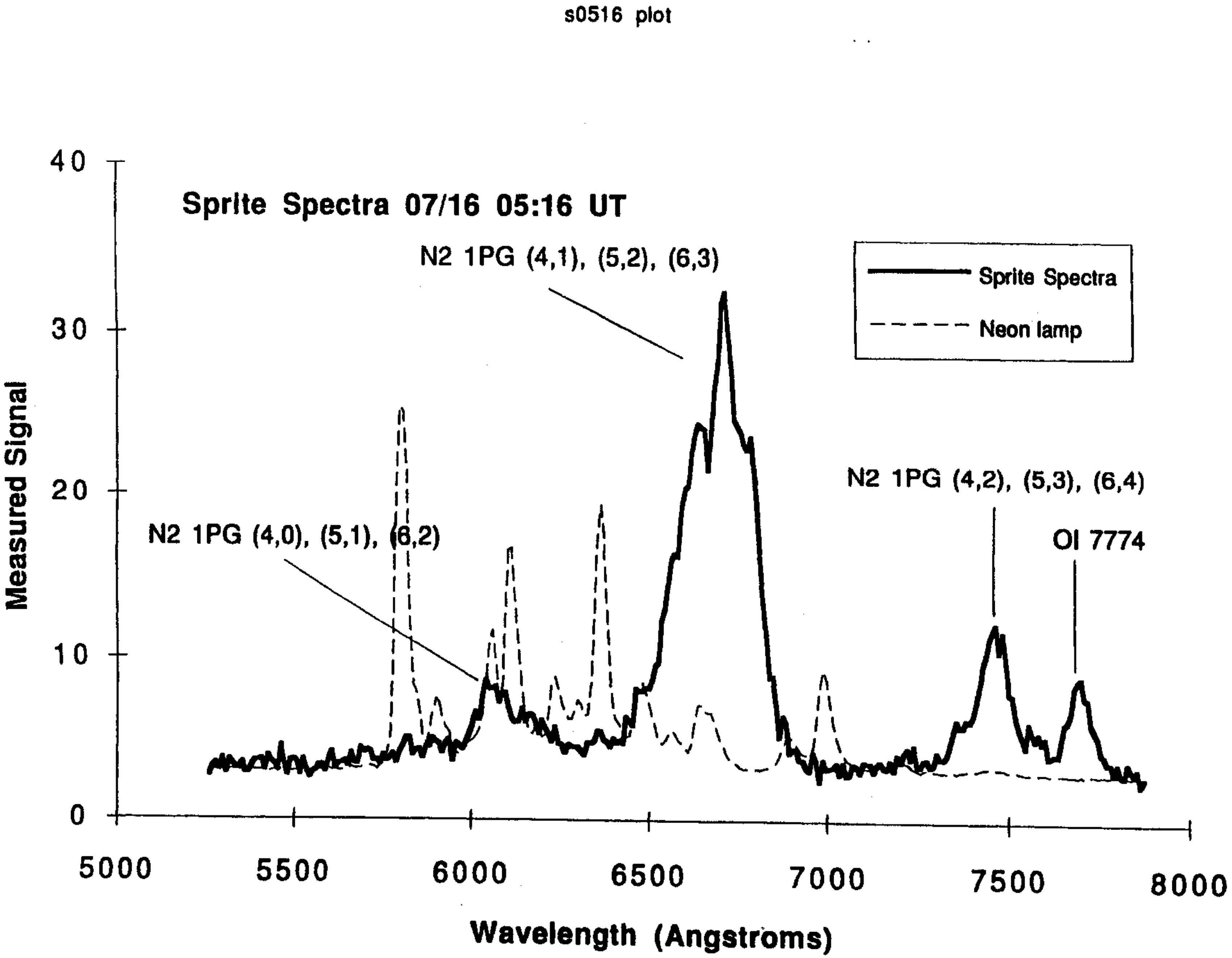
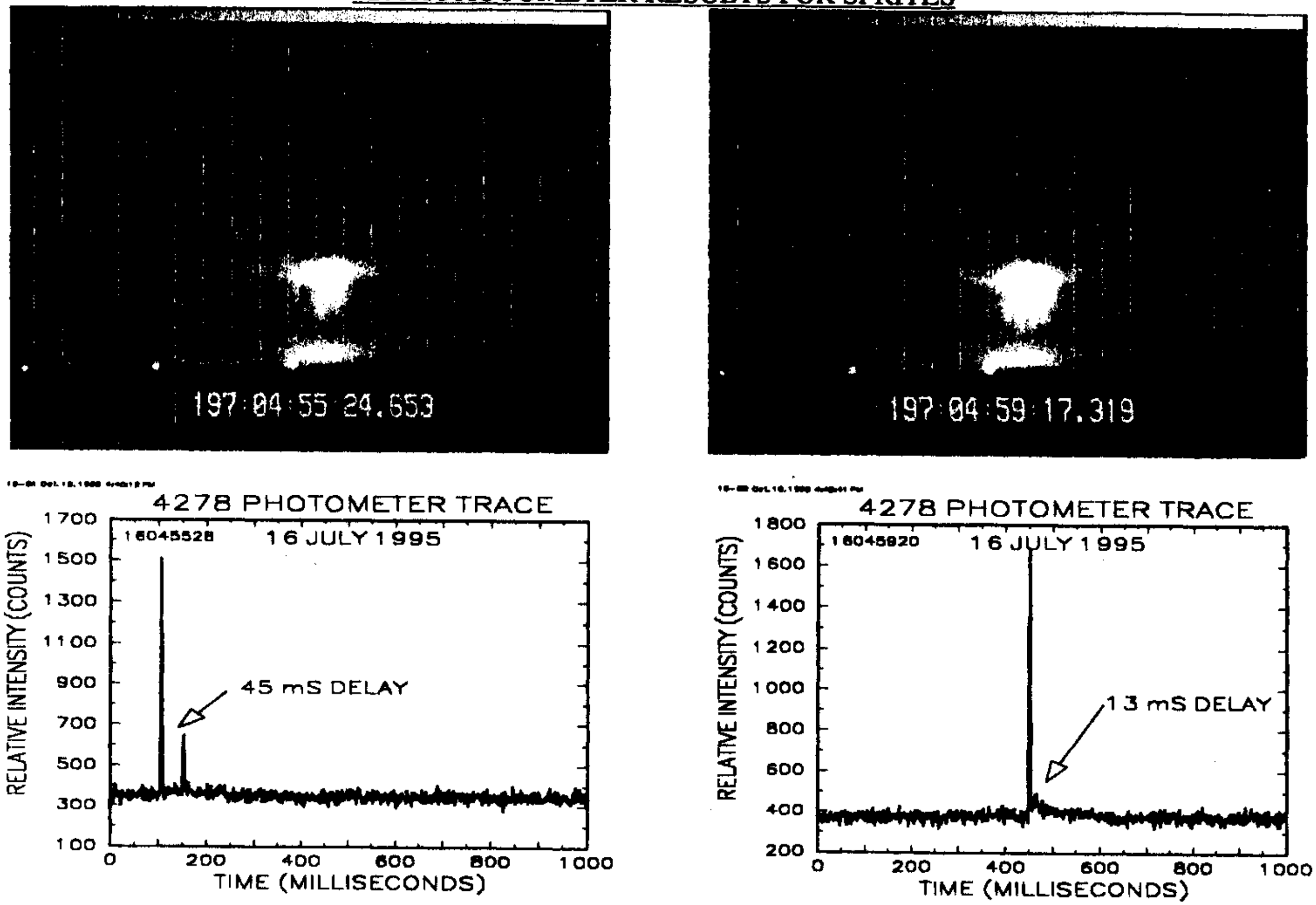


Figure 3-78. Sprite spectra obtained from YRFS at 0516 UTC 16 July 1995. Neon lamp provides a calibration. Source: Mende et al. (1995).

CHARACTERISTICS OF SPRITES

4278A PHOTOMETER RESULTS FOR SPRITES



TYPICAL SIGNAL FROM SPRITE WITH WELL-DEVELOPED TENDRIL STRUCTURE AND ELF

Mission Research Corporation

Figure 3-79. Selected output from MRC narrow band pointing photometer for two TLEs, one containing an elve, from 16 July 1995. A strong signal at 427.8 nm suggests significant ionization may be present. Courtesy: R. Armstrong, MRC.

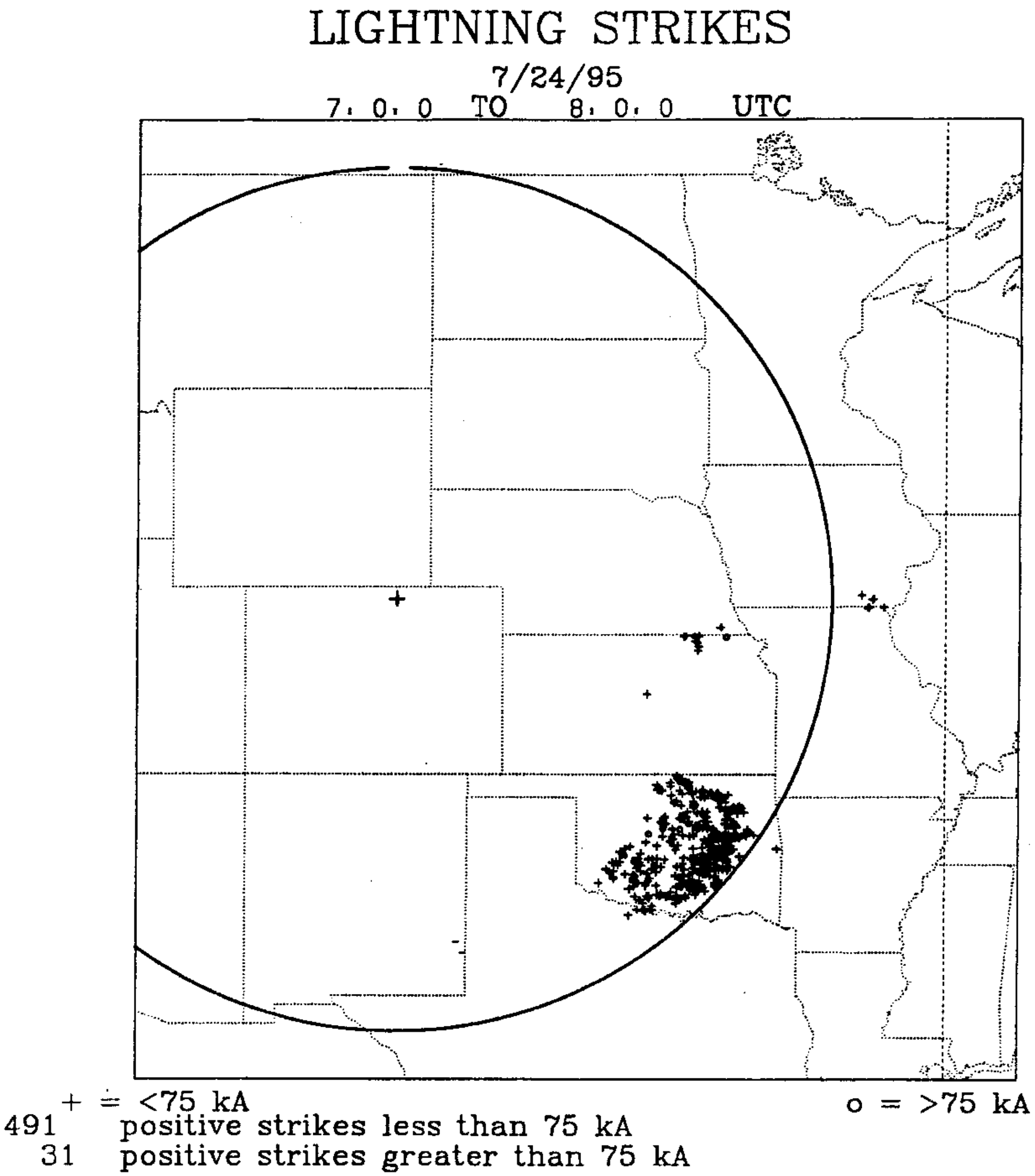
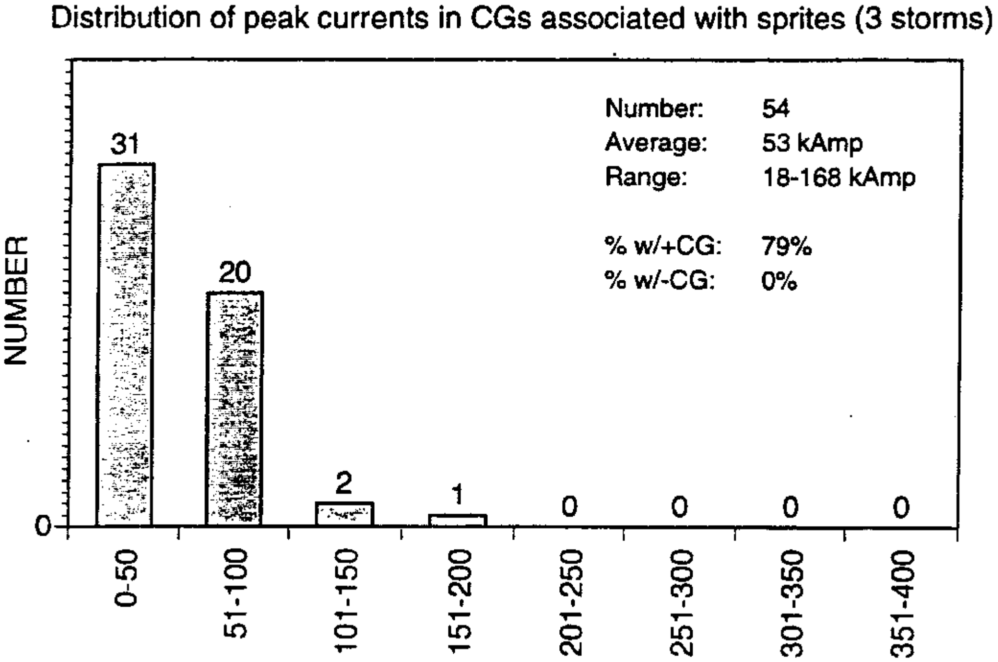


Figure 3-80. Plot of +CG flashes from the NLDN between 0700 and 0800 UTC 24 July 1995 showing activity from a large MCC in Oklahoma that was producing numerous TLEs under surveillance from YRFS.



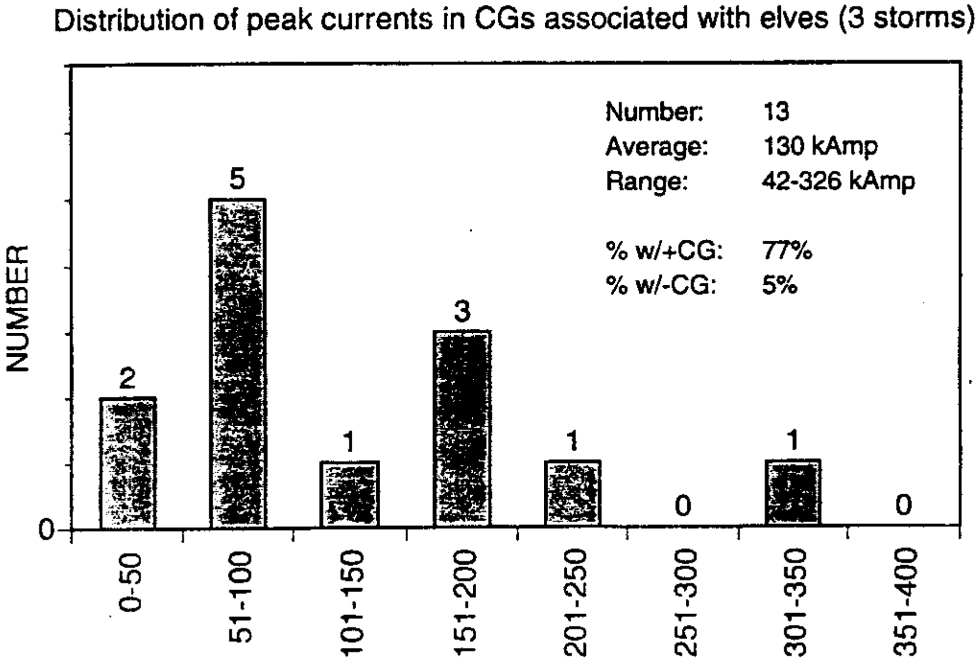


Figure 3-81. Distribution of peak currents in sprites (top) and elves (bottom) for three storms (23 June, 15 July, 16 July 1995) that were investigated in detail.

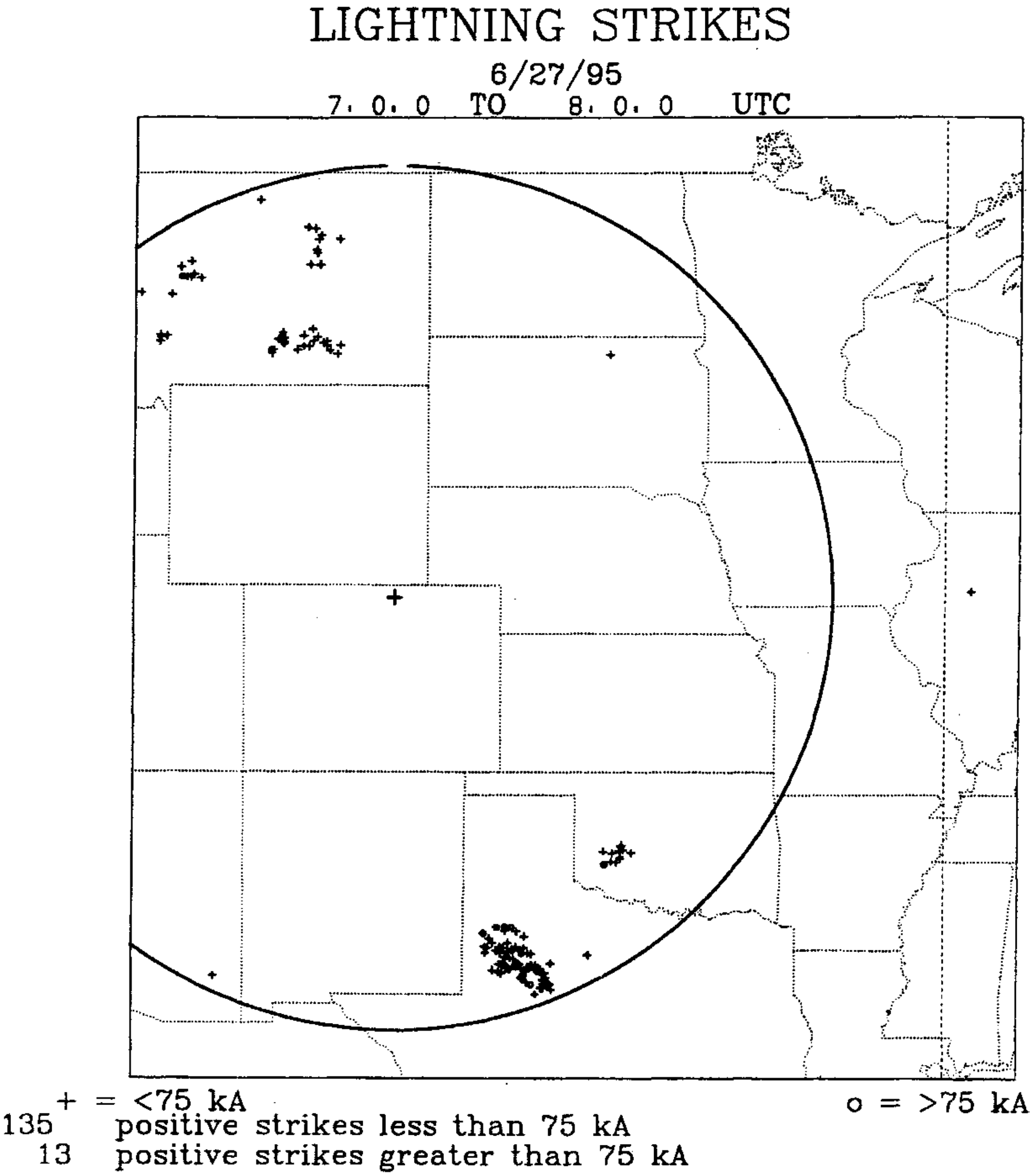


Figure 3-82. Plot of +CG flashes from the NLDN between 0700 and 0800 UTC 27 June 1995 showing activity in west central Texas some 950 km from YRFS that was producing numerous sprites and elves.

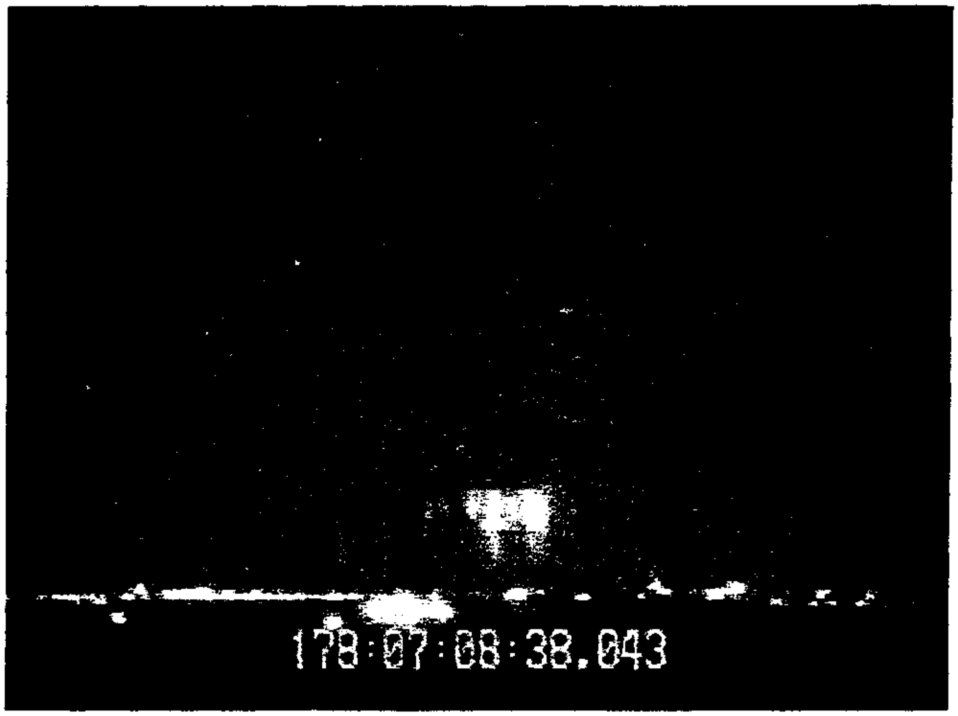


Figure 3-83. Image of distant sprite emerging from below the horizon. The distance to the sprite is estimated at about 950 km.

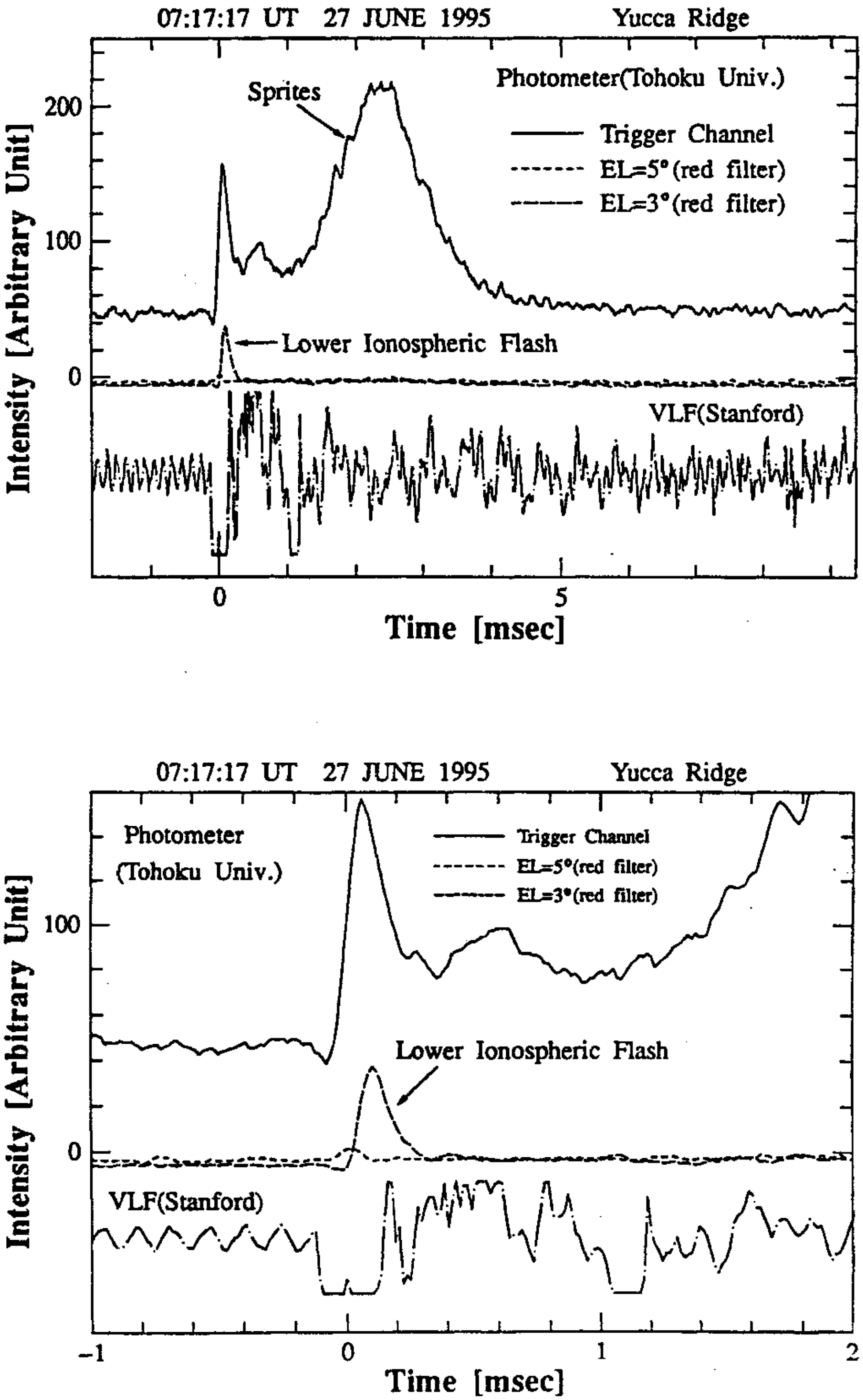


Figure 3-84. Tohoku University photometric observations on 27 June 1995 of optical emissions from an elve and sprite at a range of greater than 900 km.

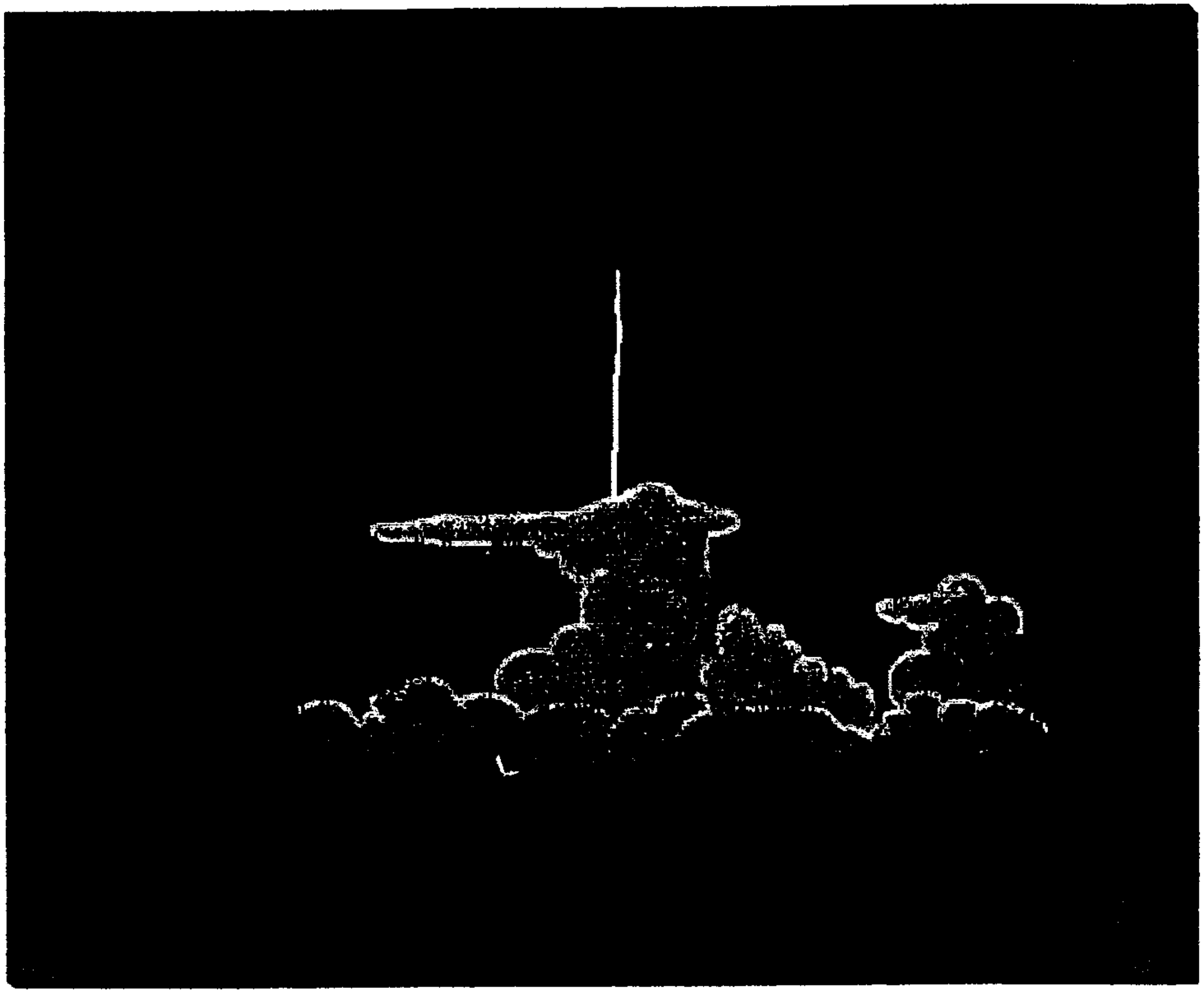
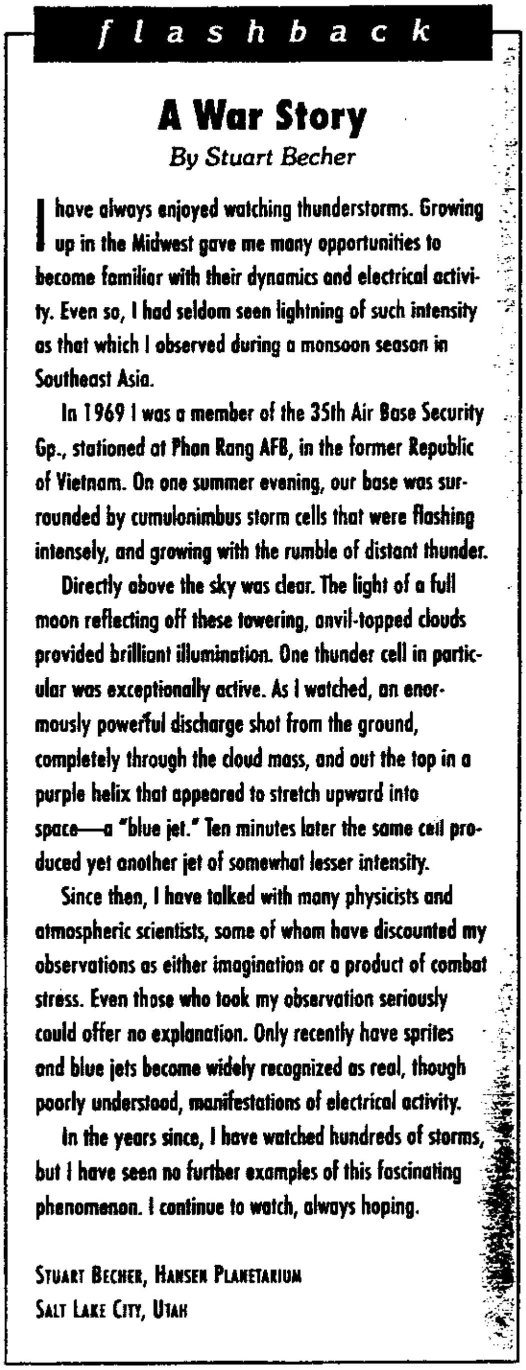


Figure 3-85. Artist's sketch of large upward lightning bolt emerging from top of thunderstorm. Observation made by a meteorologist of an event in eastern Nebraska from a commercial airliner traveling between Denver and Minneapolis. The column appeared to last for as long as 500 ms, was brilliant yellow-white in color, and extended to perhaps two times the height of the parent cloud.



flashback

A War Story

By Stuart Becher

I have always enjoyed watching thunderstorms. Growing up in the Midwest gave me many opportunities to become familiar with their dynamics and electrical activity. Even so, I had seldom seen lightning of such intensity as that which I observed during a monsoon season in Southeast Asia.

In 1969 I was a member of the 35th Air Base Security Gp., stationed at Phan Rang AFB, in the former Republic of Vietnam. On one summer evening, our base was surrounded by cumulonimbus storm cells that were flashing intensely, and growing with the rumble of distant thunder.

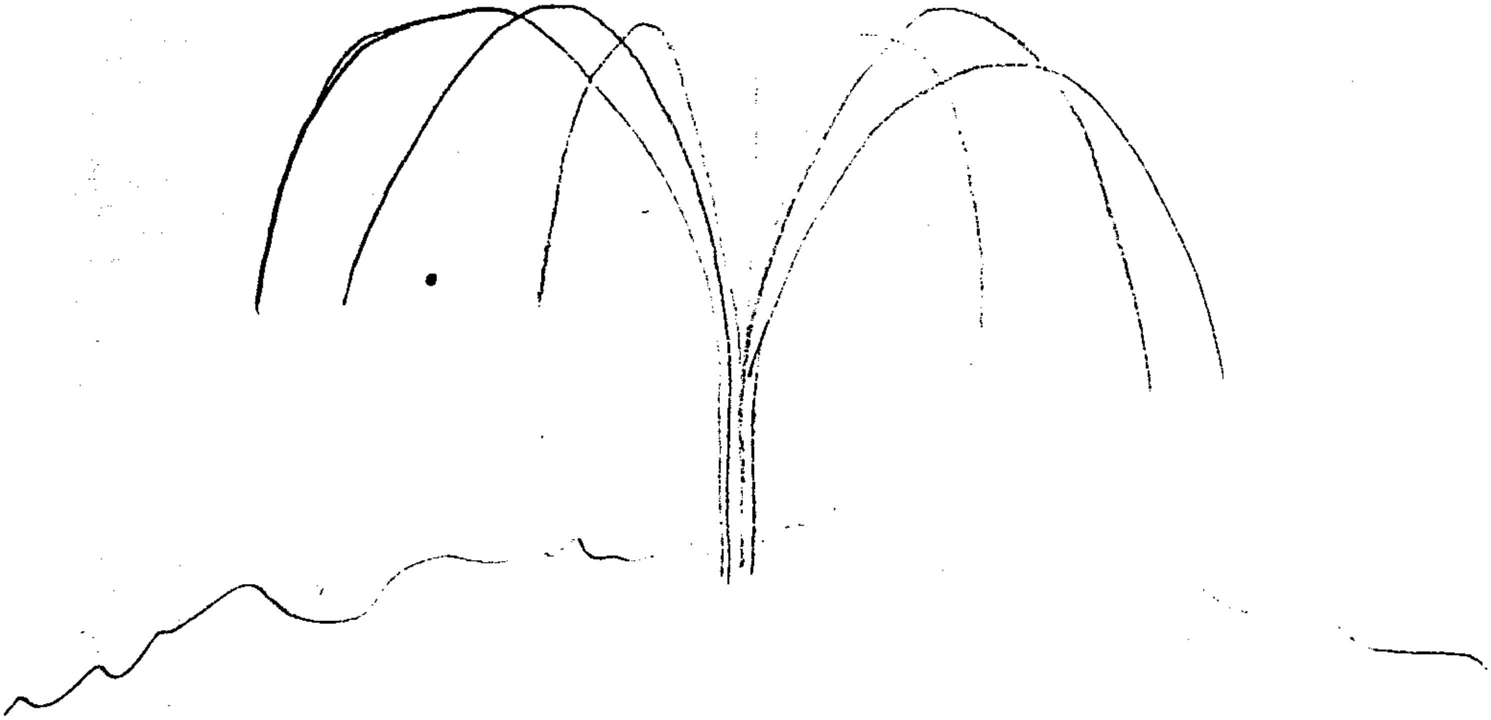
Directly above the sky was clear. The light of a full moon reflecting off these towering, anvil-topped clouds provided brilliant illumination. One thunder cell in particular was exceptionally active. As I watched, an enormously powerful discharge shot from the ground, completely through the cloud mass, and out the top in a purple helix that appeared to stretch upward into space—a "blue jet." Ten minutes later the same cell produced yet another jet of somewhat lesser intensity.

Since then, I have talked with many physicists and atmospheric scientists, some of whom have discounted my observations as either imagination or a product of combat stress. Even those who took my observation seriously could offer no explanation. Only recently have sprites and blue jets become widely recognized as real, though poorly understood, manifestations of electrical activity.

In the years since, I have watched hundreds of storms, but I have seen no further examples of this fascinating phenomenon. I continue to watch, always hoping.

STUART BECHER, HANSEN PLANETARIUM
SALT LAKE CITY, UTAH

Figure 3-86. Except from the 1995 "Weather Guide Calendar" feature story on sprites. From the description provided, it is not at all clear that this observation represents that of a blue jet.



THE LINES ARE ONLY A WIRE FRAME SUGGESTION.
NO LINES ACTUALLY WERE SEEN.

Figure 3-87. Sketch provided by airline pilot of a most unusual fountain of "light" emerging from the top of an active thunderstorm. It was visible during daylight and, most peculiarly, lasted for more than several minutes, though it occasionally flashed off like a flickering fluorescent lamp. The vertical scale is estimated at several thousand feet.

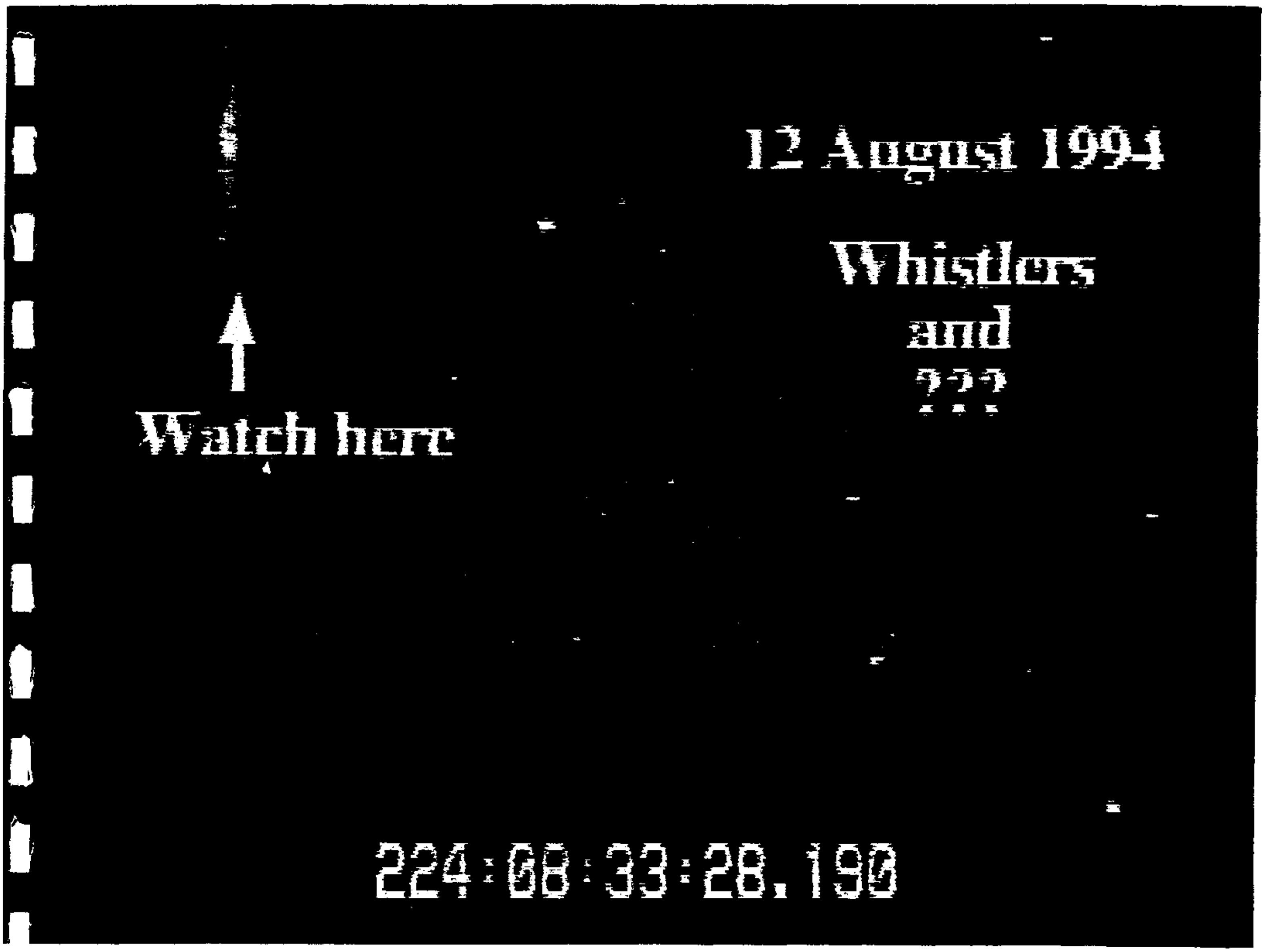


Figure 3-88. A video field showing a strange column of light which translated from left to right for about 20 degrees of azimuths during a 350 ms period. It was not a sprite and was not associated with any CG event or obvious sferic. At other times on this night whistlers had been heard on the Inspire receiver.

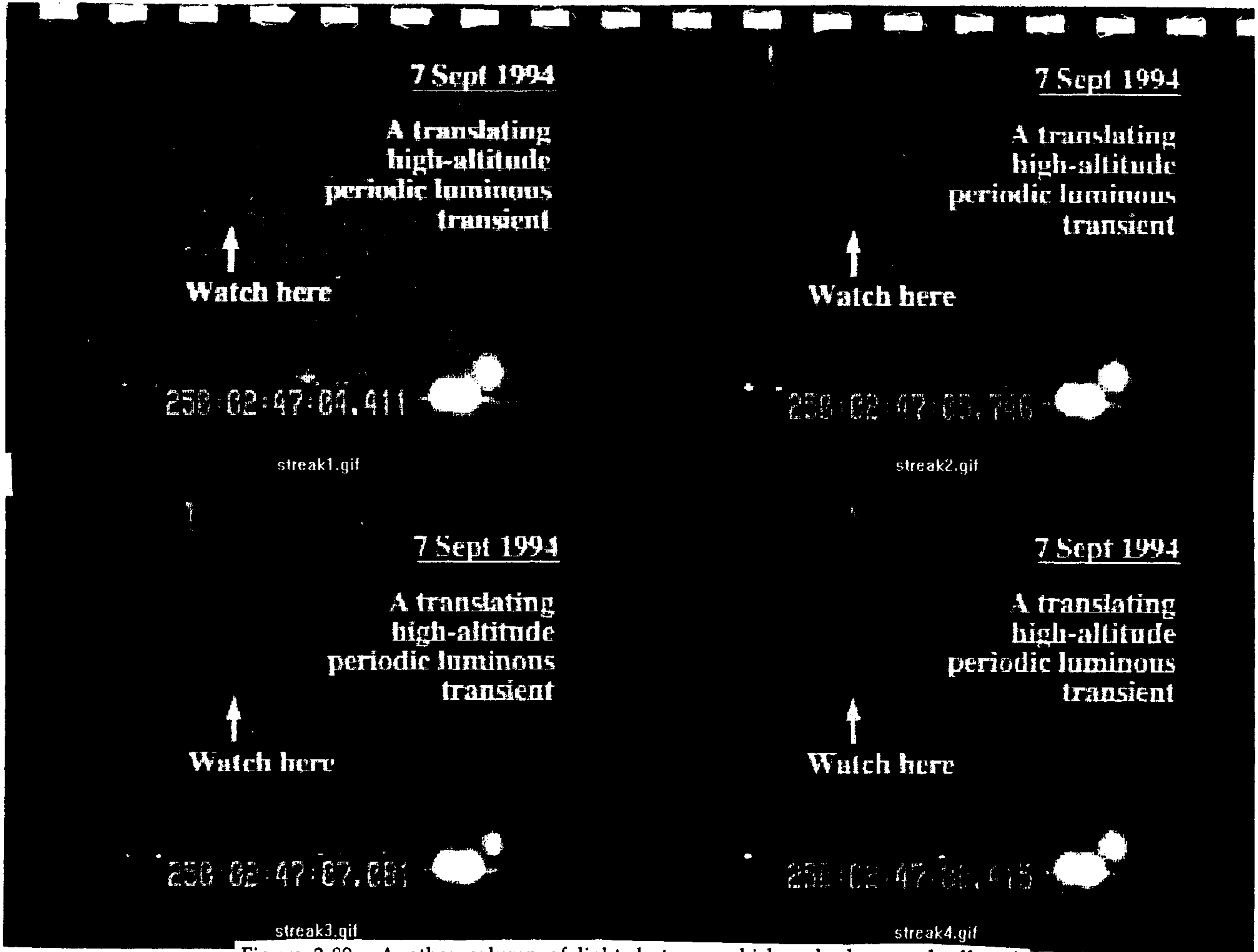


Figure 3-89. Another column of light, but one which pulsed on and off as it translated left to right across the screen. The column turned on at 1.3 second intervals. There were no associated sferics or CG events during this episode.

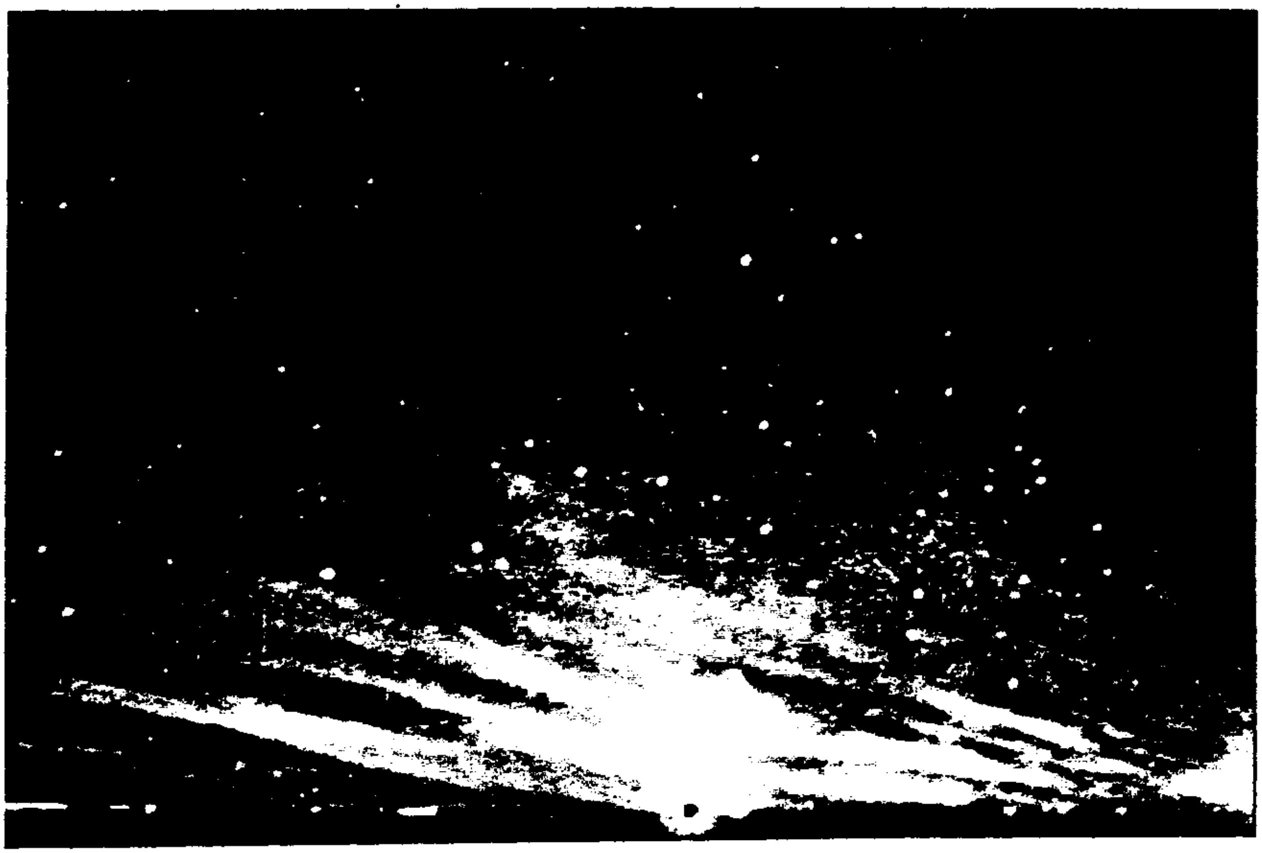


Figure 3-90. Striations in the airglow layer associated with upwelling gravity waves from a large sprite-generating MCS beyond the horizon during SPRITES'95. On this night the green striations were actually visible to the dark adapted, naked eye. Image courtesy of Mike Taylor, Utah State University.

4.0 THEORY AND METHODS OF DETECTION

4.1 Theoretical Studies of TLEs

The pace of observational investigations of transient luminous events is now being matched by a growing number of theoretical and laboratory studies of the underlying physics of these newly revealed phenomena. Teams are at work at a variety of institutions including Stanford University, Lawrence Livermore National Laboratory, the University of Maryland, the Naval Research Laboratory, Los Alamos National Laboratory and NASA Marshall to name just a few. A comprehensive review of the rapid developments in the theoretical understanding of TLEs and their numerical and laboratory simulation would be beyond the scope of this report. We will, however, highlight some of the more recent findings, especially those produced by the SPRITES'95 group and their colleagues. A relatively complete list of references is included in Section 9. We apologize in advance for ignoring much fine work that is being undertaken by various investigators and for almost certainly over simplifying the findings of the workers we do review. To optimize the accuracy of our summary, we will be quoting liberally from the various published papers in the following sections.

Figure 4-1, compiled by STAR Lab at Stanford University, summarizes much of the current thinking regarding the processes linking lightning to both optical and other emissions within the stratosphere and mesosphere. The role of the electromagnetic pulse (EMP) (Inan et al. 1991, 1996; Taranenko, 1993; Rowland et al., 1995), quasi-electrostatic heating from charge transfer within clouds (Wilson, 1925; Pasko et al., 1995; Winckler et al, 1996; Boccippio et al., 1995) and the generation of sprite tendrils and possibly gamma rays by runaway electrons in the enhanced fields above thunderstorms (Bell et al., 1995; Winckler et al., 1995; Taranenko and Roussel-Dupre, 1995) are highlighted. The blue jet is a separate but related phenomenon and will also be discussed. The interplay between the SPRITES'95 observational effort and the theoretical community has been highly beneficial in that newly found phenomena have presented challenges to be explained, while the increasing quantification of observable characteristics of TLEs has helped bound the application of the various theories.

The mechanism that presently appears to best explain the luminosity of the sprite, or at least its upper portion (the head), is heating and ionization due to intense quasi-electrostatic (QE) fields that temporarily exist at high altitudes following the sudden removal of charge within the thunderstorm below. It is suspected that the sprite parent +CG detected by the NLDN serves a diagnostic of a complex series of events in which a continuing current draws on a vast pool of positive charge resident within the MCS's stratiform precipitation region (Marshall et al., 1995; Stolzenburg, 1994). This process often visually manifests itself by the horizontally extensive (>100 km) dendritic lightning displays variously called "spider lightning" or "anvil crawlers."

Pasko et al. (1996) present a theoretical model which pays homage to the original suggestions made by Wilson in 1925 as well as explains many of the details of recent observations. The key factor is that the air density drops off faster with altitude than does the imposed electric field resulting from the massive in-cloud transfer of charge associated with the large +CG event. At some height above the storm, dielectric breakdown occurs. To achieve dielectric breakdown at altitudes at which sprites are observed the field change must be fast compared to the relaxation time (which also decreases with altitude) in the nighttime mesosphere and should exceed the local breakdown strength. Most lightning processes are faster than the relaxation time, which at 80 km is about 10 ms (but may vary by an order of magnitude). This mechanism will be most effective if the charge is neutralized over a large area. A linear or planar discharge will most likely stress a larger region above the storm than would a conventional point dipole-like discharge inducing a larger field change at a given altitude. This helps explain the possible role of the +CG / spider lightning mechanism suggested by Lyons (1994, 1996) and Boccippio et al. (1995).

The Pasko et al. (1996) model developed at STAR Lab is a two-dimensional code. The response of the system at mesospheric altitudes depends on the altitude and magnitude of the positive charge and not upon the initial charge configuration inside the cloud. The model predicts a dominance of the red N_2 1P band at higher altitudes over the blue N_2 2P emissions, as is observed. Blue becomes increasingly important only at lower altitudes (< 50 km). A variety of sprite-like structures emerge from the model as a function of the amount and rate of charge removal during the CG event. Modeling scenarios include cases in which an initial 200 C are removed in 1 ms with a slower draining of 275 C taking the next 19 ms. Localized conductivity enhancements which may occur due to external sources (electron precipitation from the magnetosphere, meteors, gravity waves, runaway electrons, perturbations from previous sprites, etc.) may significantly enhance the local field and control the transverse scale of ionization channels and partially explain how one +CG could create large clusters of sprites. The optical emissions are predicted to be in the 10^2 to 10^3 kR range, consistent with video observations (Sentman et al., 1995). The model also accounts for the observed lag times between the +CG and the onset of sprite illumination which range from several to several tens of milliseconds (Winckler et al., 1995; Fukunishi et al., 1996). The intense QE fields that result from the temporarily large uncompensated charge distributions within thunderstorms that follow a major +CG event do appear to play a critical role in formation of at least part of the sprite structure.

One of the more intriguing features of sprites are the downward extending tendrils which accompany many bright (but rarely dim) sprites. Bell et al. (1995) proposed that the tendril structure is produced by runaway electrons forcing an upward traveling beam of MeV - level particles within the large QE fields. Since neither the EMP nor QE theories allow for production of significant luminosity below 50 km, it is clear that some other mechanism, such as runaway electrons, must be invoked to explain the tendrils which have been observed to penetrate as low as 30 km. The tendency of tendrils in some sprites to have an hour glass shape, that is, flare outward at lower altitudes, still needs to be explained (Figure 4-2). Runaway electrons, triggered at a given point by a cosmic ray or some other source, would seem to be more likely to expand upward, producing a luminous V-shape, narrowest at the bottom (a mode which is often observed).

Other theories have been suggested to explain sprite formation including low frequency RF breakdown (Milikh et al., 1995). In this hypothesis, sprites are caused by radiated electromagnetic fields associated with charge acceleration in intracloud flashes or return strokes. Boccippio et al. (1995) suggest that the coincidence of sprites with ELF transients imply extraordinarily large charge transfers which favors an electrostatic over an electromagnetic triggering mechanism.

Other features within the sprites, such as the persistent luminous "hot spots" found within some events (Winckler et al., 1996) remain unexplained.

Elves present an interesting case in which theory had actually predicted their presence before observational confirmation (Inan et al. 1991). Energy release triggered by lightning discharges were believed to lead to optical emissions and significant ionization changes resulting from acceleration of ambient electrons by intense EMP (Taranenko et al., 1993 a,b; Rowland et al, 1995; Inan et al., 1996). Lightning EMP has a duration of about 50-100 μs and produces heating of electrons and optical emissions which last as long as the driving fields, primarily at 80-95 km altitudes. By contrast the QE field luminosity is largest at 60-85 km altitude range and persists for the few to tens of milliseconds that it takes the partially conducting atmosphere to respond to the "rearrangement" of the thunderstorm charge associated with the +CG flash. Inan et al. (1996) describe the physics of the lightning-EMP interaction. The peak spectral content of EMPs radiated by lightning is typically in the VLF range (3-30 kHz). Reflection of VLF waves under the nighttime ionosphere occurs at the altitudes where the normalized electron collision and plasma frequencies are equal (≈85 km). The maximum absorption of wave energy causing heating of the electrons also occurs near the same altitude (Inan, 1990). Excitation of optical emissions is a process with an energetic threshold leading to nonlinear dependence on emission intensities on the EMP intensity. The N_2 1P band is excited by impact on N_2 electrons with energies >7 eV whereas the ambient electrons in the upper atmosphere are initially at around 0.03 eV keV levels. The maximum luminosity occurs at the level of maximum heating. The latest 2-D EMP model (Inan et al., 1996) allows for electron mobility, ionization, and two-body attachment rates based on experimental data and quantifies the temporal and spatial variations of optical emission produced under varying conditions. The model results emulate many of the observed features of elves reported by Fukunishi et al. (1996). The EMP produced by CG flashes with peak currents > 80 kA can produce bright (>10 mR) optical flashes and significant ionization changes at 80-95 km altitudes. The N_2 1P band emits in a thin (≈30 km) cylindrical shell expanding in time to radial distances of up to 250 km. The duration of the optical flashes is estimated to be 300-500 μs, depending on the observed location. In limb-view (as from the Space Shuttle), the optical emissions appear as a thin layer of lateral extent up to 400 km The EMP-induced ionization changes are produced in a doughnut-shaped region between radial distances of 25 to 150 km and consist of ionization from a few to hundreds of percent at 85-95 km and depletions of a few percent at 80-85 km. Initial spectral measurements made the GI/UOA group confirm the N_2 1P band. This suggests that elves are more likely to be red than green (as suggested in some press coverage, see Figure 1-19).

The blue jet continues to remain the most mysterious of the TLEs. It is becoming clear, however, that blue jets are not related to a specific +CG flash nor, in fact, to any specific CG event. Most of the data on blue jets was obtained on a single flight by the GI/UOA group in 1994 (Wescott et al., 1995). The jets emerged from the anvil of an extremely electrically active storm near Forman, AR on 1 July 1994 (Figure 4-3). This storm was also characterized by intense hail falls. The LLTV images of the blue jets were very similar to the 10 to 20 luminous shafts of light erupting from an active squall light observed visually from a commercial airliner by Fisher (1990). There are also anecdotal reports of numerous blue jets seen by airline pilots and passengers shooting upwards from the massive Dallas, TX hail storm of 1995. One relationship that has emerged between blue jets (and the immature blue starters) and CG lightning is shown in Figure 4-4. Intense CG activity is present in the period preceding the blue jet, but briefly ebbs for 1 or 2 seconds after the event (Wescott et al., 1995; personal communication).

At least one paper has been presented to theoretically explain blue jets. Pasko et al. (1996) suggest that pre-lightning discharge quasi-electrostatic fields immediately above the thunderstorm cloud top lead to the formation and upward propagation of streamer type ionization channels. Pasko et al. (1996) hypothesize that under certain relatively rare conditions a charge of 300 to 400 C can accumulate near 20 km altitudes. This charge may have an extended dish-like distribution and can lead to breakdown ionization in regions with lateral extents on the order of 100 to 1000 meters. The 2-D model replicates some of the known characteristics of blue jets. The predicted upward propagation of jets is in the 100 km/sec range, reproducing the general shape as upward expanding beams of luminosity with cone angels <30 degrees, and accounts for the stopping at around 50 km. The model's luminosity fades away along the entire length of the column more or less as observed. The model explains the blue color of jets as the result of N_2 2P emissions. The predicted optical intensities, however, in the model are one to two orders of magnitude above that observed to date. The model predicted brightnesses, however, are quite sensitive to small changes in initial conditions.

There are other emissions from thunderstorms besides those in the optical. The production of X-rays inside thunderstorms has been known for some time (McCarthy and Parks, 1985; Beasley and Eack, 1995). Radiation fluxes on the order of 110 keV for intervals of several seconds sometimes appear to increase prior to observed lightning discharges and then return to background levels after lightning initiation. Initial energetic electrons, the source of which is not clear, produce bremsstrahlung X-rays.

While X-rays have long been under study, the apparent detection of far more energetic gamma rays from terrestrial sources was completely unexpected (Fishman et al, 1994). Some 50 brief (≈millisecond) but intense flashes of gamma rays have been detected sporadically (over 4 years) by the orbiting Compton Gamma-Ray Observatory (CGRO). The flashes appear to originate from altitudes of above 30 km in the vicinity of thunderstorms. Theoretical models (Taranenko and Roussel-Dupre, 1996; Chang and Price, 1995) have been offered to explain a possible linkage between sprite-generating electrical processes and the gamma ray bursts. Until recently no direct connection between lightning (and sprites) with terrestrial gamma rays has been obtained. Inan et al. (1996).however, have used ELF/VLF sferics measurements taken at Palmer Station, Antarctica, to provide at least indirect evidence of active thunderstorms near the inferred source regime of two gamma-ray bursts of terrestrial origin. In one case, a relatively intense sferic occurring within ±1.5 ms of the time of the burst suggests a possible linkage between lightning and gamma-rays. Moreover, the character of the wave forms was similar to that known to be associated with sprite-producing +CG events (Reising et al., 1996). A hard association between sprites and gamma-ray bursts would have significant implication for our understanding of the energetics of sprite processes. At this time estimates of the electron energies associated with sprites varies by up to five orders of magnitude in various studies.

Not all theoretical studies relevant to TLEs have been numerical in nature. Williams et al. (1985) presented laboratory studies of streamers produced from the discharge of electrically charged plastic blocks. More recently, Jarzembski and Srivastava (1995) conducted laboratory experiments of low pressure discharges from plates and wires which produced interesting analogs to sprites and blue jets.

One of the primary tasks of this Phase II project was to devise means to detect the presence of TLEs. This has been accomplished, and in more ways than would have been thought probable at the onset of the program in 1993. It would appear that TLEs, particular sprites and elves, manifest their presence over a wide portion of the electromagnetic spectrum. Both optical and RF-based detection systems have been demonstrated to be practical or at least possible.

A brief review of detection methods for TLEs follows.

4.2 Optical and Visual Detection

By far the simplest technique for monitoring sprites, blue jets and elves is the use of LLTV systems. They are readily available from several manufacturers. No special filters are required. The spectral response of the photocathode can be an issue, however. Many systems are sensitive in either the red/near infrared or in the blue portion of the visible spectrum. It is possible that an LLTV well suited for tracking sprites will not be capable of detecting any but the brightest blue jets. It should be noted that the dependence to date on the GEN II red photocathode by many investigators making optical measurements may have resulted in missing important details of sprite structures and as well as the blue jet phenomenon.

It is relatively easy to see and recognize sprites in real-time on the monitor of an LLTV system, but such a technique is not foolproof and is certainly not automated. The use of pointing photometers (especially those filtered to pick up bands associated with the N_2 1P emissions) might provide an option for an automated optical system.

The advantages of LLTV systems include their relatively low cost, low maintenance and ease of operations. The obvious drawbacks include their inability to see through obscuring clouds, the manual nature of signal extraction and the fact that they must be directed to the proper location in the sky. LLTV also only works during the nighttime hours (30 minutes after sunset and before sunrise).

It would certainly be plausible, and useful, to install one or more LLTV systems atop a tall building in the Tallahassee or Tampa Bay areas with lenses suitable for covering the space above the KSC region. Relatively low-cost video remoting is now possible using phone lines. Monitoring for TLEs "above the launch" pad could be accomplished, time of day and cloud clover permitting.

It should be noted that it is possible to detect a percentage (probably between 10 and 50%) of sprites with the naked eye. There has been great public interest in how this might be done. Figure 4-4 is an excerpt from the material prepared for the 1996 Accord Publishing Co. "Weather Guide Calendar" which includes descriptions of TLEs and how they might be seen with the naked eye.

4.3 ELF and VLF techniques

An operational sprite/elve detection system is ideally one that would work continuously throughout the diurnal cycle regardless of cloud cover, would not require an operator, and would automatically detect and locate events in real-time with high probability of detection and a low false alarm rate. It appears that many of these specifications can be met with systems receiving and processing signals in the ELF and VLF.

Farrell and Desch (1992) proposed that the TLE discharges should have slow rise times with the emitted energy reaching peak values in about 10 milliseconds. By applying a dipole radiation model they concluded that the emitted radio wave emanating from TLEs is strongest below 50 Hz, and possess a significant rolloff at higher frequencies. Various current distributions were analyzed in order to determine the radio spectrum and they concluded that near 10 kHz, the emission from their hypothetical cloud-to-stratosphere discharge should be as much as 50 dB lower than a typical CG return stroke. Though recent observations have shown this not to be exactly the case, it appears that indeed distinct signatures diagnostic of sprites and perhaps elves may reside in the ELF and even higher frequencies.

The potential for diagnosing sprites using Schumann Resonance (SR) measurements had earlier been proposed by Dave Sentman (University of Alaska) and Earle Williams (MIT). A much more complete theory for using Q-bursts to diagnose, on a nearly global scale, the presence of CGs having a high potential for sprites is given in Williams et al. (1996). The Schumann resonances are a global electromagnetic phenomenon excited by lightning discharges and contained in the

Earth-ionosphere cavity. The basic formulation derives from the normal mode equations of Wait (1962).

Recently, SR has been used as a sensitive diagnostic for global tropical surface temperature (Williams, 1992) due to the apparent relationship between tropical global lightning activity and mean surface layer wet bulb temperature. That effort, however, is based upon monitoring the intensity of the basic background SR signal. The quasi-steady electromagnetic field strength signal recorded at a series of discrete frequencies (8 Hz, 16 Hz, 24 Hz, etc.) are the SR modes. These are maintained by the *totality* of global lightning activity. This is in contrast to the *transient responses* of the Earth-ionosphere cavity caused by extraordinarily energetic lightning bolts. These transients exhibit amplitudes more than an order of magnitude greater than the quasi-steady resonance and *are easily detectable*. These transients are called Q-bursts. In the Phase II proposal it was hypothesized that Q-bursts are generated by lightning discharges traveling upward into the ionosphere from the tops of electrified clouds. Recent findings suggest that it is the extraordinarily large +CG that triggers the sprite and also launches the Q-burst into the Earth-ionospheric cavity. While the Q-burst may not emanate from the sprite region per se, it has substantial prognostic value. Q-bursts had been recognized in observations for as long as SR data were acquired (Schumann, 1954) but the specific source at the storm scale had not yet been identified. Lightning events with extraordinary luminosity called super bolts (Turman, 1977) and powerful positive ground flashes (Sentman, 1988) have both been suggested as causing Q-bursts. The results of Boccippio et al. (1995) suggest the latter and perhaps the former are in fact the case.

The detailed theory provided by William et al. (1996) (see Appendix D) illustrates how both single station and multi-site direction finding techniques can be applied to locating Q-burst generating CGs (those having a relatively very high chance of producing a sprite). Figure 4-6 illustrates a prototype three-station ELF direction finding network which could provide coverage of the entire United States, including the KSC region. Since the source is ideally required to be greater than 2 Mm distant for accurate determination of the Q-burst, the two more distant sites would be used for detection and location. Thus the KSC region could be covered by Rhode Island and YRFS. The required PC-based software to automatically detect Q-bursts has been written by R. Boldi and C. Wong of MIT/Lincoln Labs.

Wong (1966) has also developed a techniques to use single station SR transient records to locate Q-bursts on a worldwide basis (Figure 4-7). We note the accuracy of this technique is probably no better than 1 Mm.

Not all +CGs produce sprites. It is estimated that between 10% and 50% of the +CGs in a "typical" storm have sprite producing potential (with great variability inter- and intrastorm). Many very large peak current CGs of both polarities within the field of view of the LLTV have not generated sprites. Why? Possible explanations include the fact that single stroke negative flashes generally lack continuing currents (Shindo and Uman, 1989; Rakov and Uman, 1990) whereas the majority of positive flashes exhibit a prominent continuing current that dominates the total charge transfer. Unfortunately continuing currents in +CG sprite producers are not identified by the NLDN on account of their system band pass (1 kHz - 500 kHz). Analysis of the spectra of transients from NLDN-identified large negative and positive CGs has shown that negative flashes typically have a white noise spectrum. By contrast ELF spectra associated with sprite +CGs is notably red, consistent with Ogawa's (1966) Q-burst nomenclature indicating the dominance of low frequency content and also consistent with a prominent continuing current component in the charge transfer to ground. Williams et al. (1996) noted, however, that the spectra for a single strike +CG flash with a 114 kA peak current - one which did not generate a sprite - also had a white noise spectrum and thus little evidence of a continuing current. Thus aside from large peak currents, the continuing current appears to be part of the electrodynamic forcing required to produce both sprites and Q-burst ELF transients. Figure 4-8 is Earle Williams' compilation of the relationships between lightning characteristics and TLE generation. The charge transfer and event duration for discrete strokes and for the "fast" and long continuing currents are included, both for positive and negative polarity. The systematically larger charge transfers for positive polarity, itself still poorly understood, may be the main reason for what appears to be exclusive association between +CGs and sprites. The fast continuing currents, drawn as dashed regions since solid quantitative data are lacking, may well be the source of the ELF slow tail. The "fast" continuing current may also be an important initiator of dielectric breakdown in the mesosphere because this time scale is shorter than the electrostatic relaxation time at sprite altitudes and charge transfer may exceed that in discrete strokes.

During SPRITES'94 and '95 it was clearly demonstrated that the optical sprite almost always was associated with discharges that launched a detectable Q-burst. Thus the probability of detection for sprites using Q-bursts is expected to be high. Little is known at this time about the false alarm rate for such a technique. As mentioned either single or multiple-station ELF systems could be used, the later having a greater potential accuracy. Several variations on the approach could be envisioned for KSC. A single station ELF site, at Rhode Island or at YRFS, could automatically detect and identify the times of Q-bursts, transmitting the information over a low-speed data line to KSC. There, real-time NLDN data stream would be checked for the presence of large +CG events occurring within a well defined time window. The temporal coincidence of a Q-burst with a +CG should yield the location and time of a flash having a relatively very high probability of generating a sprite. The association between elves and blue jets with Q-bursts still remains to be investigated.

The long distance detection of Cg flashes associated with sprites has recently been tested using data from the Antarctic and Germany and validated against SPRITES'95 observations (Fullekrug et al., 1996). Sferics from nineteen sprite occurrences recorded by the LLTV cameras at YRFS on 15 July 1995 were investigated. The sprite-producing +CG locations were determined using the NLDN. These lightning events were also recorded with a timing precision of ±1 ms by slow tail observations in the ELF range (Reising et al., 1996) at the STAR Lab site at Palmer Station, Antarctica. The Institut fur Geophysik takes continuous measurements of the horizontal magnetic field components from 0.1 to 20 Hz with a sampling frequency of 100 Hz at Silberborn, Germany. An example of the Q-burst from the sprite at 06210.22 UTC is shown in Figure 4-9. Using the magnitude of the E-W and N-S components, the arrival azimuths can be determined. Given that the source of the signal is known from the NLDN with great precision, it is possible to determine the arrival azimuth deviation (Figure 4-10). Though there are several outliers the technique appears capable of determining the angle from the distant source on the order of ±5 degrees. The sprite associated flashes radiate considerable energy in the ELF range and simultaneous broad band ELF/VLF measurements at Palmer Station observed the slow tails and quantified the horizontal magnetic intensity. The enhancement of the Earth-ionosphere cavity resonance can be revealed by comparison of the spectral composition of discrete events with low and high values of the horizontal magnetic intensities. Figure 4-11 shows the mean spectral horizontal magnetic intensity for each group of events where the error bars reflect the standard deviation of the mean. The lower bars reflect the mean spectrum of the noise background and the upper bars exhibit the enhancement of the first two Earth-ionosphere cavity resonances at 8 and 14 Hz. These results show the temporal coincidence of sprite-associated lightning flashes and excitation of Earth-ionosphere cavity resonances at the remote location many megameters distant. While these findings are still preliminary, they do strongly support the notion that simultaneous ELF observations of the horizontal magnetic field variations at scattered locations around the world would likely provide the global distribution of the sources of the Earth-ionosphere cavity resonances. A large percentage of these are likely to be sprites, although this has yet to be verified quantitatively.

Analysis of the Palmer Station ELF/VLF data are continuing to yield evidence of continuing currents in sprite-producing CG flashes (Reising et al., 1996). Sferics launched by sprite-producing +CGs on 12 July 1994 and 15 July 1995 have large ELF slow tails following the initial VLF oscillating portion indicating the presence of continuing currents in the source region. One-to-one correlation of measured sferics with NLDN data in both time and arrival angle (measured to an accuracy of ±1° at 12,000 km range as shown in Figure 4-12) allows unambiguous identification of lightning flashes originating in the storm of interest. Results indicate that sprites are produced by those +CG flashes which excite sferics with an enhanced "slow tail" component, indicating the presence of a continuing current in the parent CG. At long distances from their source, sferics are repeatedly observed to have an oscillating VLF portion lasting ≈1 ms, sometimes followed by two or three half-cycles of an ELF (< 500 Hz) slow tail (Hepburn, 1957; Sukhorukov, 1992). Theoretical calculations show that the slow tail is excited at significant levels only by source lightning discharges with a slowly varying continuing-current component with a time constant on the order of several milliseconds (Wait, 1960). Figure 4-13 shows sferics originating within the same thunderstorm with (b) and without (a) a detectable slow tail as measured at Palmer. Those +CGs without slow tails had no sprites and those with slow tails did produce sprites image by the LLTV at YRFS.

For the 12 July 1994 case, 31 of the 44 optically detected sprites (70%) had NLDN detected +CGs, whereas 42 or the 44 (95%) produced a detectable sferic at Palmer Station. Similar numbers were found for 15 July. The slow tail magnitude at Palmer actually proved to be a more definitive predictor of sprite occurrences than NLDN peak currents. Large slow tails produced by lightning with current lasting on the order of several milliseconds is consistent with the model predictions of Pasko et al. (1996). It should be noted, however, that while large peak current +CG events with slow tails are strongly correlated to sprite formation, only 50% of the +CGs with ELF slow tail magnitudes greater than 1.5 mV/m produced sprites on the two days studied. This means the occurrence of a +CG with a continuing current is a necessary but perhaps still not sufficient condition for production of sprites above LLTV thresholds. Whether or not slow tails are associated with the large +CGs which produce only elves remains unknown.

Figure 4-14 shows the broad band VLF sferics recorded in the near field for one of the sprites of 15 July 1995. The extremely intense sferic shows particularly strong low frequency (<3 kHz) components. It is unclear at this time whether near field VLF sferics can be used to unambiguously identify sprite producing CGs. By contrast, modulations in the signals from the U.S. Navy VLF transmitters have shown significant perturbations when sprites occur within ±50 km of the signal path (Figures 4-15 and 4-16). It would appear feasible to monitor signals from the various Navy transmitters (see Figure 3-63) at KSC and to automatically detect changes in amplitude above pre-defined thresholds. If these could be correlated with a large +CG event within ±50 km of the signal path, it would provide a diagnostic for a stroke with a high potential for being a sprite producer. The STAR Lab group is further proceeding during SPRITES'96 to establish a network of VLF receivers to monitor the NAA and NLK signals (Figure 4-17) in order to detect, locate and "image" by holographic methods the ionization produced by TLEs. A somewhat similar concept is being investigated by the University of Otago which has installed ten of their PC-based VLF OmniPAL receivers at sites along the Front Range (Dowden, 1993; Dowden et al., 1996). As a test of whether such methods are robust, we would propose that the analysts of these VLF data predict, in a blind test mode, when and where sprites are detected during periods of LLTV operation so that the detection capabilities of these systems can be evaluated.

4.4 Active Remote Sensing

A question that has only been minimally explored to date is whether active remote sensing techniques might be applied to sprite detection. Hoffman (1960) mentioned the observations of Atlas (1958) as evidentiary of the high current jet whistler generation hypothesis. Atlas presents a scope photograph showing a "sferic" extending above 80,000 ft (25 km). Another perspective is provided in Rumi (1957) who analyzed VHF (27.85 MHz) radar observations during the summer and fall of 1955 at Ithaca, NY, to provide useful information not only about lightning, meteors and aurora, but also about the possible existence and characteristics of "upwards discharges" from the top of the troposphere to the bottom of the ionosphere.

During SPRITES'95, the team from SRI International established a 28 MHz radar system at YRFS, but were only able to operate for four days. Weather conditions were marginal at best, with only one night having sprites within their 60 degree field of view, and those at a considerable distance. At this time, no definitive results have been released.

More recently Roussel-Dupre and Blanc (1996) reported on the presence of ionization possibly associated with high-altitude discharges using an HF radar operating at 2.2, 2.5, and 2.8 MHz in west Africa. On several occasions, echoes lasting several hundred ms at night and 1 to >10 s during the day were observed. These echoes generally correlated with lightning activity prior to their onset. The data are consistent with specular reflections from columns of ionization produced at 55-65 km altitude and with minimum electron densities of 6×10^4 - 10^5 cm^{-3}. The source of these echoes was proposed to be upward propagating discharges initiated by runaway air breakdown. If these electron densities can be confirmed, they are much higher than implied from some of the initial interpretations of sprite spectra. This has important implications not only for detectability using radar but also for mesospheric chemistry impacts.

4.5 Forecasting Techniques

In operations where alert lead times are required to be issued before the start of TLE occurrences, forecasting such conditions becomes a requirement. The same techniques can also be used to diagnose meteorological conditions in which, in lieu of actual observations, sprites can be assumed with some degree of confidence.

During the 1994 and 1995 Colorado campaigns it was necessary to prepare nightly nowcasts of sprite viewing potential based upon available meteorological information, which included radar reflectivity, GOES infrared cloud images and real-time NLDN plots of polarity-designated CG data. By using the criteria that the radar echo must have a contiguous area of greater than 20-25,000 km^2 and +CGs were typically 5% percent or more of the total, we would nowcast the development of sprites within the next two hours. Figure 4-18 shows the radar echo size distribution for a sub-set of the 1994 storm systems surveyed. For cells less than 20,000 km^2, even those with intense CG activity, including many positives, sprites were not observed over the U.S. High Plains. While there may be exceptions to this rule, it remains to be documented. During 1994, 27 of the 31 sprite nowcasts issued based on the above criteria were correct. The probability of detection was 0.89 with a critical success index of 0.82.

The same criteria were employed during SPRITES'95. Figure 3-1 lists the forecasts made and the number of sprites that were observed. All storms for which sprites were forecasted eventually produced one or more sprites. The radar echo size criteria again proved to be an effective discriminator between storms which did and did not produce sprites. The correlation between radar echo area and the number of sprites, however, is far less robust as can be seen by the plot of echo size versus the observed sprite count (Figure 4-19).

The combined forecast statistics from 1994 and 1995 are shown in Figure 4-20. For a total of 67 storms for which forecasts were made at the beginning of the observation period, 94% of the categorical (Yes/No) forecasts proved correct. The probability of detection was 0.94 with a low false alarm rate of 0.08. The critical success index (CSI) was 0.93 and the true skill score (TSS) was 0.86. These numbers, by comparison to nowcasts for severe storm phenomena such as tornadoes, are very good.

It remains to be seen, however, whether the same rules can be applied universally. It is conceivable that deep tropical convection might generate sprites from storms with different morphological features. We note that in the several airborne sprite reconnaissance missions over Peru, Brazil and Central America made by the GI/UOA team, relatively few sprites were imaged. In those cases presented at conferences, most of the cells that generated sprites, at least as determined by satellite imagery, typically had minimum scale lengths on the order of 100-150 km on a side.

Follow on efforts in prediction studies should also plan to monitor more of the smaller storms. Intense super cells storms, often associated with hail and very active lightning, including a large number of +CG flashes, are not uncommon along the Front Range (Figure 4-21). While many dissipate before sunset, thus preventing LLTV monitoring, some survive into the night hours. Verifying the lack of sprites (but maybe not blue jets?) from a greater population of such systems would be of interest.

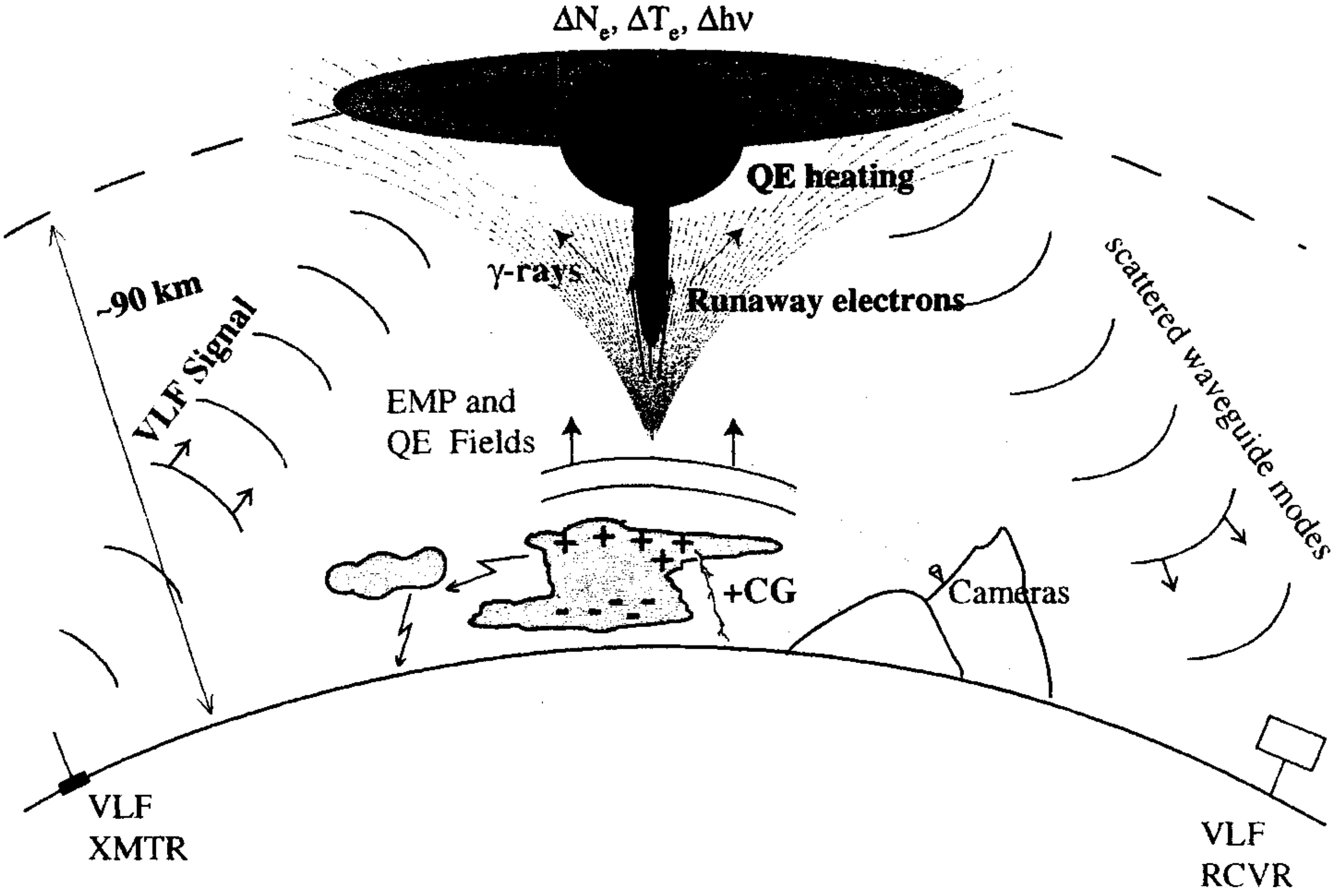


Illustration* of different mechanisms of lightning-ionosphere interactions operating at different altitudes and producing optical emissions ($\Delta\nu$) observed as sprites and elves, as well as heating (ΔT) and ionization changes (ΔN) detected as very low frequency (VLF) signal changes.

*Prepared at Stanford University

Figure 4-1.

Figure 4-2. A well developed sprite with tendrils extending both downward and outward as it approaches the underlying cloud.

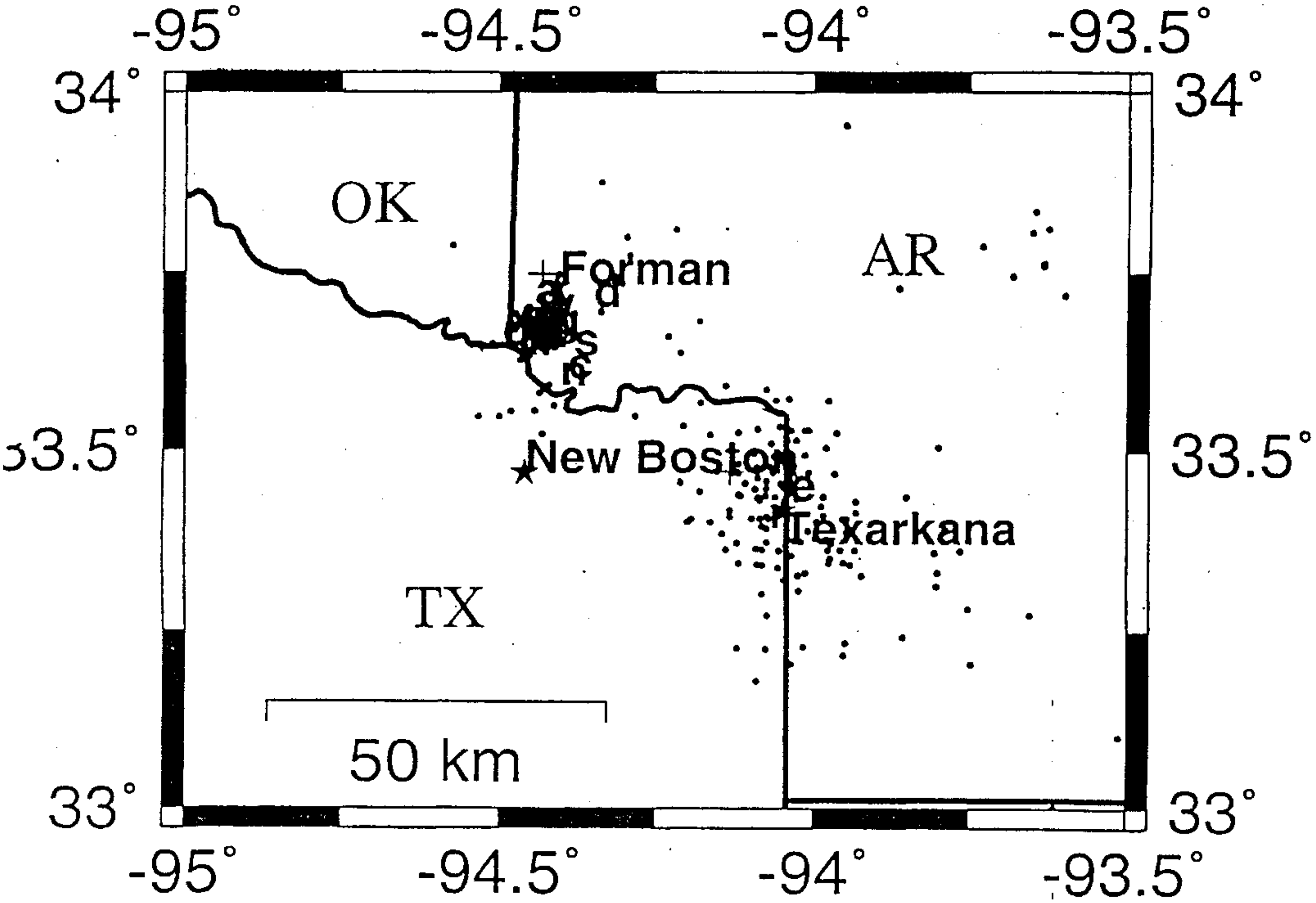


Figure 4-3. NLDN lightning plots associated with the 1 July 1994 hail storm that generated a large number of blue jets observed by the GI/UOA team. Map courtesy Gene Wescott.

BLUE JETS

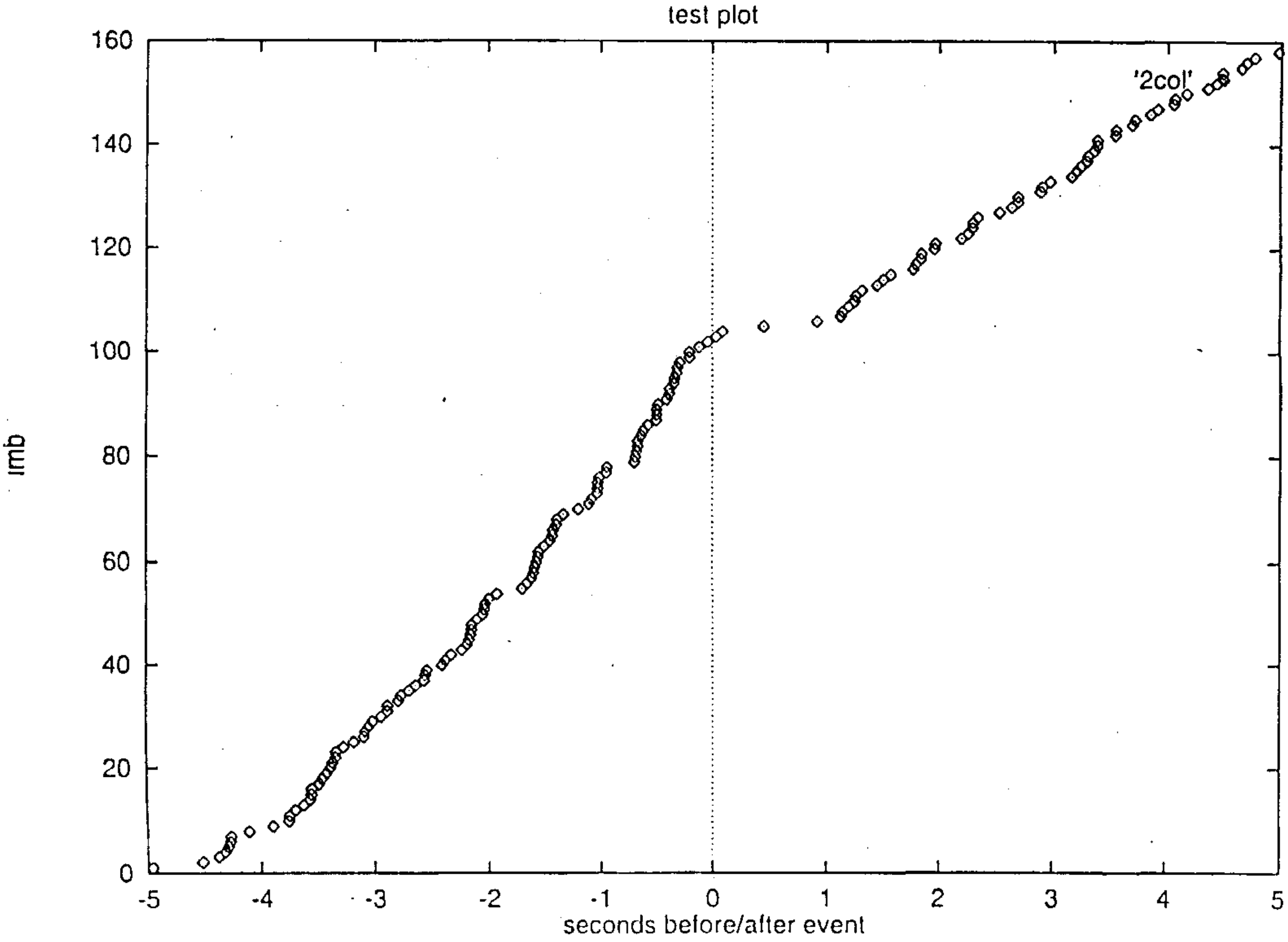


Figure 4-4. Cumulative frequency of the occurrence of CG flashes with respect to the start of blue jets. There is a distinct lull for more than a second after the jet starts. Courtesy Gene Wescott.

Want to Go Sprite Hunting?

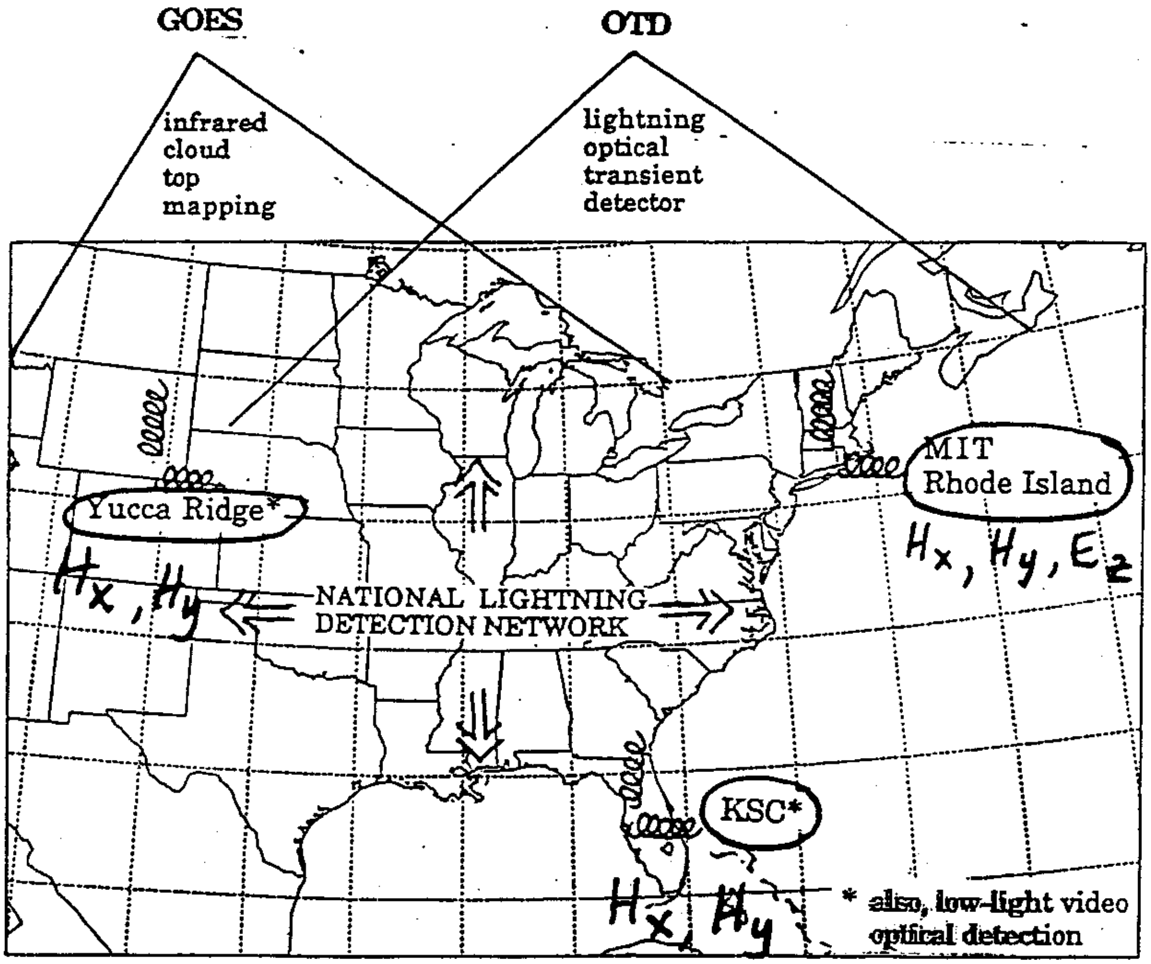
Now that we know about all the "electrical action" above the clouds, a natural question is: can we see and photograph them?

The answer is yes, sort of.... Taking standard photographs will not work unless you have a film with an ASA of 2 million (don't bother to ask). To make images, you need a low light video system. But under certain circumstances you can see sprites with the naked eye. Here's how.

Sprites occur high above large thunderstorm systems. Since they are so high, it is much easier to see them if they are more than hundred miles away. But not every thunderstorm produces sprites, even if it has vigorous lightning. To improve your chances, check out the radar echoes on your local TV or the Weather Channel. Look for thunderstorm systems that are at least 100 miles on a side. Find a location with a good view of the horizon. The further away from the city lights, the better. Also a dark night, without any moon helps a lot. Let your eyes adapt to the dark for at least ten minutes. Look in the direction of the big storms. If you can see the illuminated tops of the distant storms, shield your eyes from the lightning flashing within the clouds. Concentrate your view at an altitude about 5 times the high of the cloud top - not the storm itself. Then be patient. In the most active storms, sprites occur every one or two minutes, but every five to ten minutes is more likely. They literally occur in the blink of an eye. and often you are more likely to perceive them out of the corner of your eye. What will you see? To many it looks like the aurora borealis turning on and off in an instant. Their true color is salmon red, but at such low light levels eyes play tricks and you might think it green, orange or white. The best places for sprite watching? Probably the northern High Plains of the U.S. in a broad belt from Colorado to Minnesota.

Elves occur far too quickly, one half thousandths of a second, to be perceived by the human eye. The extremely rare blue jets can be seen with the naked eye. They appear to shoot out of cloud tops as blue flames and may go to altitudes 2 or 3 times that of the cloud. Large hail storms may be the best blue jet candidates.

Figure 4-5. Text for 1996 "Weather Guide Calendar", Accord Publishing Co.



PROPOSED PROTOTYPE Q-BURST LOCATION NETWORK

Figure 4-6. Proposed prototype Q-burst location network using multi-station direction finding techniques.

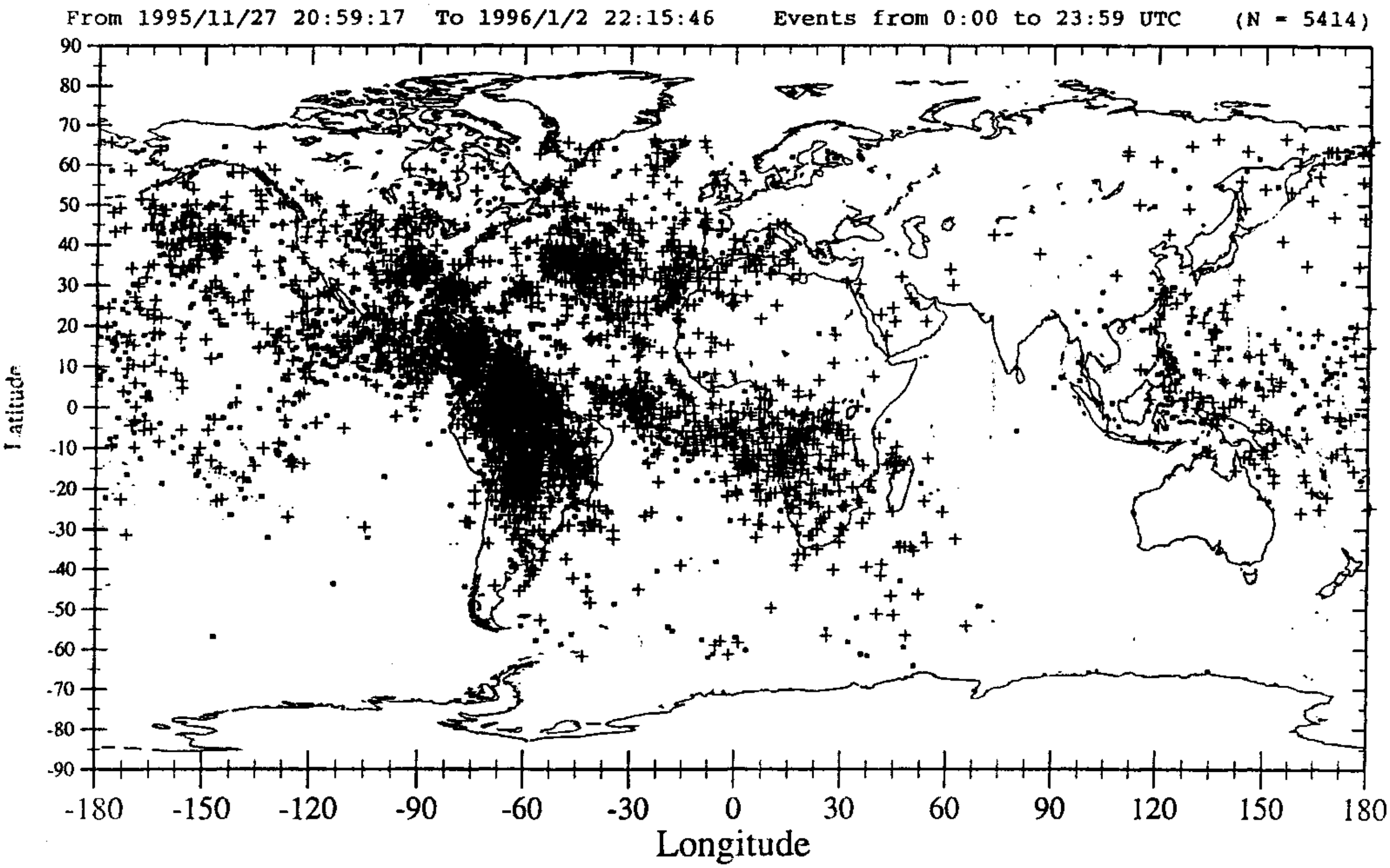


Figure 4-7. ELF transient locations over a six week period using single station techniques developed by Wong (1996) and described in Williams et al. (1996).

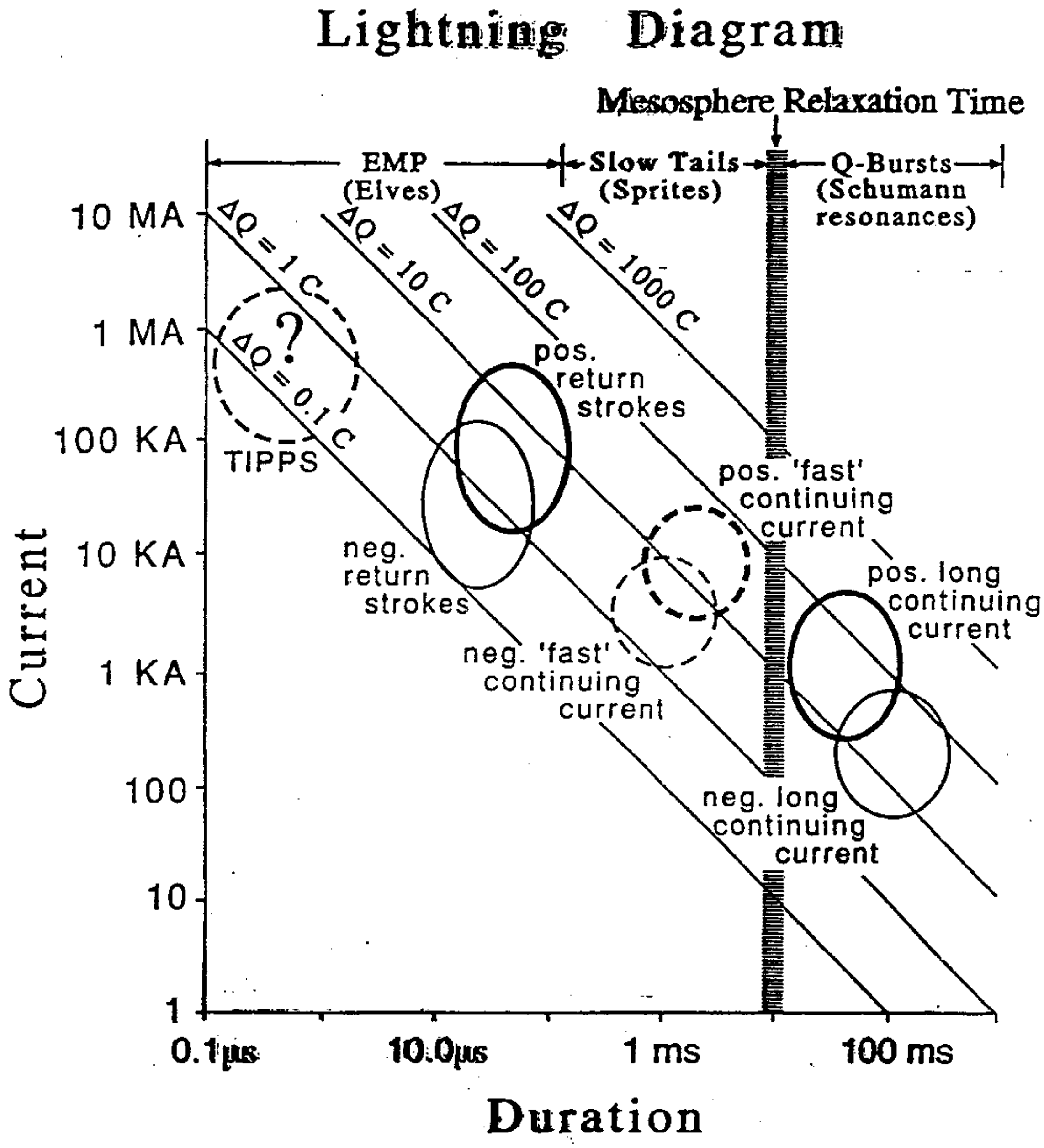
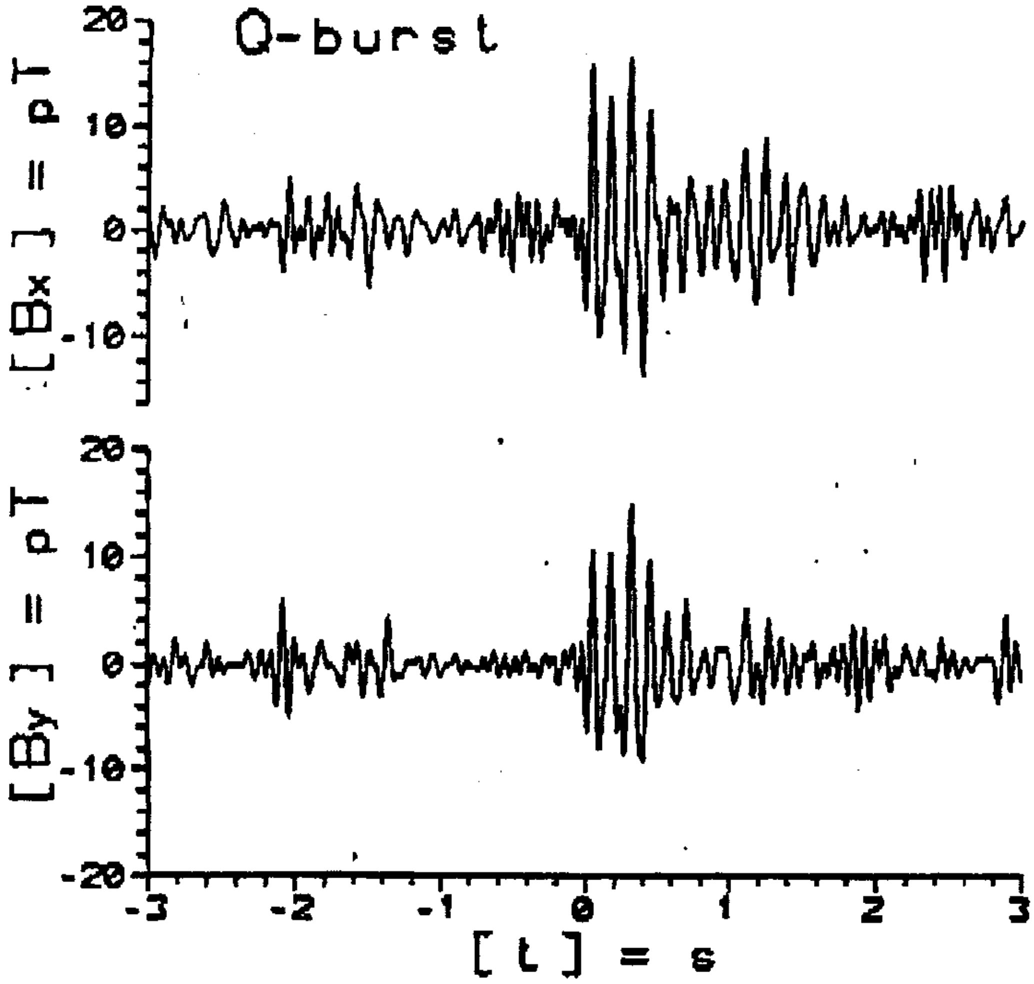
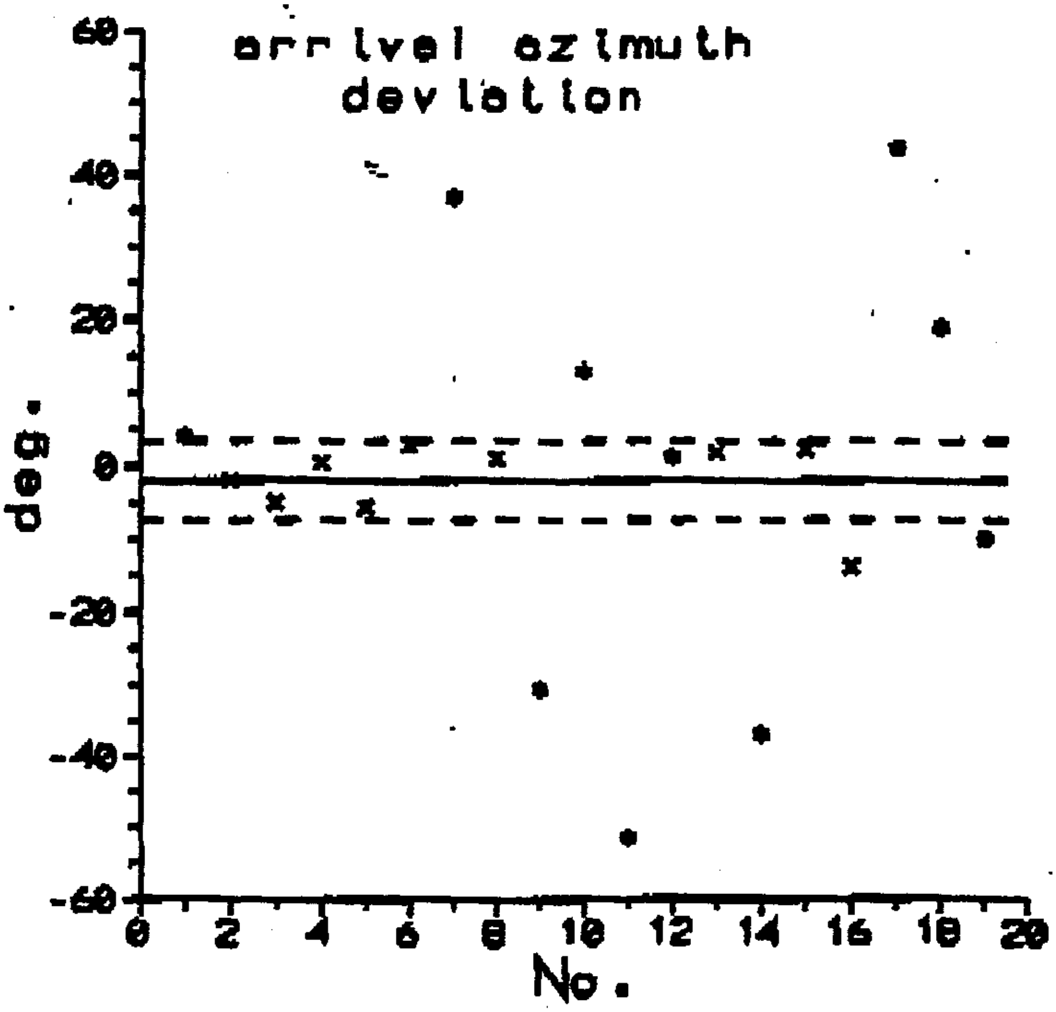


Figure 4-8. A possible ordering of the response of the atmosphere to lighnting discharges of differing peak currents and durations, as proposed by Williams et al. (1996).



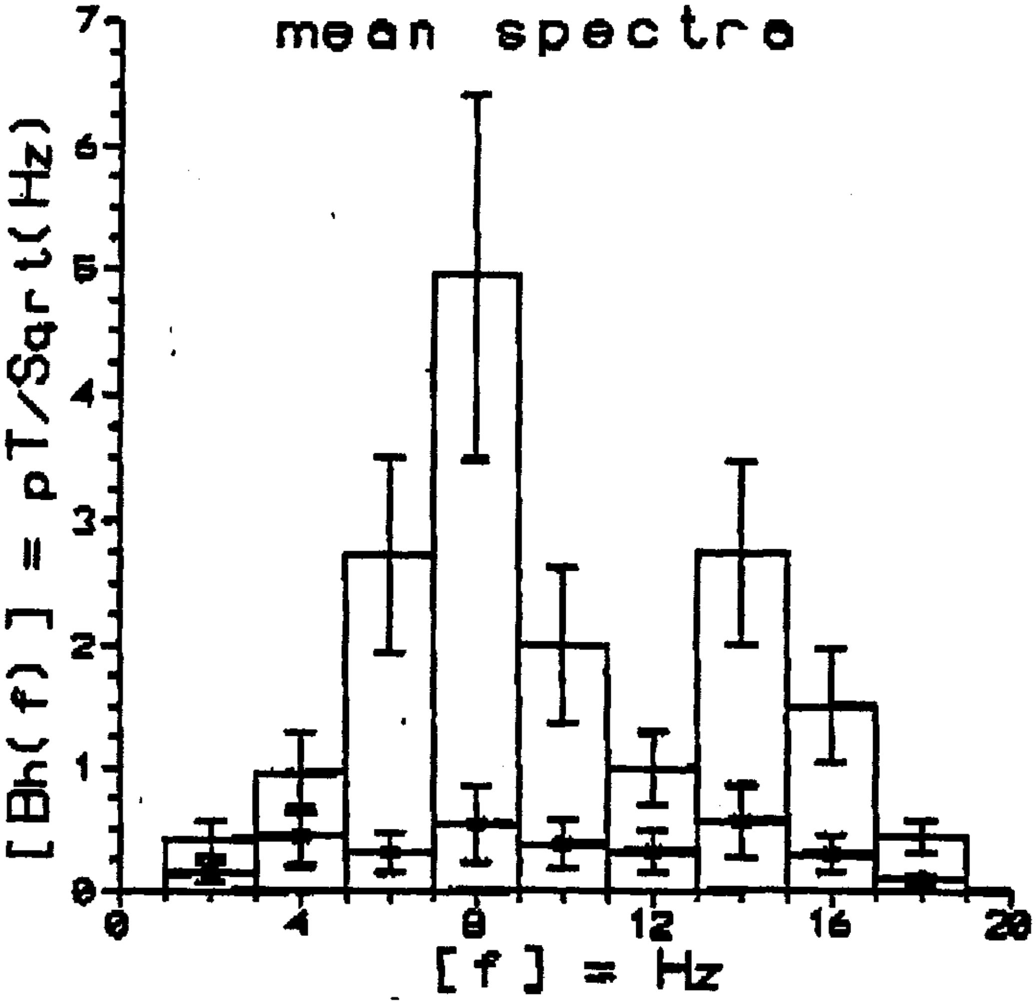
Time series of the magnetic north (B_x) and east (B_y) directions at Silberborn around the sprite occurrence No. 5 at 0.00 seconds.

Figure 4-9. Source: Fullekrug et al. (1996).



Deviation of the measured arrival azimuth from the expected value according to the orientation of the Poynting vector along the great circle path.

Figure 4-10: Source: Fullekrug et al. (1996).



Mean spectral composition of low ((*) labeled lower bars) and high (upper bars) horizontal magnetic intensity at Silberborn.

Figure 4-11: Source: Fullekrug et al. (1996).

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SECTION 4

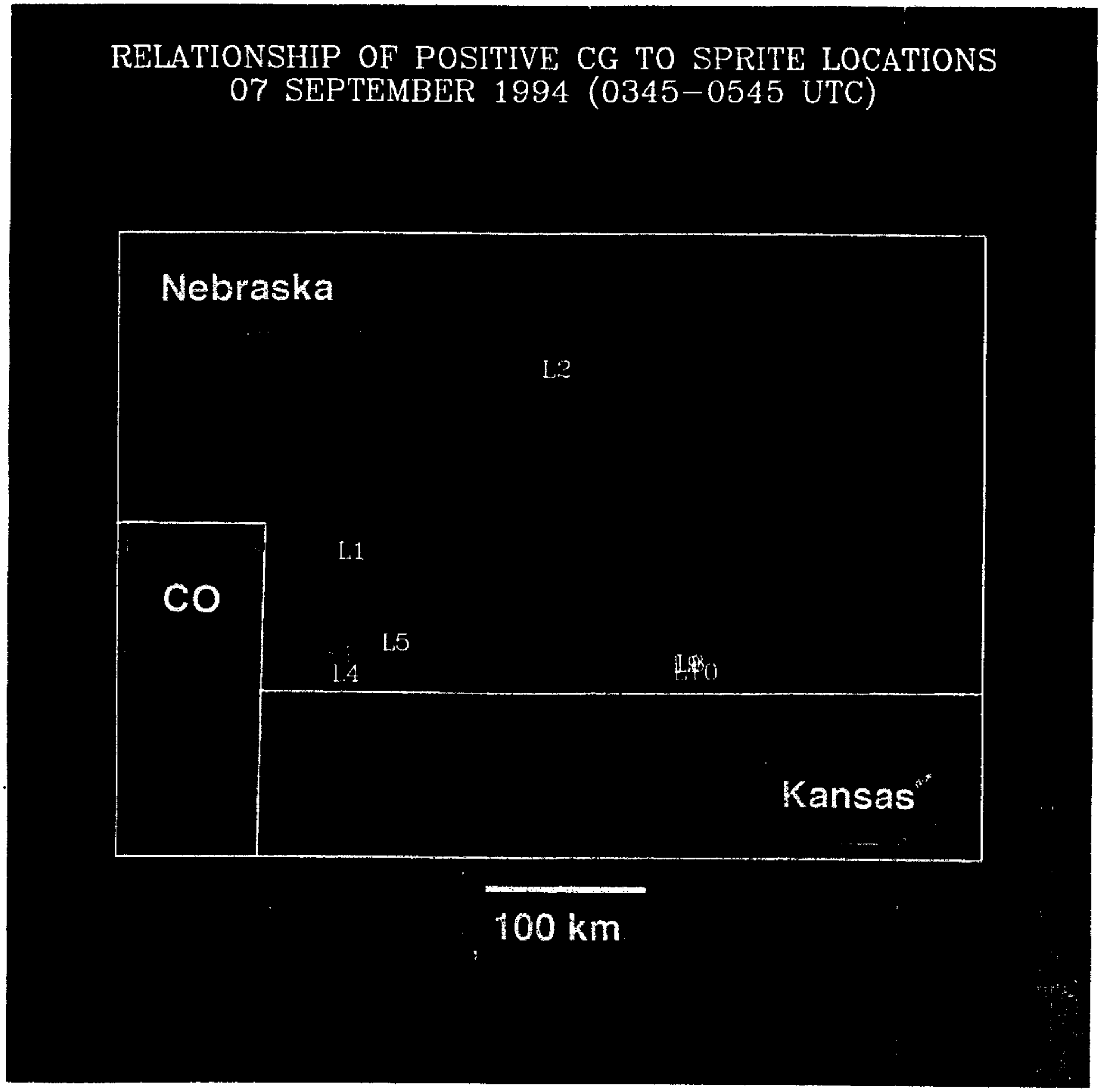

Figure 3-18. Comparative locations of the parent +CG flashes (indicated by L) versus the center of their associated sprites (S) as determined by dual image photogrammetry conducted by Perry Malcolm.

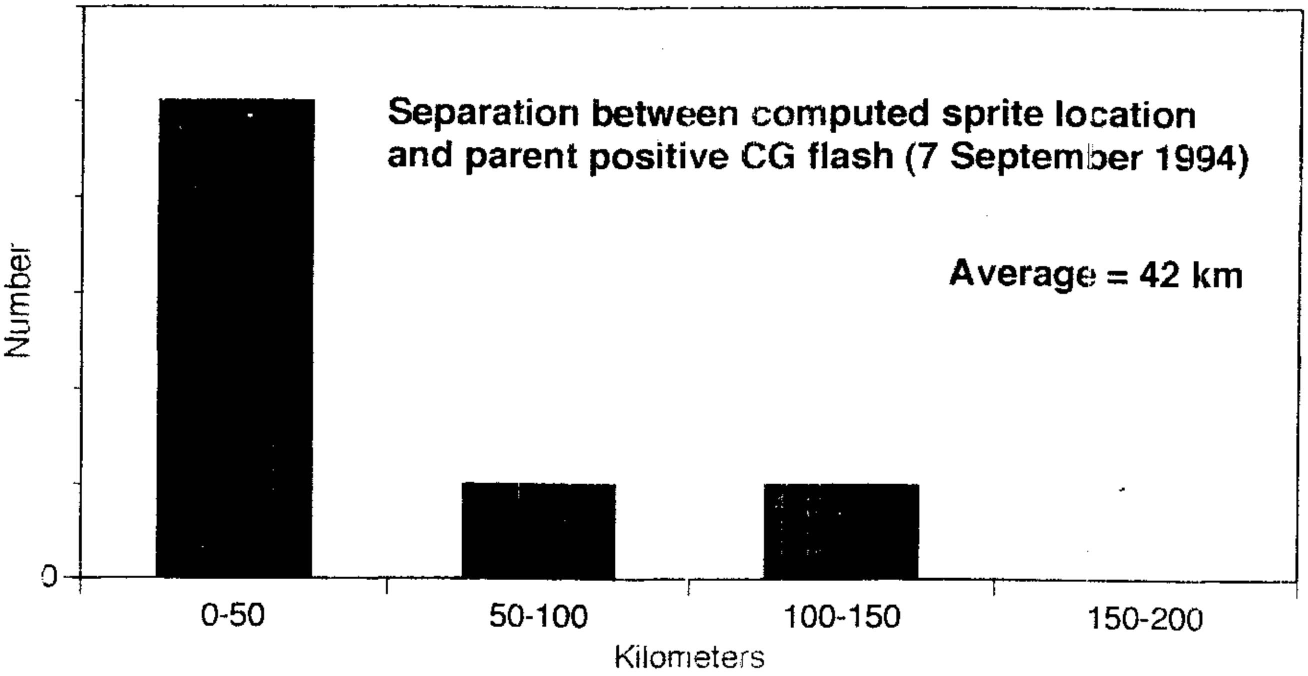

Figure 3-19. Histogram of the spatial separations between the location of the sprite +CG and the center of the sprite for the 7 September 1994 case.

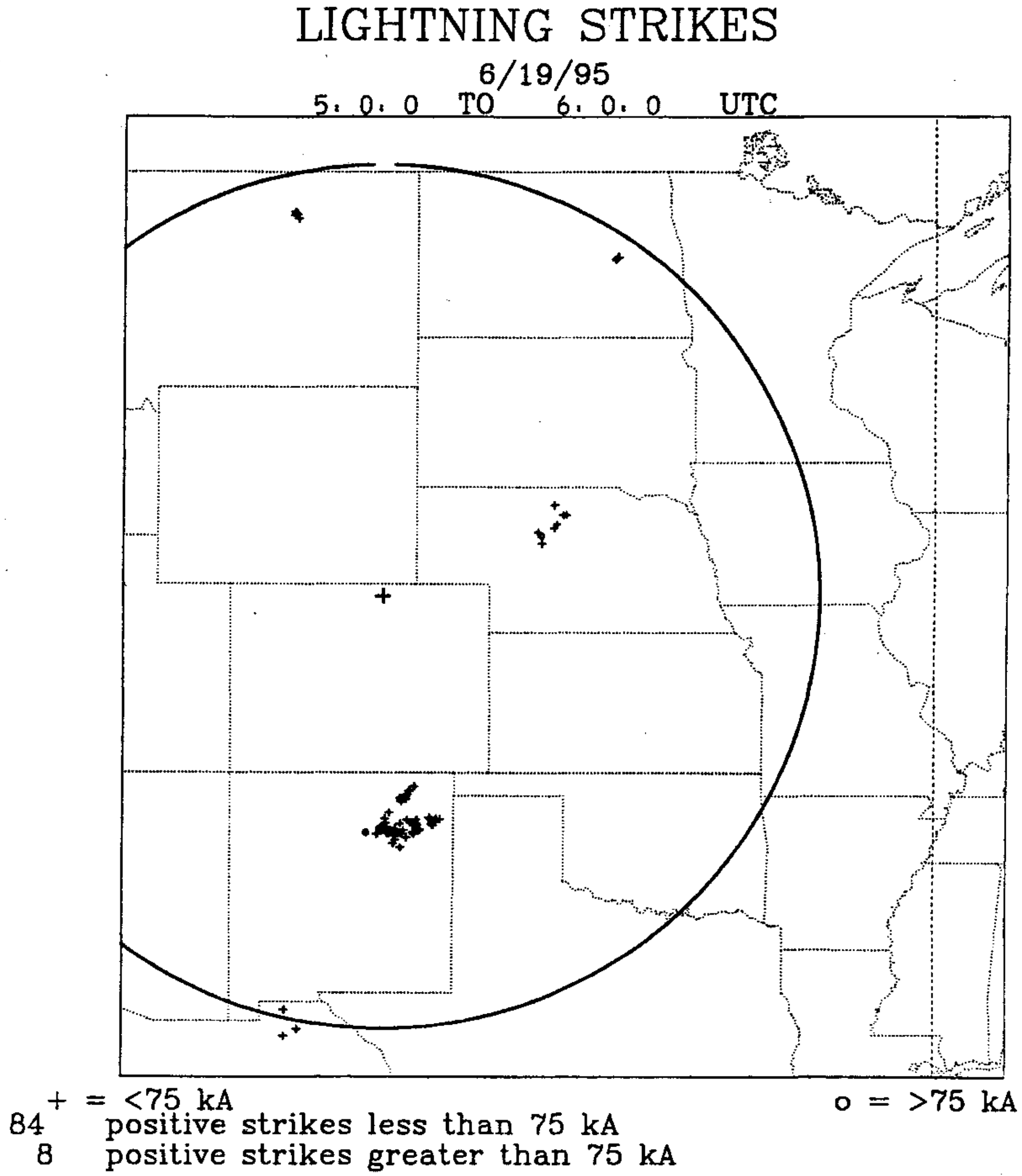

Figure 3-20. Positive CG locations between 0500 and 0600 UTC 19 June 1995 outline a storm in northeastern New Mexico being imaged by both the YRFS camera (+) and the GI/UOA camera (atop Mt. Evans, west of Denver).

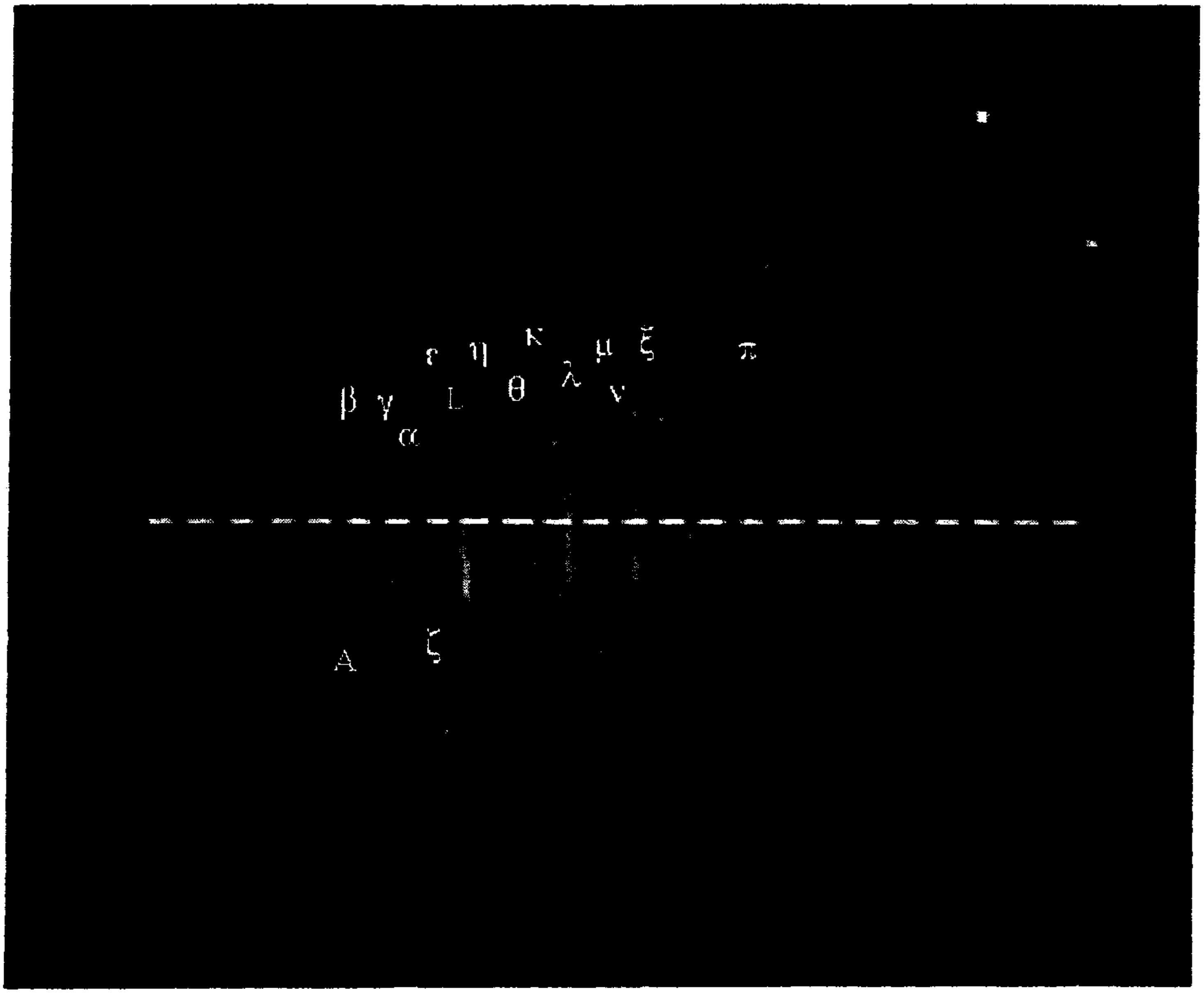

Figure 3-21. Sprite at 0635 UTC 1 June 1995 taken by GI/UOA Mt. Evans camera. Greek letters refer to individual elements identified and located. Courtesy Gene Wescott.

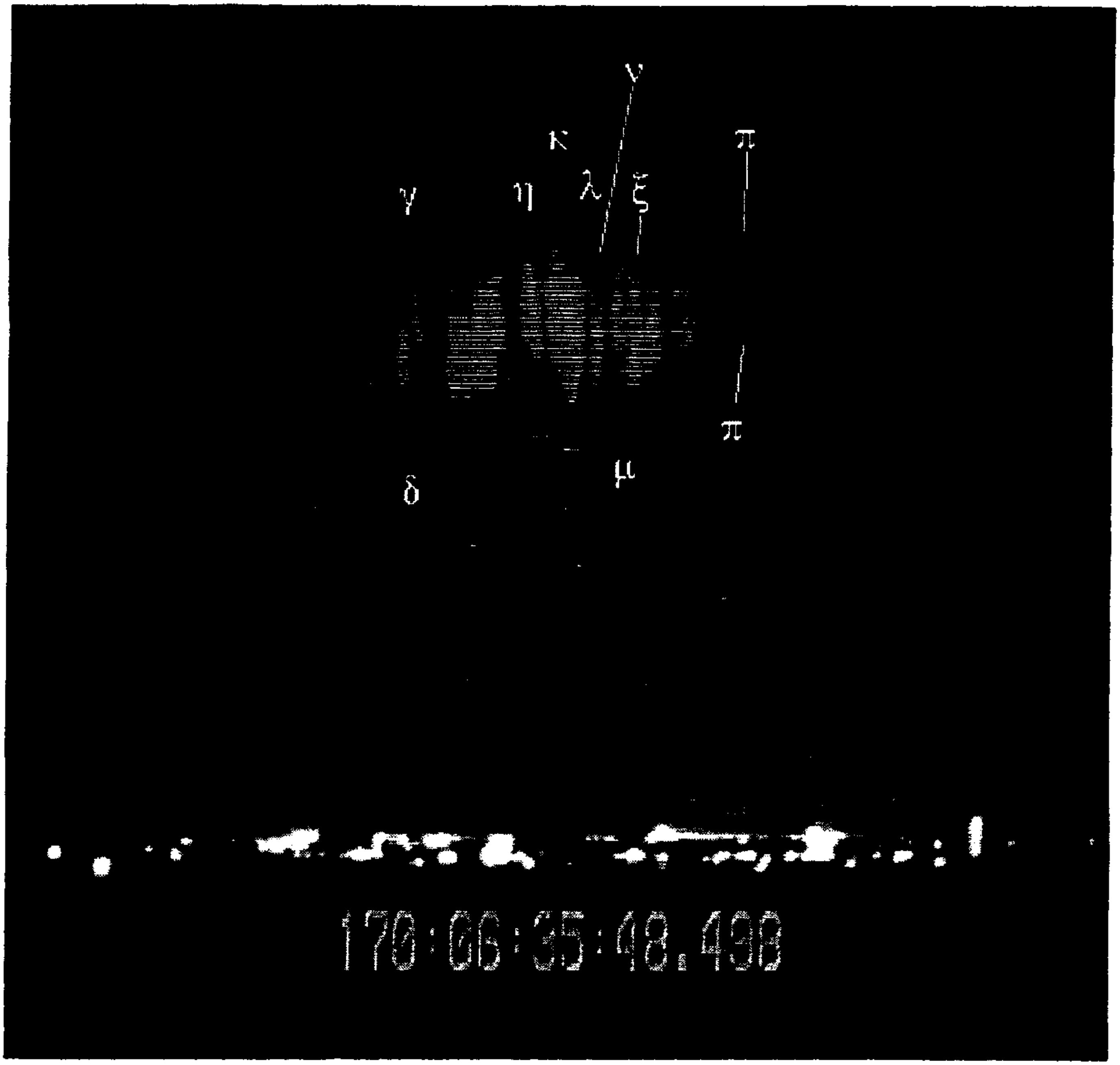

Figure 3-22. Same sprite as previous figure, taken by YRFS camera.

06 35 48.584	35.898	-103.642	85.513	Top of sprite α, ΔS = 27.19 km.
	35.916	-103.585	84.844	Top of sprite A, ΔS = 28.08 km.
	35.934	-103.595	75.631	Bottom of sprite A.
	36.195	-103.734	86.375	Top of sprite γ, ΔS = 8.93 km.
	36.175	-103.733	76.623	Bottom of sprite.
	35.917	-103.730	89.452	Top of sprite ϵ, ΔS = 22.82 km.
	35.983	-103.761	79.085	Bottom of sprite ϵ.
	36.107	-103.854	86.741	Top of sprite ι, ΔS = 7.67 km.
	36.104	-103.851	75.827	Bottom of sprite ι.
	36.198	-103.928	85.296	Top of sprite η, ΔS = 16.60 km.
	36.160	-103.919	75.296	Bottom of sprite η.
	36.170	-103.965	86.982	Top of sprite θ, ΔS = 18.34 km.
	36.153	-103.956	77.369	Bottom of sprite θ.
	36.156	-103.988	83.752	Top of sprite κ, ΔS = 19.95 km.
	36.104	-103.963	73.622	Bottom of sprite κ.
	35.901	-103.936	88.815	Top of sprite λ, ΔS = 14.93 km.
	35.901	-103.941	74.109	Bottom of sprite λ.
	36.033	-104.034	86.958	Top of sprite μ, ΔS = 25.58 km.
	36.023	-104.028	76.196	Bottom of sprite μ.
	35.892	-104.037	88.898	Top of sprite ξ, ΔS = 34.86 km.
	35.870	-104.025	75.907	Bottom of sprite ξ.
	35.877	-104.082	87.449	Top of sprite o, ΔS = 38.89 km.
	35.877	-104.080	77.479	Bottom of sprite o.
	35.956	-104.226	87.915	Top of sprite π, ΔS = 44.80 km.
	36.026	-104.239	77.247	Bottom of sprite π.
	35.917	-103.729	84.388	Top of sprite ζ, ΔS = 22.83 km.
	35.919	-103.729	75.671	Bottom of sprite ζ.
06 35 48.484	**36.120**	**-103.770**		**+83.8 stroke.**

Figure 3-23. Sample of dual-image photogrammetry for 0635 UTC sprite performed by GI/UOA. Courtesy Gene Wescott.

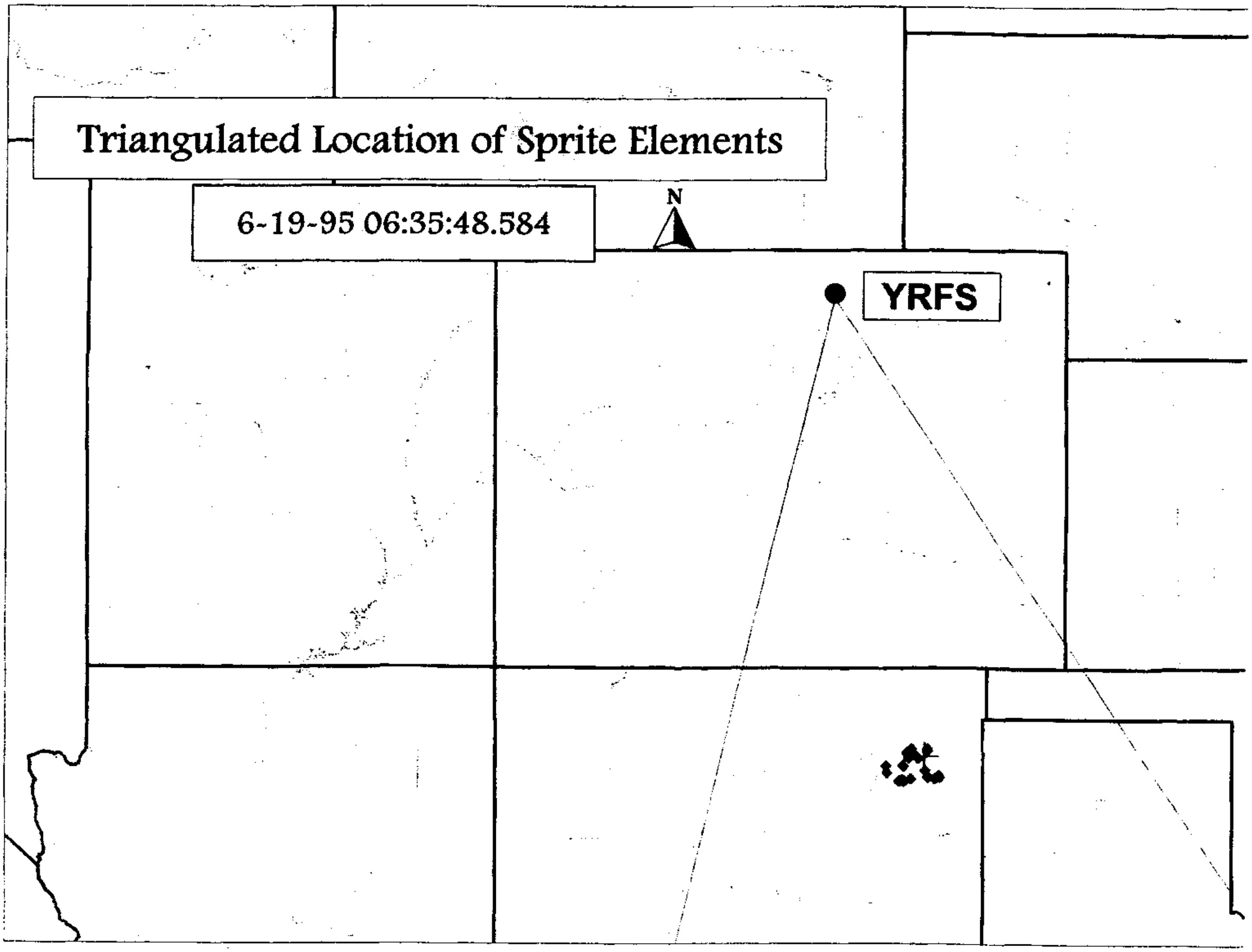

Figure 3-24. Triangulated location of sprite elements from 0635 UTC 19 June 1995 sprite. Cross marks NLDN location of parent +CG.

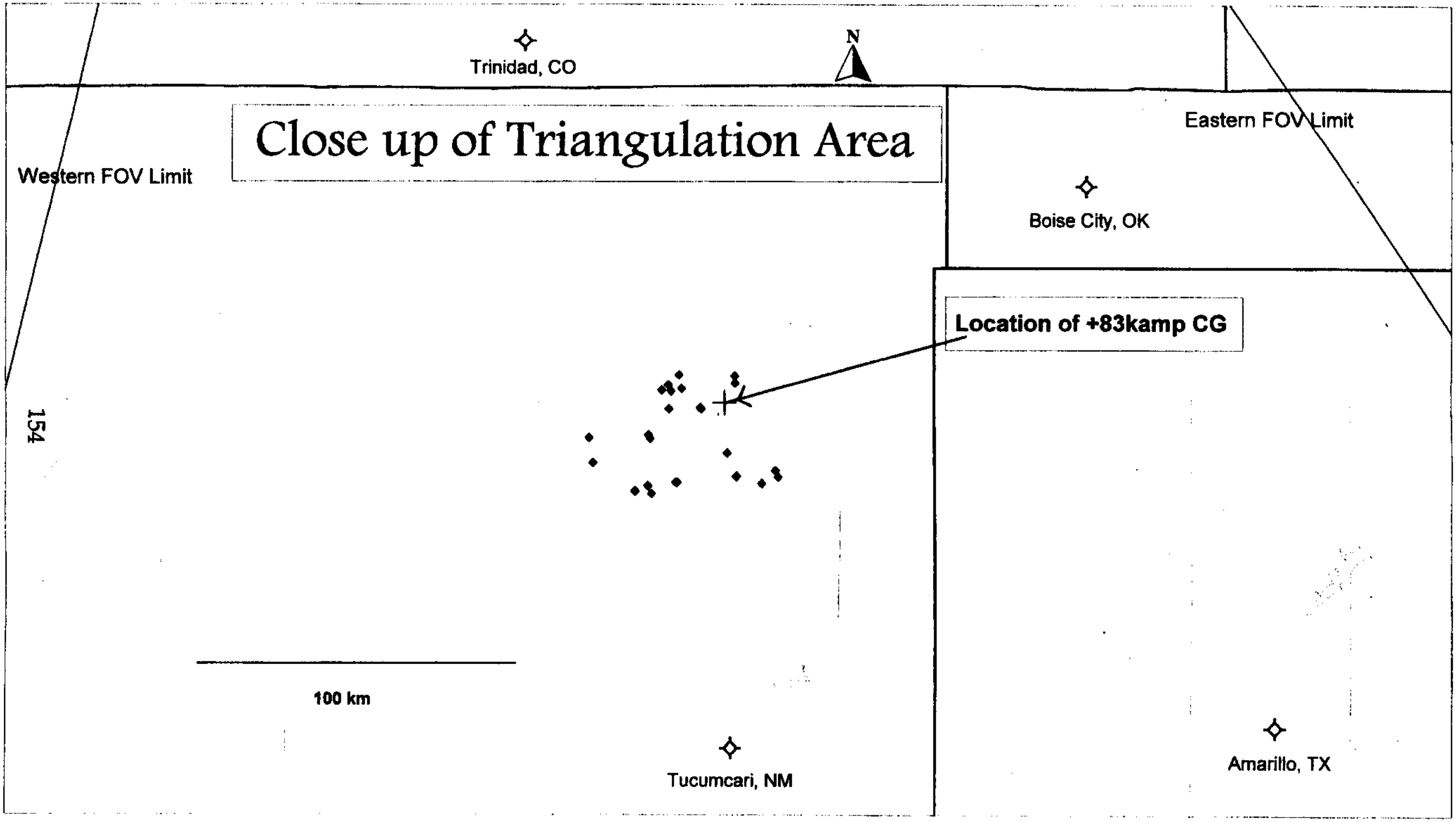

Figure 3-25. Close up of previous figure showing the relationship of the various sprite elements to the parent +CG.

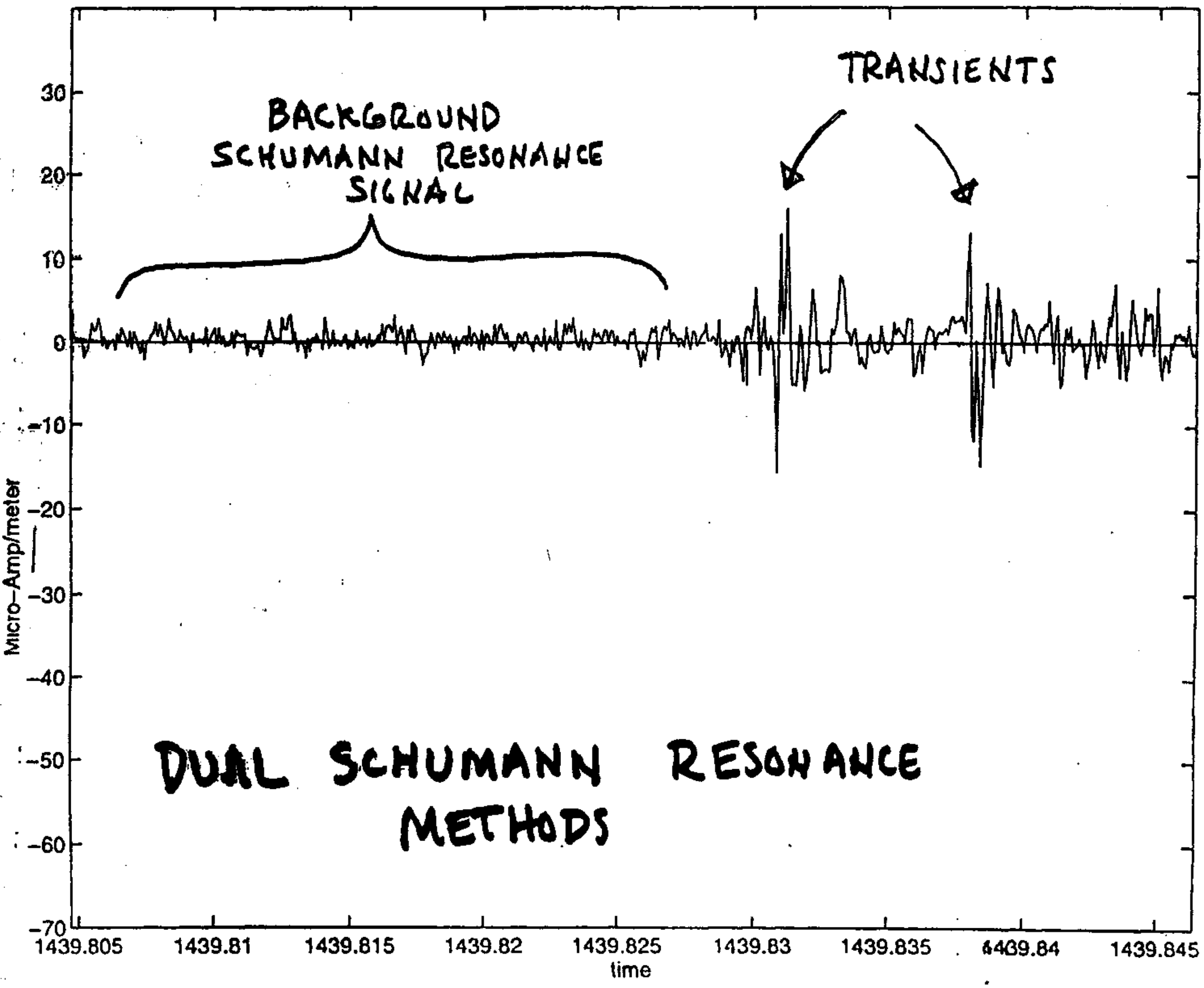

Figure 3-26. Example of Schumann resonance data collected at MIT Rhode Island site, including both the background signal and several Q-burst ELF transients. Courtesy Earle Williams.

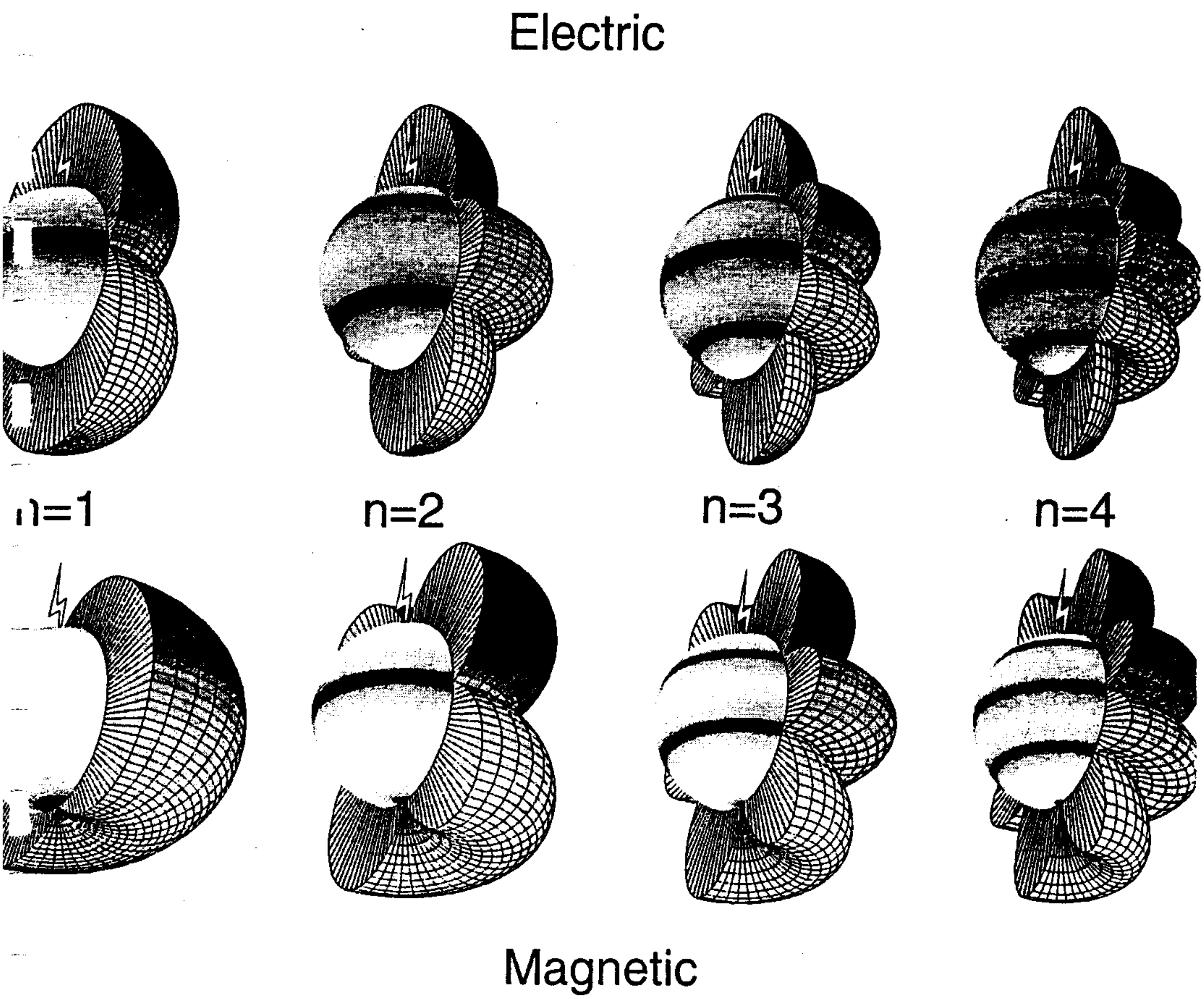

Figure 3-27. Examples of the lowest four modes of the Schumann resonance wave form propagation in the Earth-ionosphere waveguide as simulated by Sentman (1996).

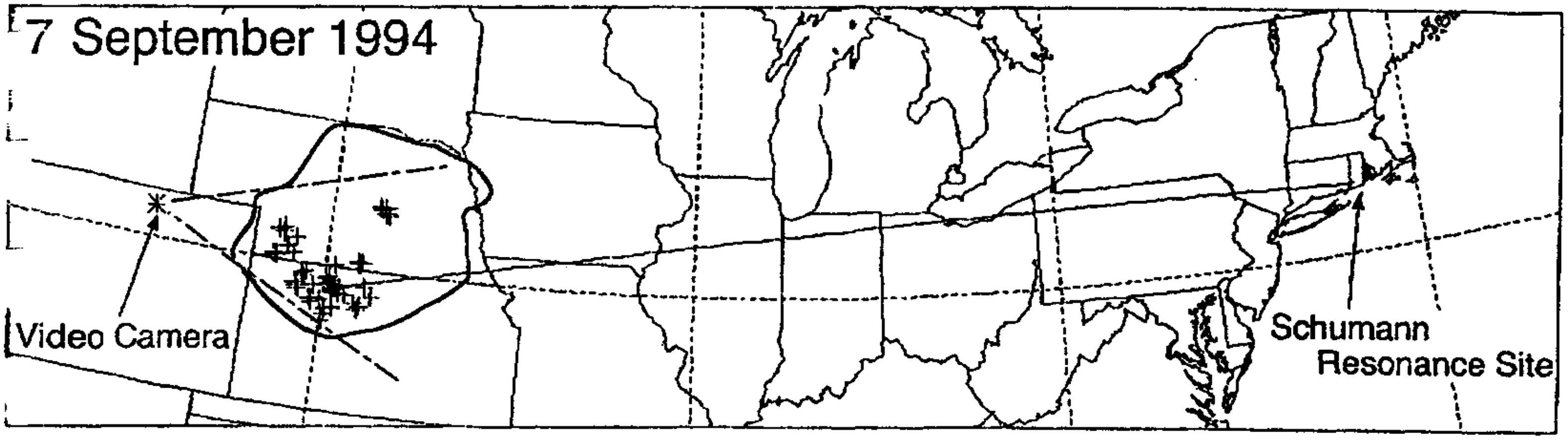

Figure 3-28. Experimental design for monitoring optical sprites and Q-bursts on night of 7 September 1994. The MIT Schumann resonance site was located in West Greenwich, RI about 2700 km east of YRFS. Source: Boccippio et al. (1995).

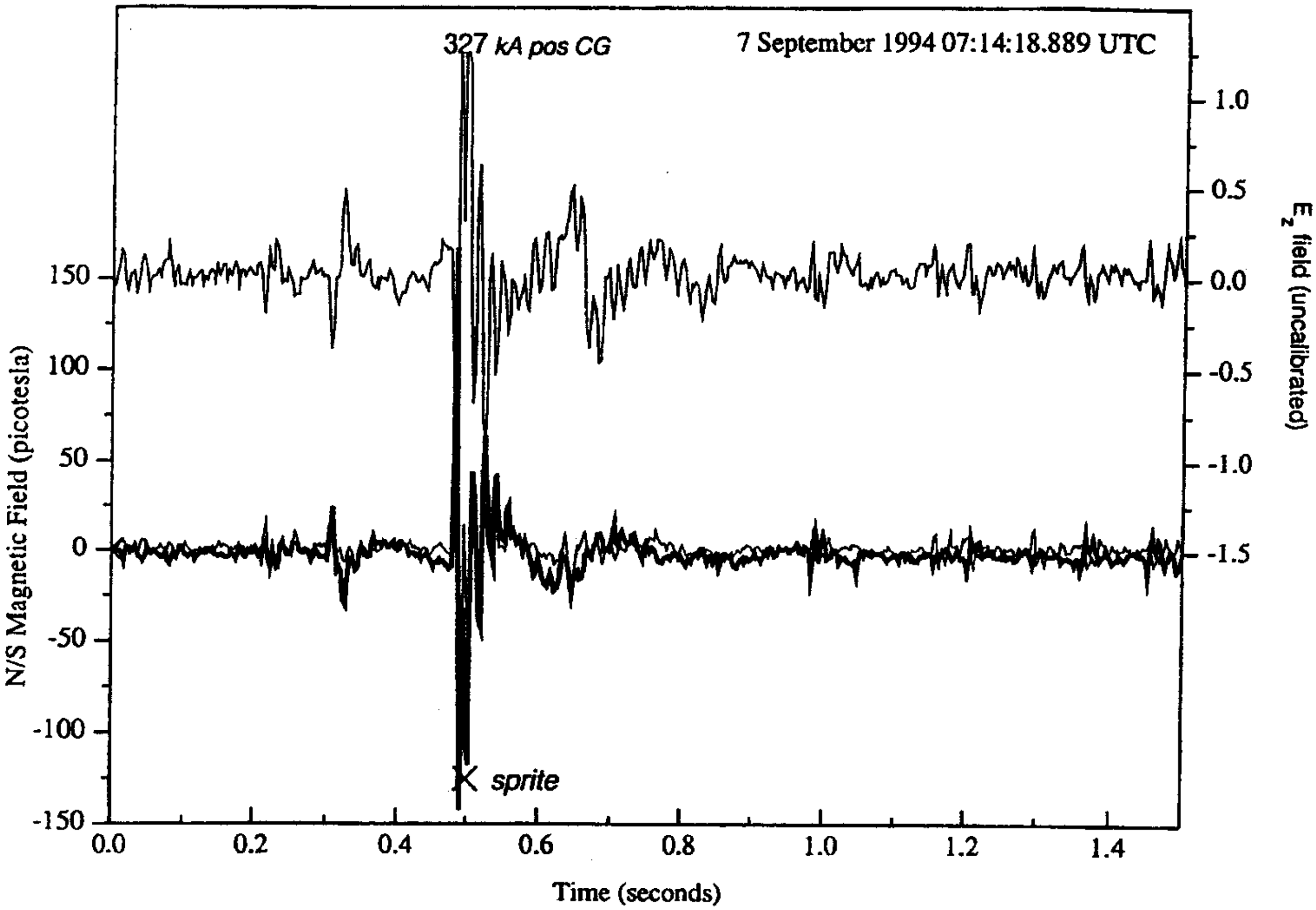

Figure 3-29. Example of Q-bursts as indicated by the vertical electric field and N-S magnetic field intensity recorded in Rhode Island for a sprite at 0714.18 UTC 7 September associated with a 327 kA +CG. Source: Boccippio et al. (1995).

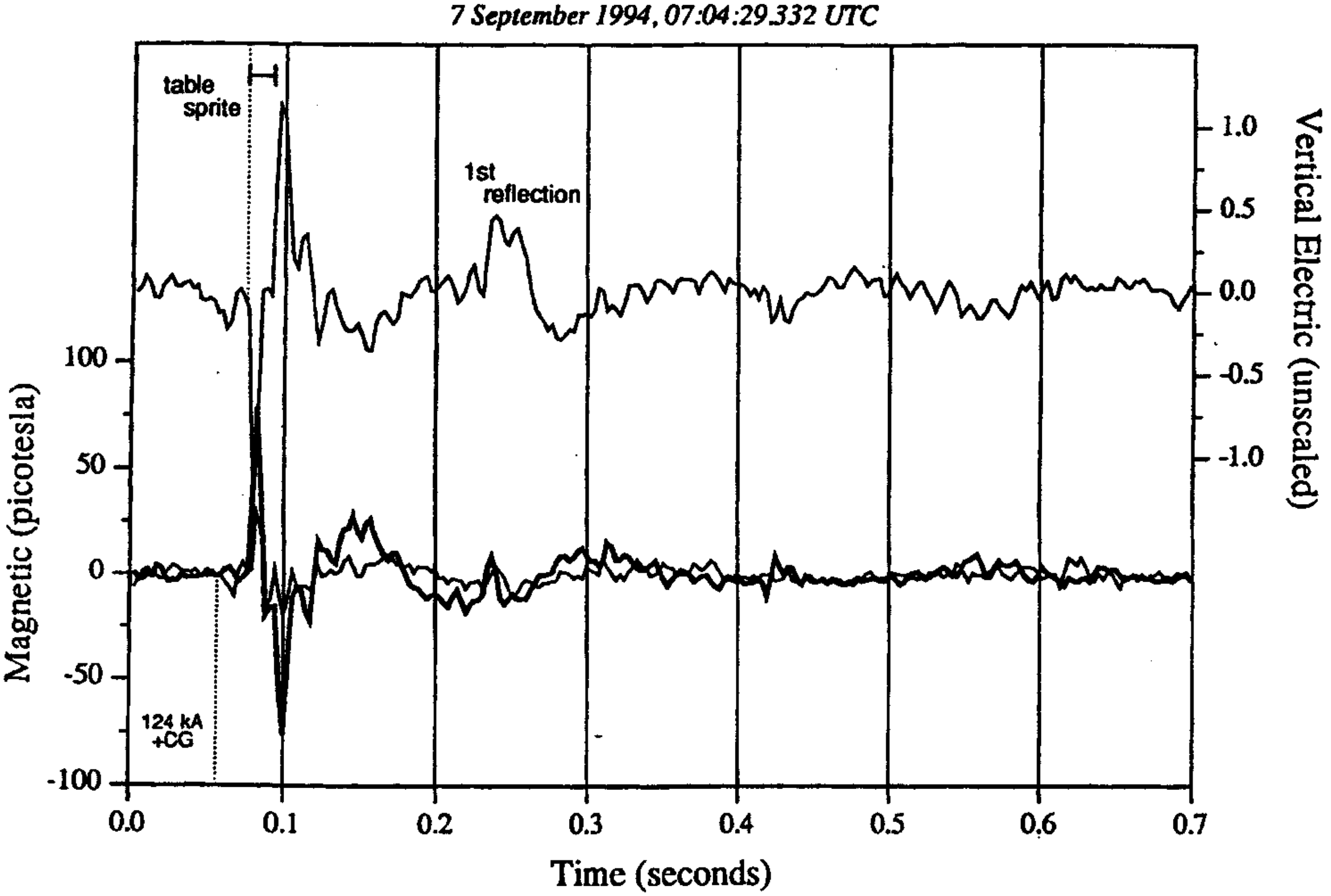

Figure 3-30. The same as the previous figure except for the optical sprite/Q-burst/+CG event of 0704.29 UTC. Source: Boccippio et al. (1995).

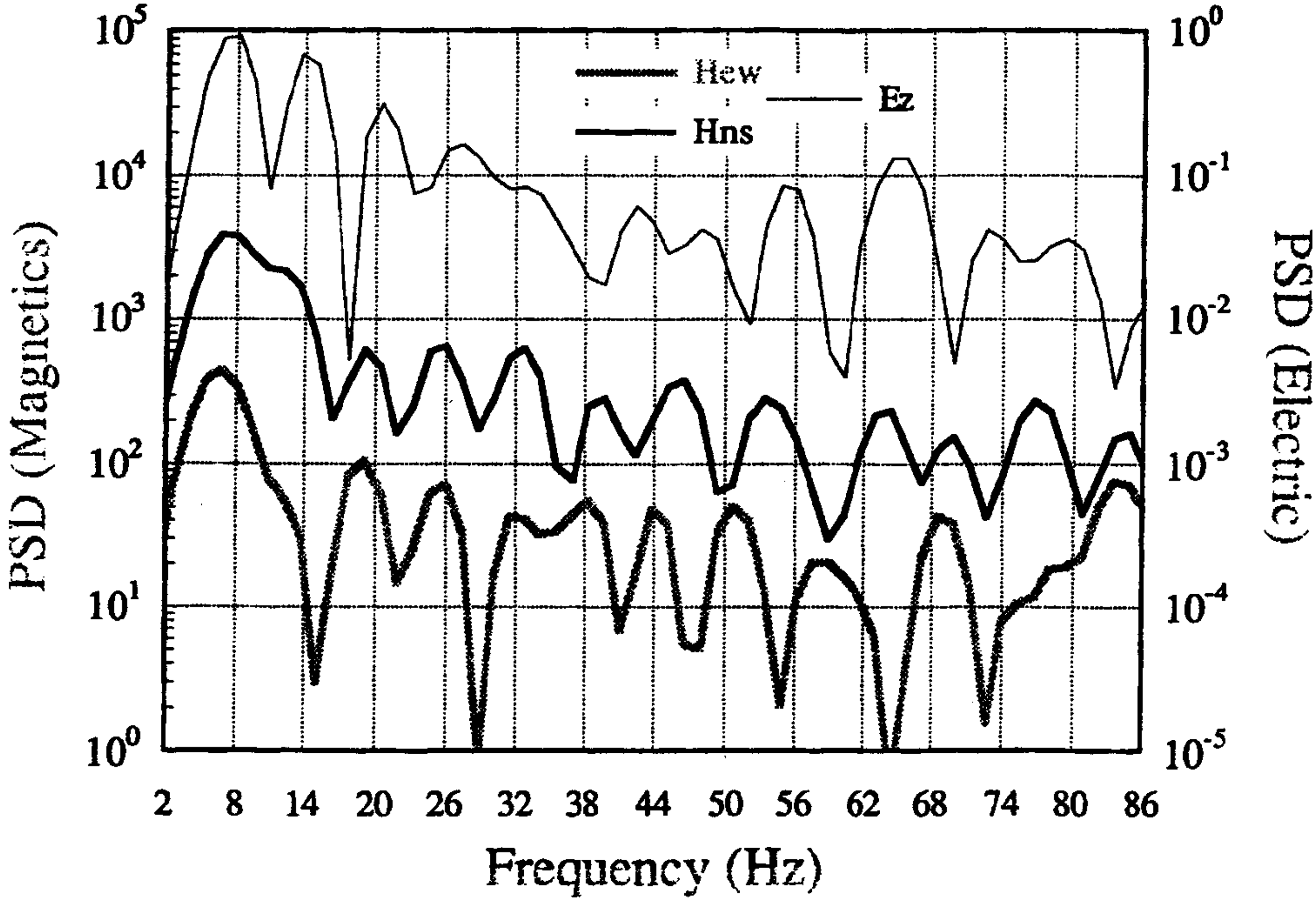

Figure 3-31. Spectral decomposition of a Q-burst from 0714.18 UTC 7 September 1994. Theory predicts that the SR modes should be spaced by approximately 6 Hz, beginning with the fundamental mode at 8 Hz. The fundamental and higher mode structure are well resolved in this event, substantiating the global nature of the transient. Source: Boccippio et al. (1995).

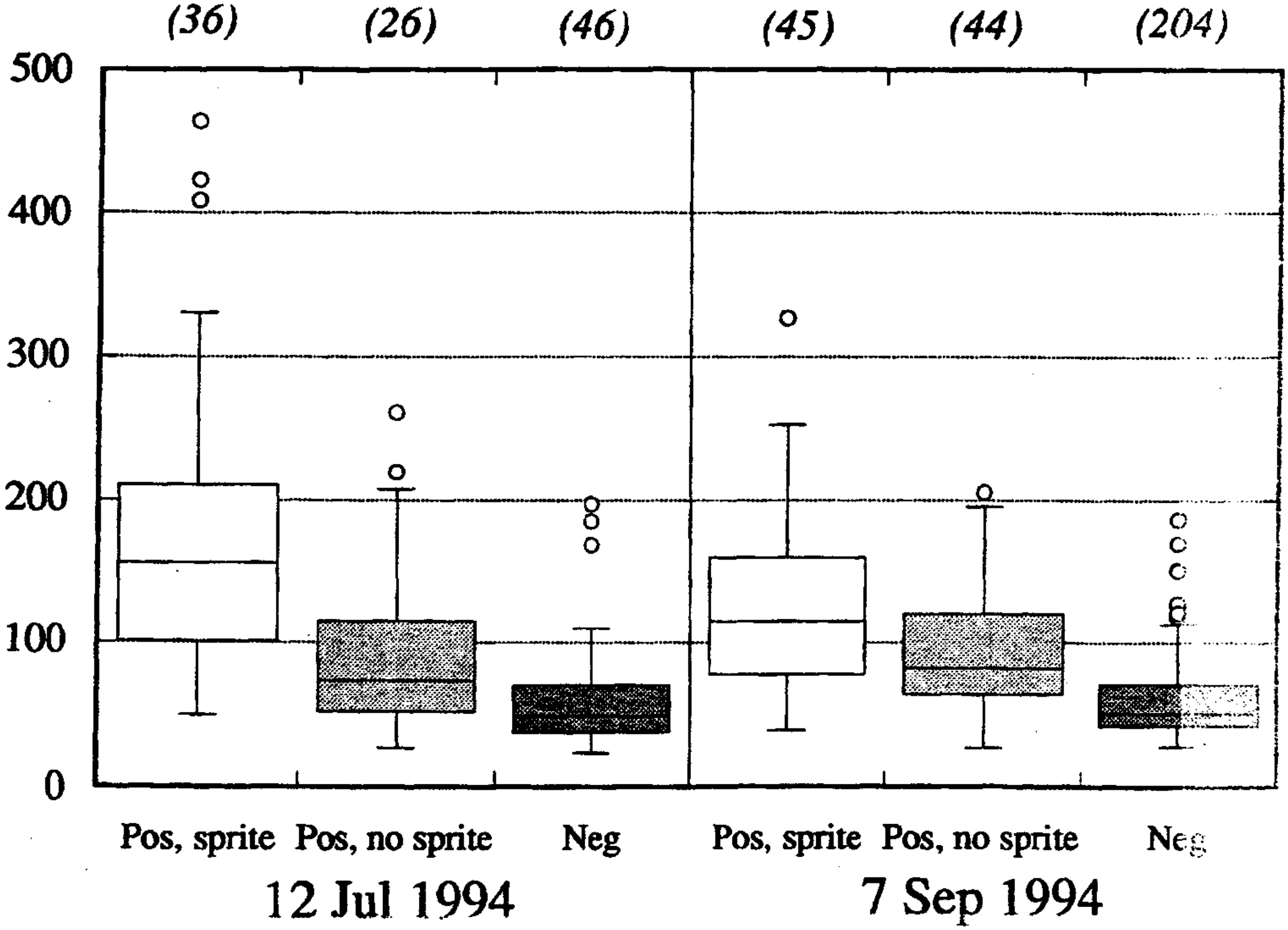

Figure 3-32. Box plot statistics of +CG peak currents from NLDN within 10 s of sprites in the two MCSs studied. The plots show the median, quartiles and outlier points for the CG strokes associated with and not associated with sprites. These statistics are for the entire storm systems. Source: Boccippio et al. (1995).

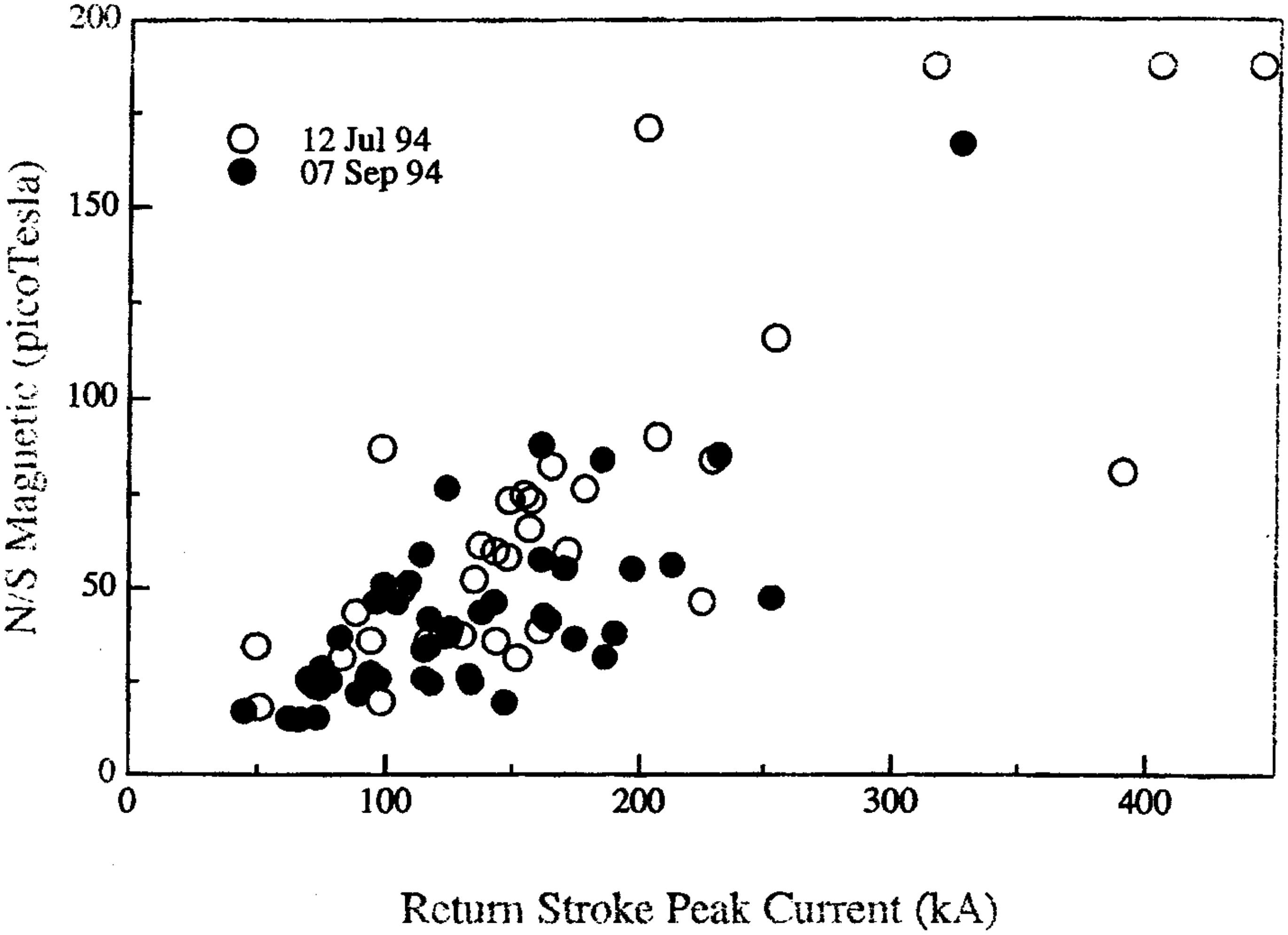

Figure 3-33. Correlation between the magnitude of the initial ELF magnetic field rise and coincident CG peak currents from the NLDN for the events of 12 July and 7 September 1994. Source: Boccippio et al. (1995).

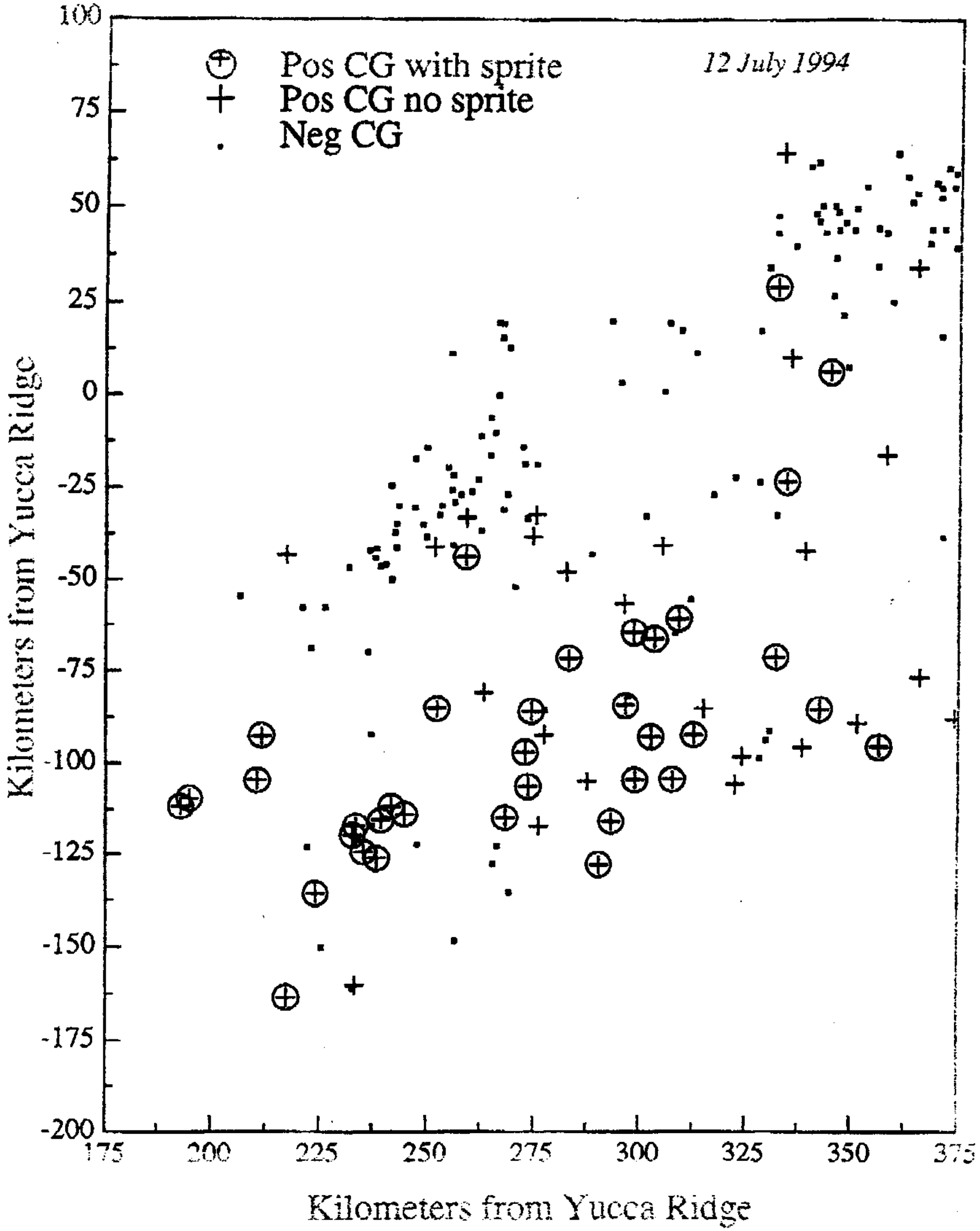

Figure 3-34. Spatial distribution of lightning CG flashes with 10 s of sprites in the 12 July 1994 MCS. The +CG were largely located in the region of stratiform precipitation. Source: Boccippio et al. (1995).

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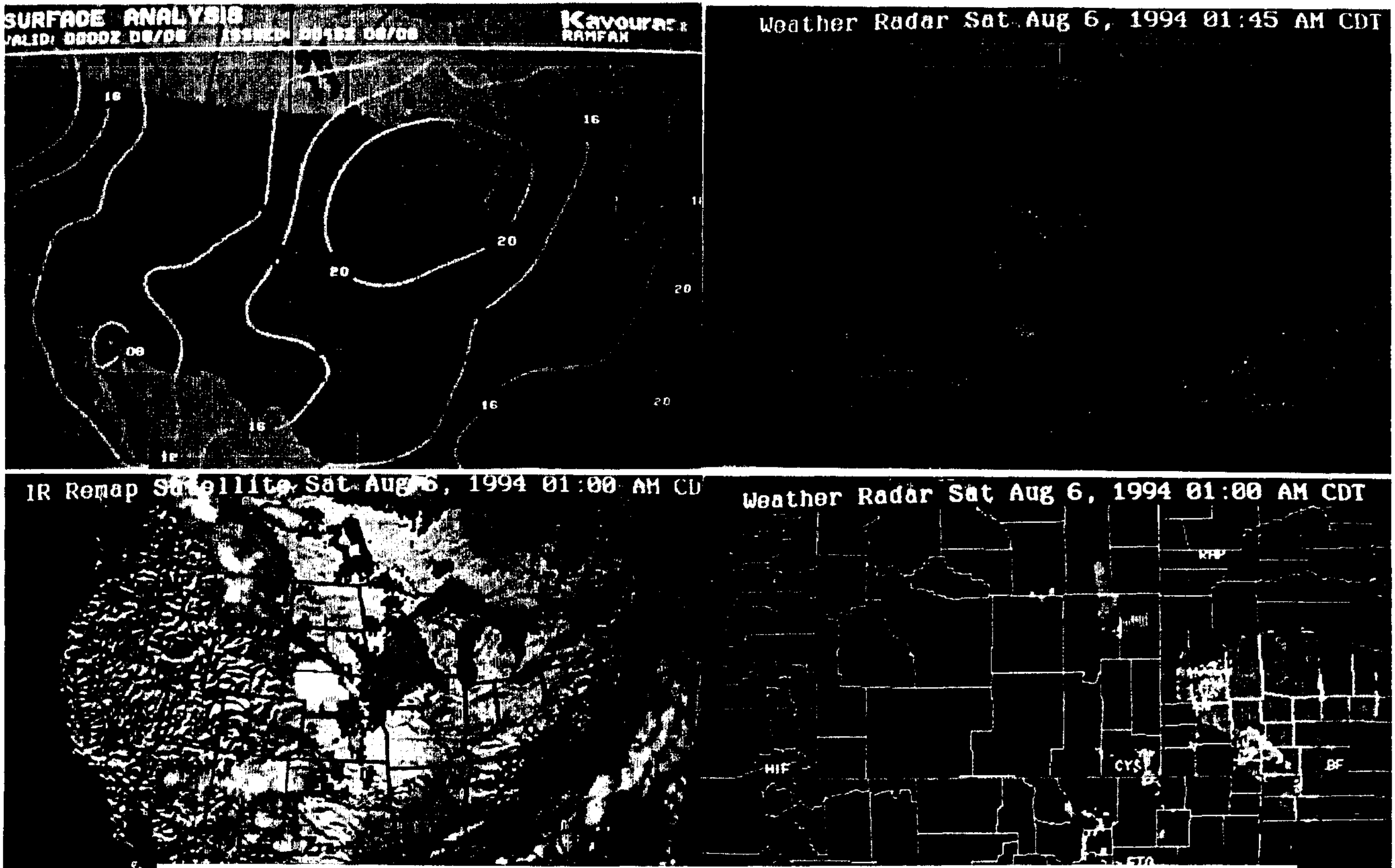


Figure 3-35. Surface weather map, national radar reflectivity composite, IR satellite view and regional radar composite during height of sprite producing MCS of 6 August 1994.

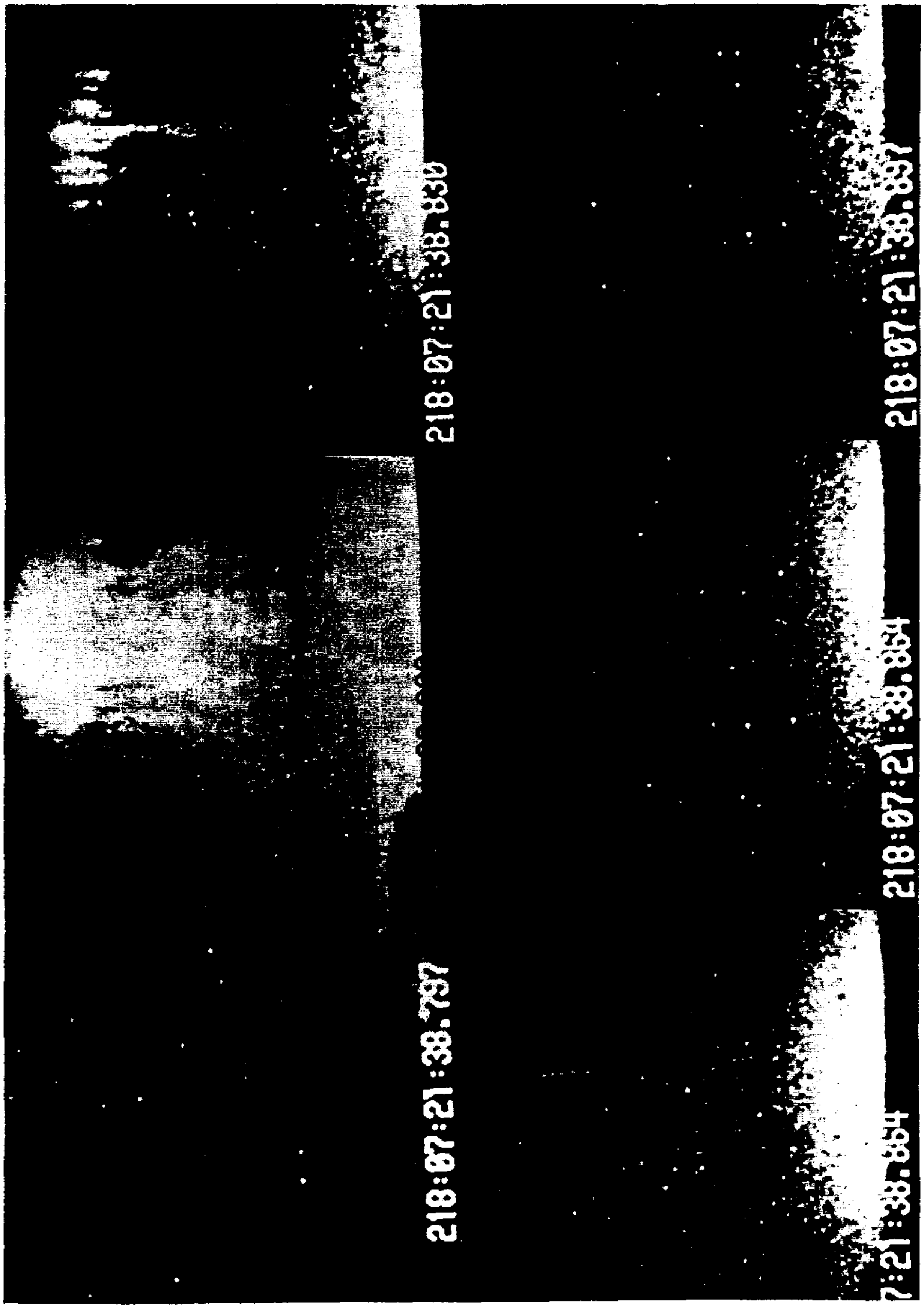


Figure 3-36. A sequence showing a large sprite taken by the LLTV at YRFS, 0721.38 UTC 6 August 1994. Shown are six successive 16.7 ms fields. The parent +CG had a peak current of 141 kA and was located 337 km distant.

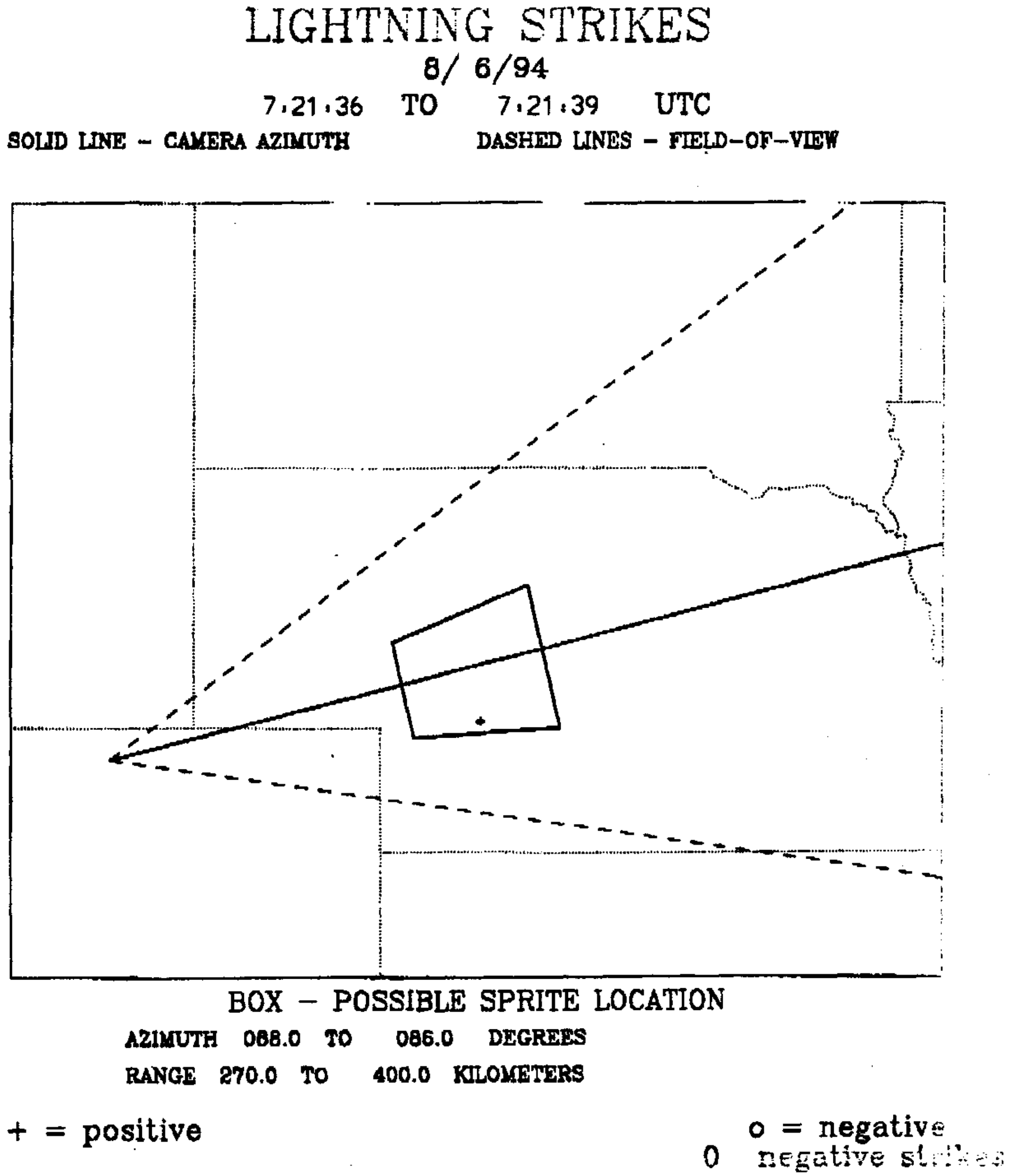
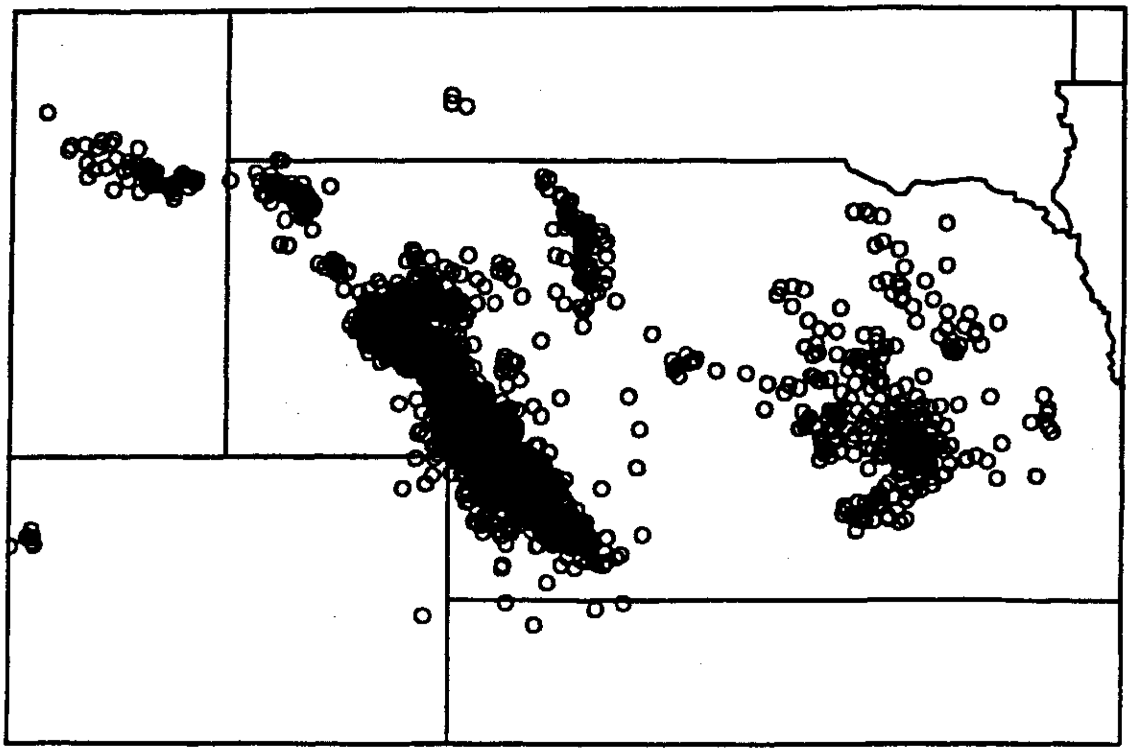
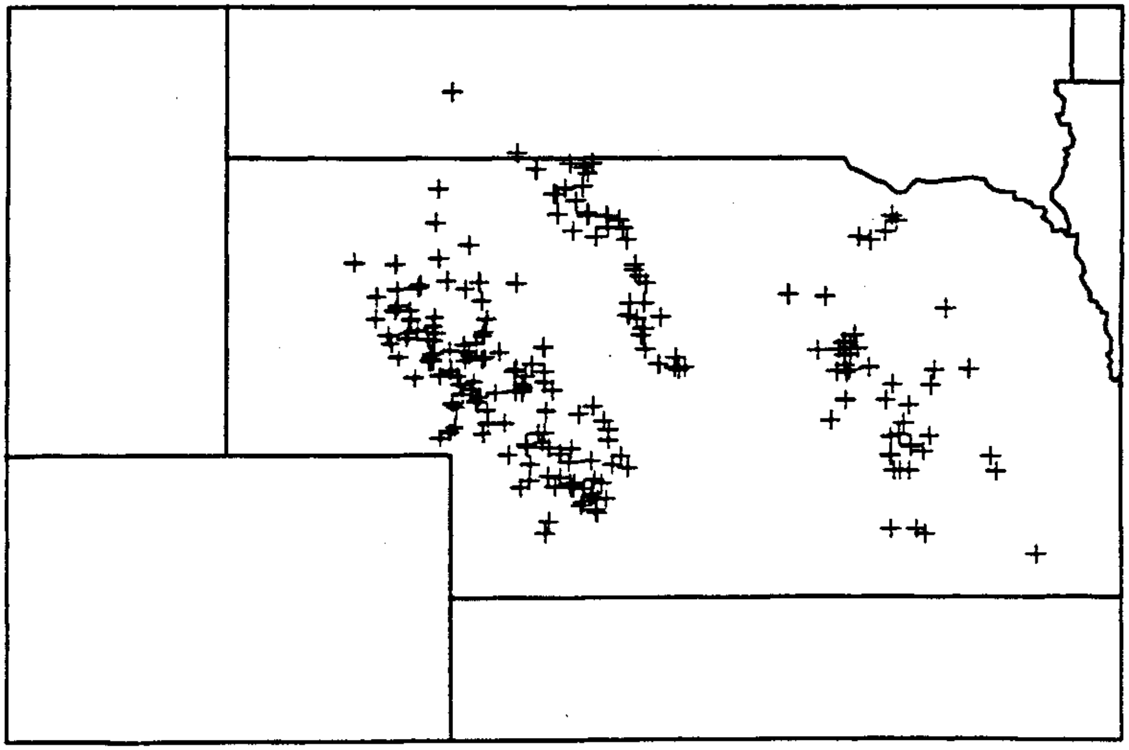


Figure 3-37. Field of view of the LLTV camera used in the previous figure, along with the location of the parent +CG and the approximate area covered by the sprite.

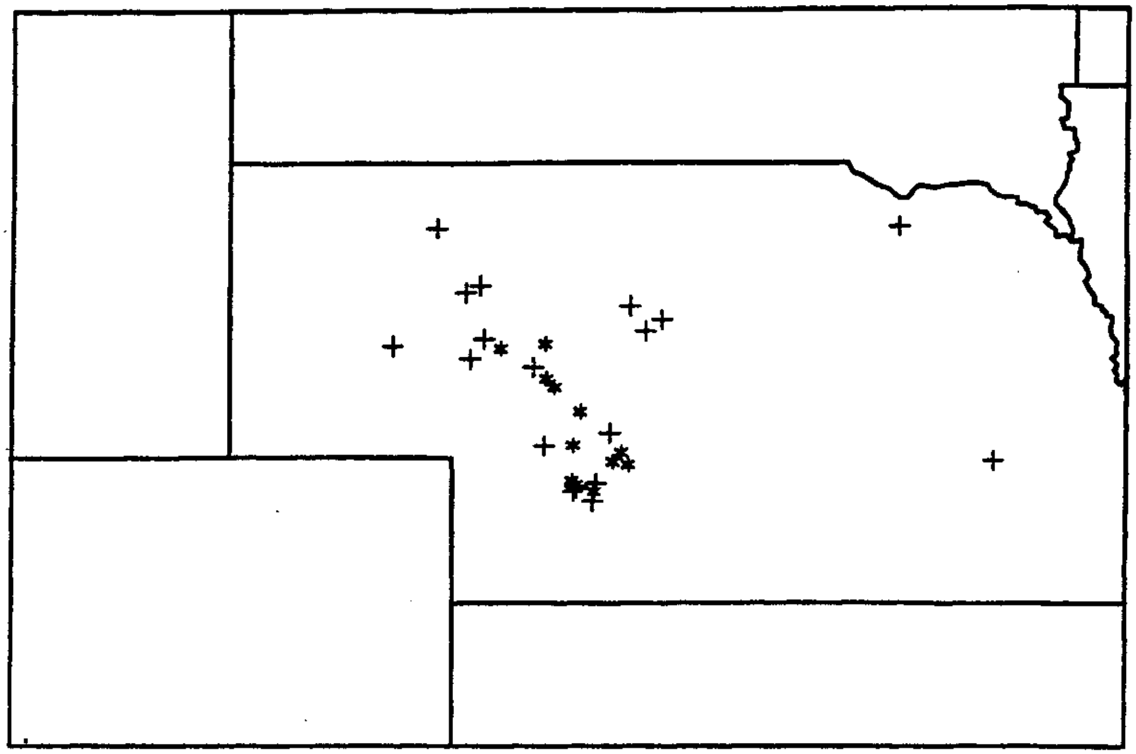


Plot of 2679 negative CG flashes detected by the NLDN during the sprite occurrence interval (0440 - 0758 UTC) on 6 August 1994.



Plot of 217 positive CG flashes detected by the NLDN during the sprite occurrence period (0440 - 0758 UTC) on 6 August 1994.

Figure 3-38.



Same as previous figure, except showing only +CG flashes with peak currents between 75-100 kA (+) and > 100 kA (*).

Figure 3-39. Location of +CG flashes between 0600 and 0800 UTC with peak currents between 75-100 kA (+) and > 100 kA (*).

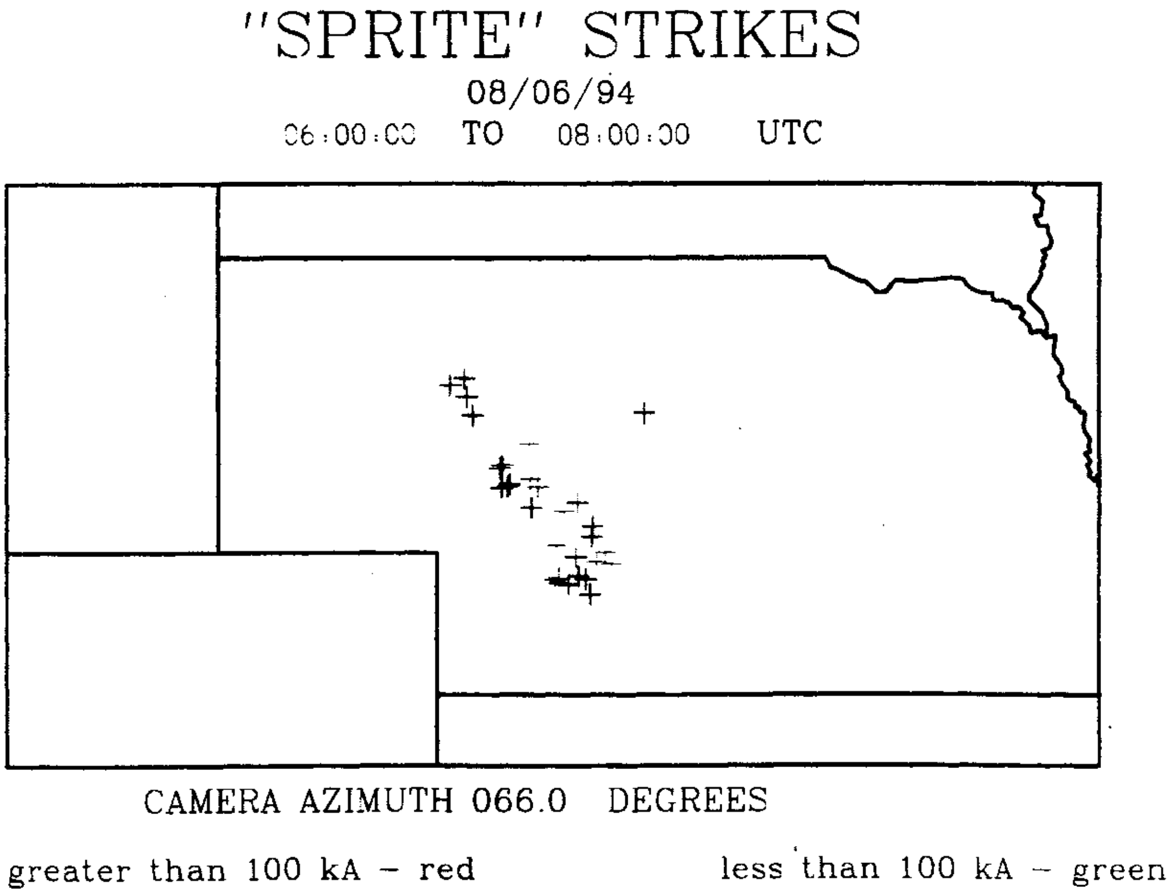


Figure 3-40. Position of the +CG events associated with 34 of the 36 sprites detected by low-light video on 6 August 1994. No sprites were closely associated with -CG flashes.

start ntical transient	field	NL data				CG position from YRFS		est. sprite altitude		sprite phenomenology						sprite center to +CG
event number	time (UTC	time (UTC)	polarity peak current (kA)	multiplicity	range (km)	azimuth (°)	top (km)	base (km)	visual perception	# video fields	brightest field	w/h aspect ratio	cloud flash visible	VLF signature	distance (km)
1	0440:43.005	none	-	-	-	-	-	-	-	5	2	4.00	Y	N	-
2	0445:44.057	0445:44.049	+ 36	1	325	45	79	53	-	6	2	0.83	Y	Y	0
3	0450:42.105	none	-	-	-	-	-	-	-	11	2	1.00	Y+	Y	-
4	0456:06.096	0456:06.096	+ 95	2	307	49	83	47	-	11	1	1.77	Y	Y	+10
5	0458:31.174	0458:31.173	+ 45	1	292	53	79	44	green	6	1	1.00	Y	Y	+15
6	0528:13.024	0528:13.018	+ 58	1	262	61	70	41	-	7	2	2.00	Y	Y	+60
7	0535:38.736	0535:38.570	+ 67	2	331	61	80	54	-	9	1	0.75	Y	Y	+80
8	0542:59.644	0542:59.337	+ 44	2	253	65	64	44	-	8	2	1.50	Y	Y	+85
9	0547:50.718	0547:50.711	+ 64	1	316	54	76	56	-	8	2	2.10	Y	Y	+48
10	0600:25.321	0600:25.328	+ 32	1	300	64	81	48	orange	7	2	2.10	Y	Y	+65
11	0605:56.788	0605:56.788	+ 86	1	296	58	80	45	-	7	1	1.43	Y+	Y	+50
12	0610:26.442	0610:26.356	+ 49	1	307	75	64	49	-	5	1	0.78	Y	Y	+87
13	0610:26.609	0610:26.356	+ 49	1	307	75	79	39	orange	6	1	1.08	Y	Y	+105
14	0614:33.105	0614:32.892	+ 33	1	304	78	73	49	-	6	3	0.97	Y	Y	+32
15	0614:33.589	0614:33.565	+ 77	2	308	59	74	60	-	6	1	0.46	Y+	Y	+67
16	0618:04.070	0618:04.084	+ 34	2	309	75	72	50	-	8	2	1.20	Y	Y	+23
17	0618:04.750	0618:04.723	+ 51	2	303	61	75	63	pink	8	1	1.87	Y+	Y	+65
18	0624:36.892	0624:36.881	+ 43	1	303	75	73	41	pink?	12	7	2.50	Y	Y	+78
19	0635:02.485	0635:02.452	+ 110	1	332	71	78	43	-	6	1	1.50	Y+	Y	+65
20	0645:20.102	0645:20.099	+ 106	2	325	75	76	31	pink?	6	1	1.40	Y+	Y	+20
21	0657:37.390	0657:37.391	+ 152	1	330	76	82	37	pink	6	1	1.56	Y+	Y	+10
22	0700:07.639	0700:07.622	+ 89	1	338	89	80	52	-	5	1	3.67	Y	Y	+15
23	0700:25.741	0700:25.716	+ 68	1	422	72	78	68	-	6	1	2.08	Y	Y	+28
24	0703:49.762	0703:49.751	+ 55	1	307	72	72	54	-	6	2	1.43	Y	Y	+10
25	0707:44.096	0707:44.676	+ 43	1	305	72	71	44	green	16	6	1.71	Y+	Y	0
26	0709:15.220	0709:15.203	+ 129	1	335	89	81	60	-	3	1	2.50	Y	Y	+5
27	0709:57.896	0709:57.884	+ 40	1	322	79	73	60	-	7	2	5.00	Y+	Y	+10
28	0711:42.585	0711:42.572	+ 150	2	338	89	80	61	-	2	1	2.00	Y+	Y	0
29	0721:38.847	0721:38.824	+ 141	2	337	84	79	31	orange	5	1	1.13	Y	Y	+15
30	0725:24.823	0725:24.810	+ 153	1	346	80	79	57	pink?	7	1	1.88	Y	Y	+10
31	0730:21.152	0730:81.147	+ 72	1	354	88	76	46	orange	7	2	2.35	Y	Y	+28
32	0734:29.701	0734:29.686	+ 52	4	359	89	79	62	green	6	1	4.55	Y	Y	+20
33	0742:10.028	0742:10.018	+ 128	1	367	87	84	33	salmon	6	1	1.36	Y+	Y	+15
34	0744:47.852	0744:47.844	+ 58	1	362	91	77	42	green	5	1	1.20	Y	Y	+15
35	0748:42.537	0748:42.530	+ 137	2	379	87	84	50	green	11	1	2.50	Y	Y	0
36	0757:24.308	0757:24.299	+ 196	2	374	86	88	59	green	7	1	1.52	Y+	Y	+50

Figure 3-41. Characteristics of sprites and their associated CG flashes.

Characteristics of sprites and their parent CG flash on 6 August 1994

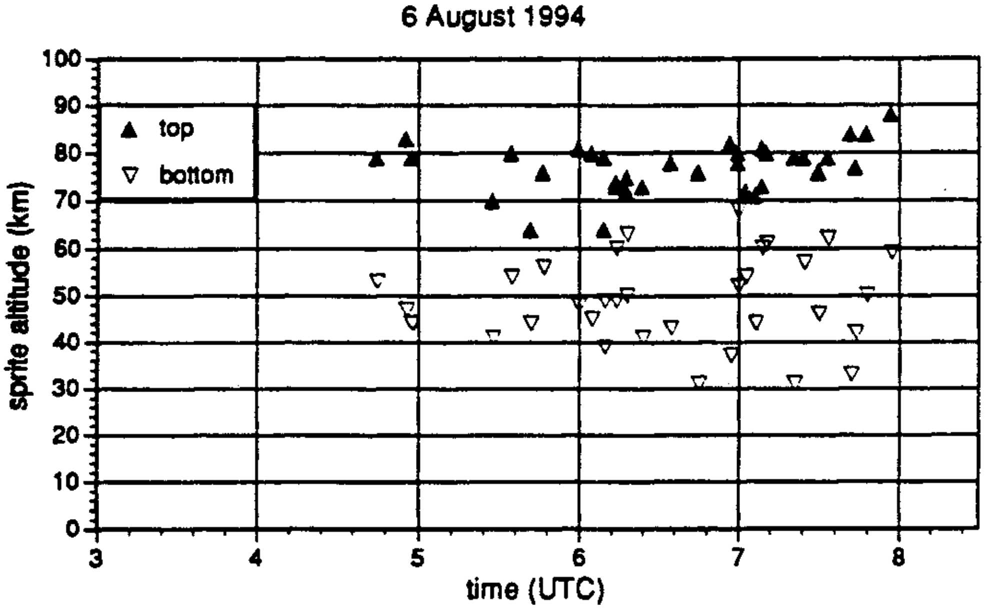
CG characteristics							Pos. CG w/o sprite						Pos. CG w/sprite								
Time UTC	Total CGs	Total pos. CG	% pos. CG	Pos. CG w/o sprite	Pos. CG w/sprite	%pos. CG w/sprite	Highest (kA)	Average (kA)	Avg. multiplicity	% multiple	#>82 kA	Sprites	Highest (kA)	Average (kA)	Avg. multiplicity	% multiple	% sprites w/pos. CG	% pos. CGs w/sprite	# visible	% sprites visible	Avg. W/H
0300-0330	144	33	22.9	33	0	0	72	24	1.15	12.9	0	0	-	-	-	-	-	0	0	-	-
0330-0400	320	18	5.6	18	0	0	91	26	1.05	5.5	1	0	-	-	-	-	-	0	0	-	-
0400-0430	415	37	8.9	37	0	0	86	23	1.32	18.9	1	0	-	-	-	-	-	0	0	-	-
0430-0500	563	33	5.9	30	3	9.1	95	26	1:03	3.2	1	5	45	41	1.0	0	60	0.88	1	20	1.42
0500-0530	735	38	5.2	37	1	2.6	73	27	1.03	27.3	0	1	58	58	1.0	0	100	0.13	0	0	2.0
0530-0600	421	34	8.1	31	3	8.8	111	30	1.10	19.4	1	3	64	57	1.67	67	100	0.71	0	0	1.58
0600-0630	363	34	9.4	26	8	23.5	73	27	1.08	7.6	0	9	86	51	1.38	38	100	2.47	4	44	1.32
0630-0700	352	22	6.3	19	3	13.6	97	37	1.05	5.3	1	3	152	123	1.33	33	100	0.85	2	67	1.47
0700-0730	384	40	10.4	31	9	22.5	102	42	1.10	9.7	3	9	153	92	1.22	22	100	2.34	3	33	2.38
0730-0800	463	25	5.4	19	6	24.0	70	30	1.32	15.7	0	6	196	107	1.83	50	100	1.3	6	100	2.75
0800-0830	510	19	3.7	19	0	0	59	22	1.26	15.7	0	0	0	-	-	-	-	0	0	-	-

Figure 3-42.

[illegible]. Characteristics of positive CGs on 6 August 1994 mesoscale convective system

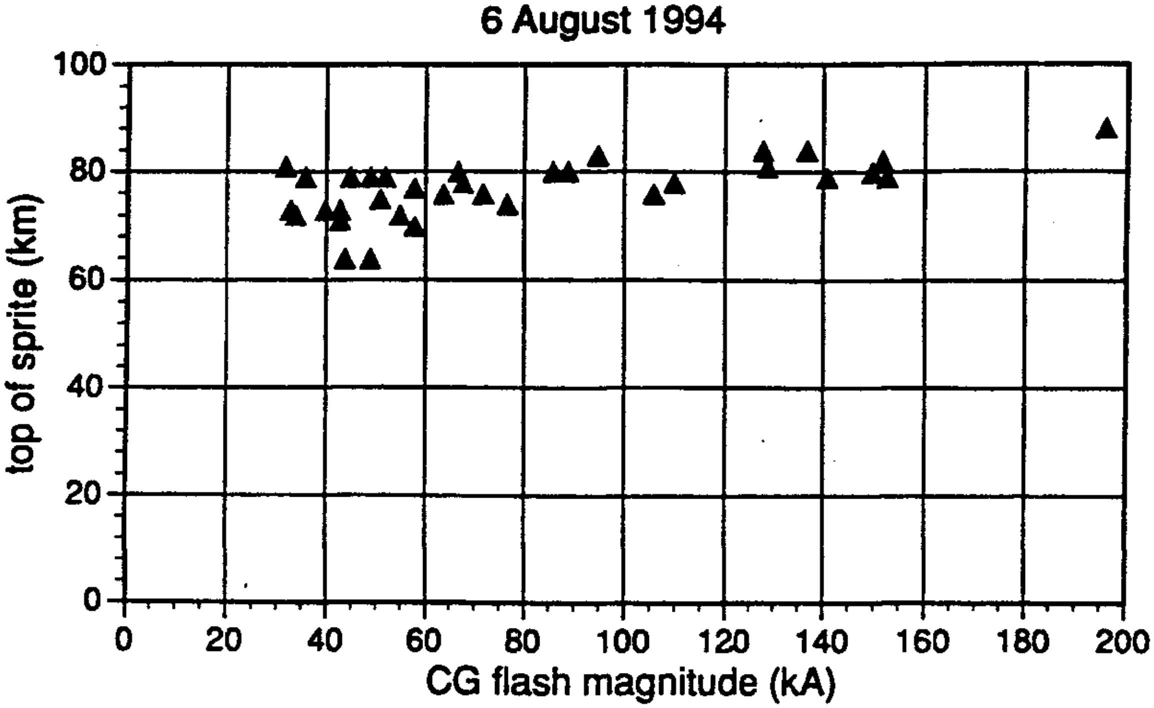
	number	peak currents (kA)			stroke multiplicity	
		avg.	max	min	% multiples	avg.
Pos. CGs with sprites	34	81	196	32	35	1.41
Pos. CGs w/sprites visible	16	89	196	43	31	1.31
Pos. CGs w/sprites not visible	18	66	150	32	39	1.50
Pos. CGs without sprites	299	30	111	4	11	1.13

Figure 3-43.



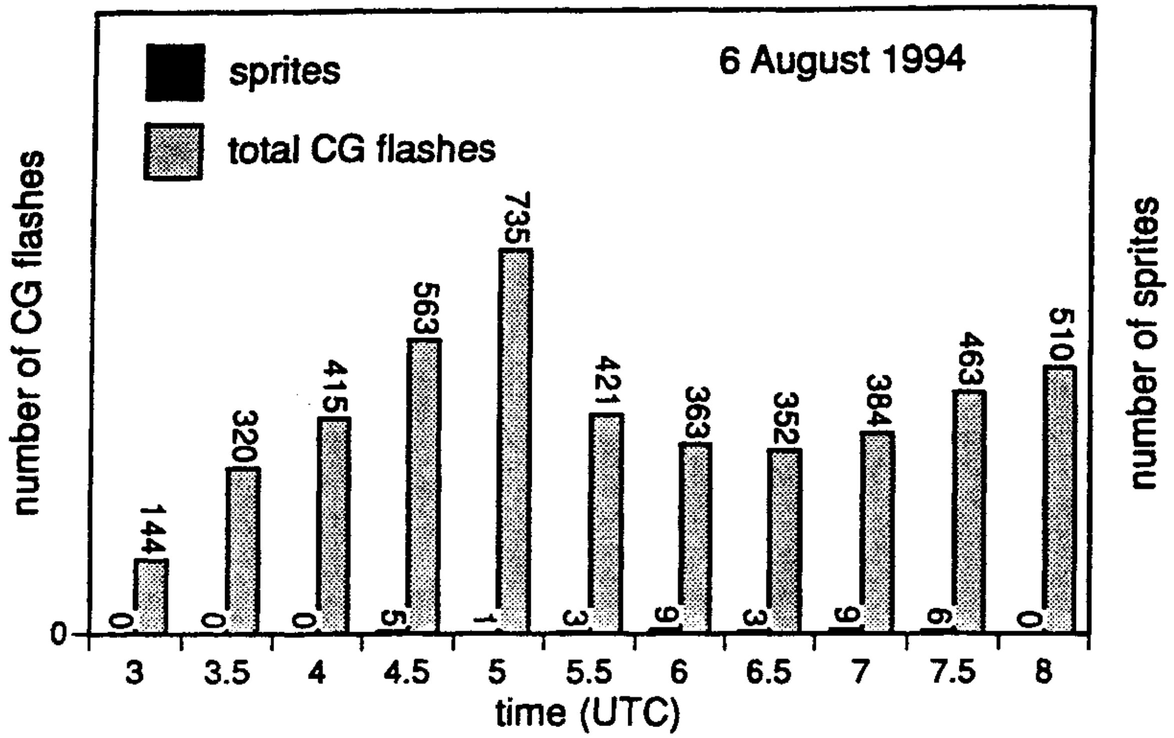
The estimated top and bottom of the sprite luminosity as imaged by the Xybion low-light camera, assuming the range is accurately provided by the location of the parent +CG flash.

Figure 3-44.

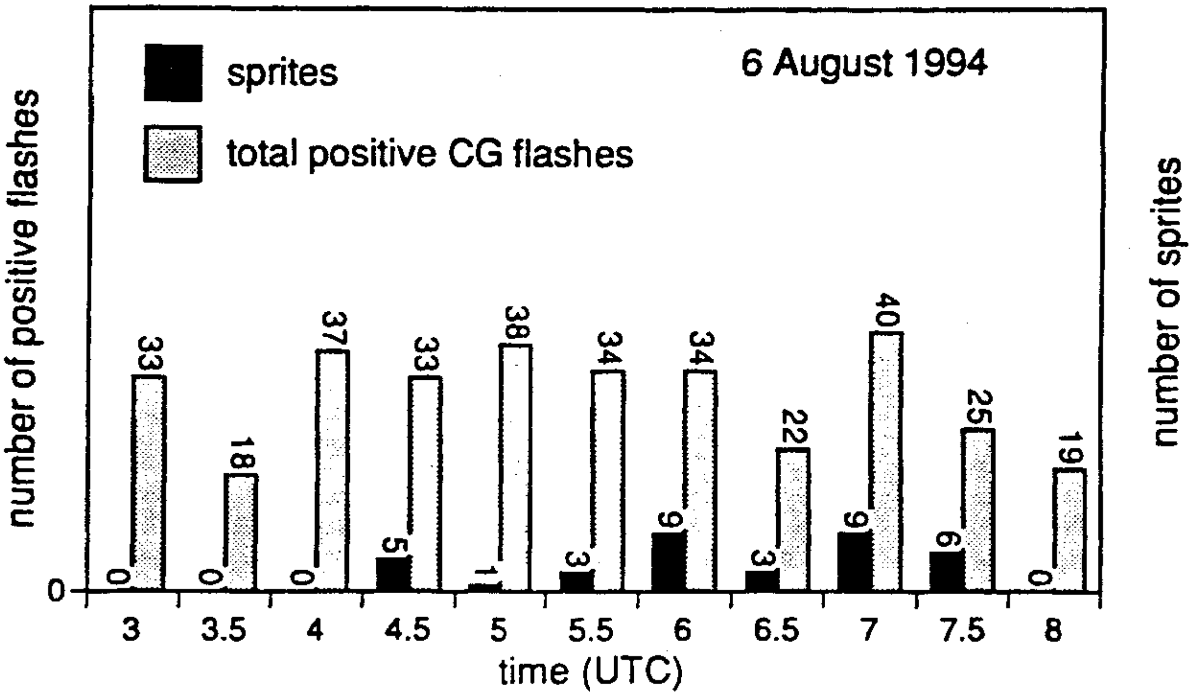


Estimated height of the top of the sprite luminosity as a function of the peak current (kA) of the parent +CG flash.

Figure 3-45.

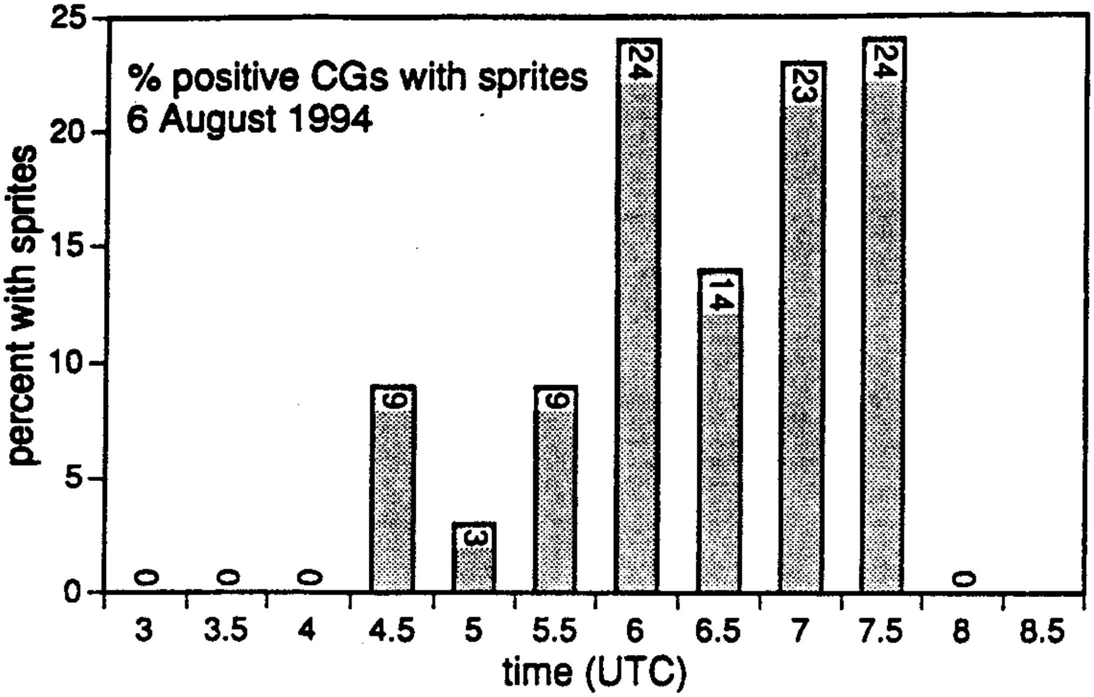


Histogram of the total number of CG flashes (both polarities) and the number of sprites in 30 minute segments between 0300 and 0830 UTC 6 August 1994.

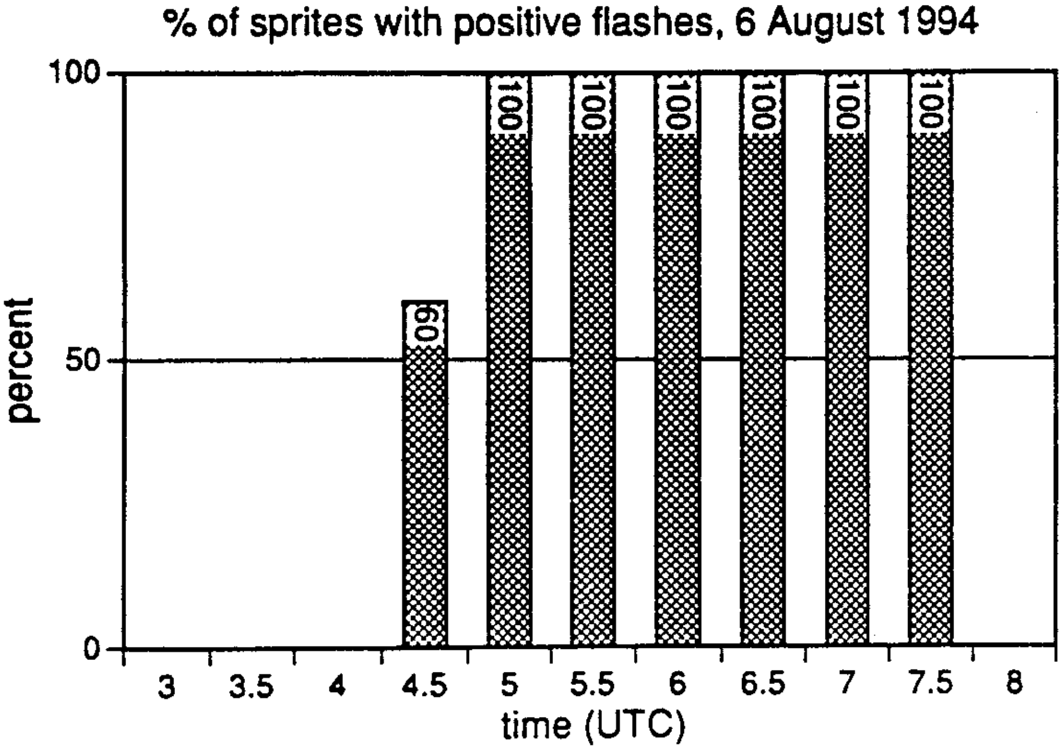


Histogram of the total number of CG flashes (positive polarity only) and the number of sprites in 30 minute segments between 0300 and 0830 UTC 6 August 1994.

Figure 3-46.

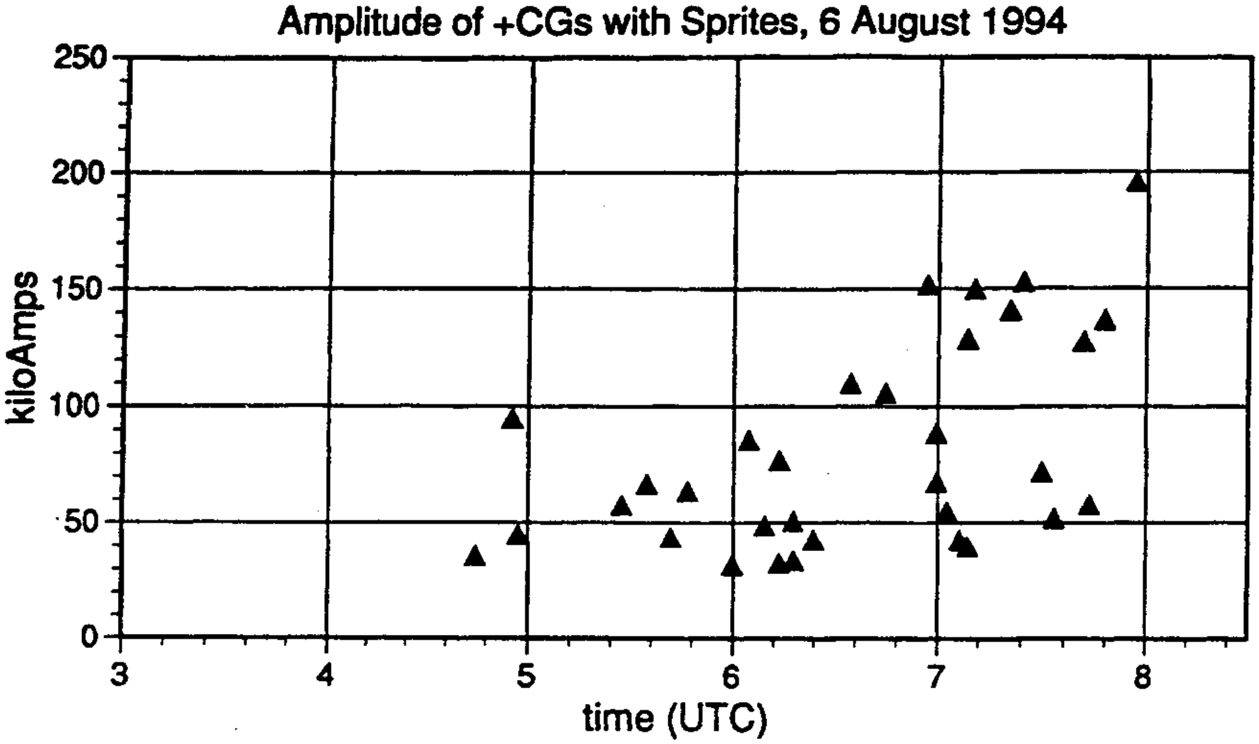


Percentage of +CGs with sprites, 30 minute increments, between 0300 and 0830 UTC 6 August 1994.

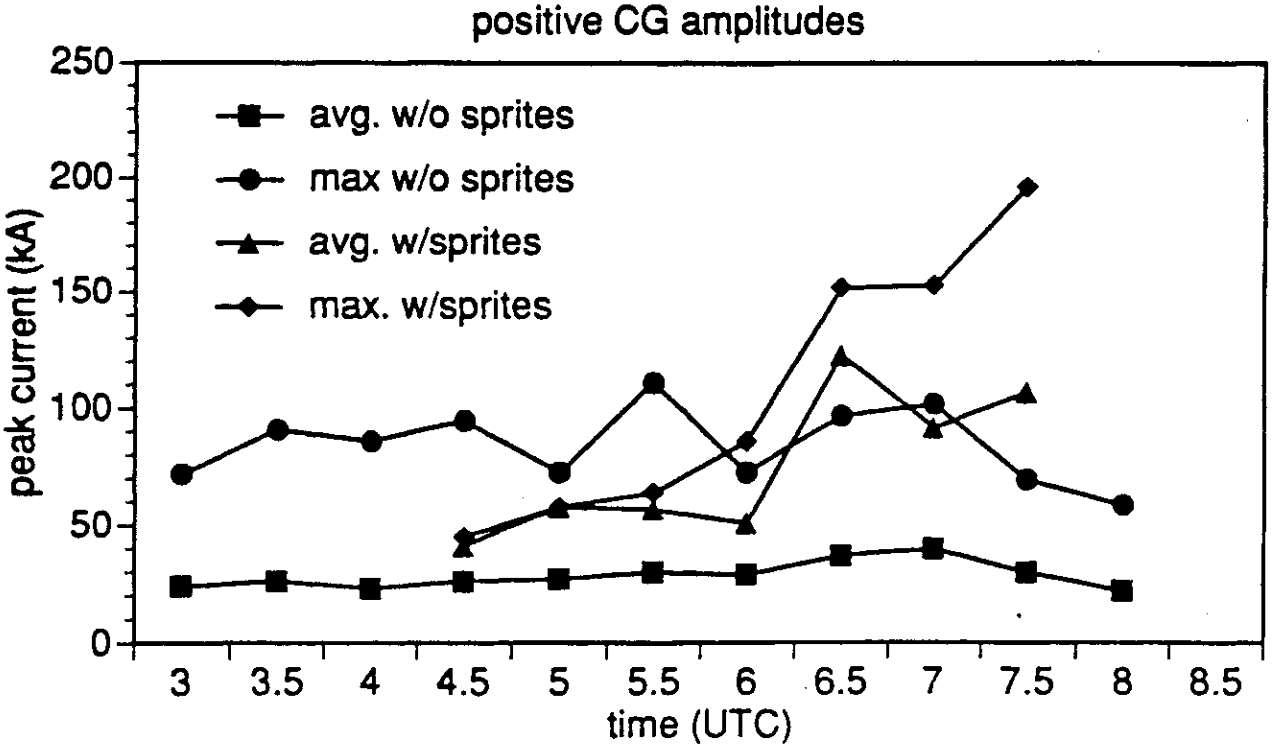


Percentage of sprites associated with +CG flashes, in 30 minute increments, between 0300 and 0830 UTC 6 August 1994.

Figure 3-47.

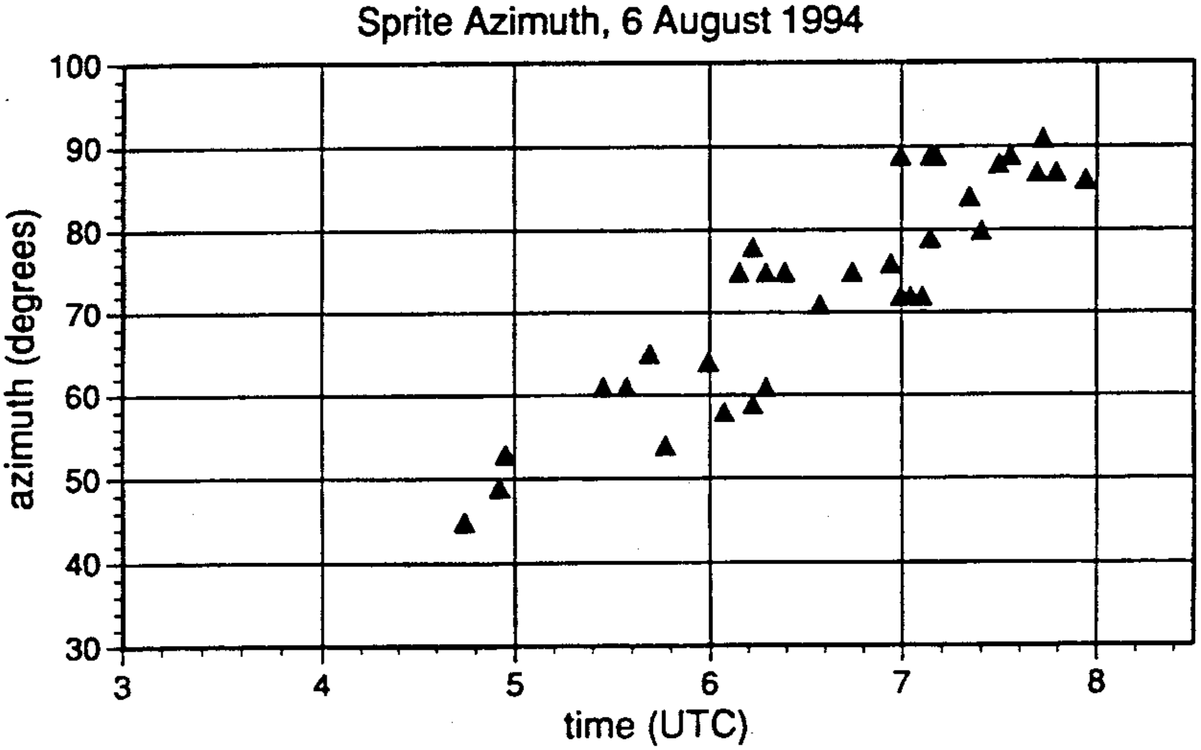


The peak current (kA) of +CG flashes associated with sprites as a function of time.



Average and maximum values of peak currents for +CGs with and without sprites, 30 minute increments, 0300-0830 UTC, 6 August 1994.

Figure 3-48.



The azimuth of sprites detected by a low-light camera as a function of time on 6 August 1994, suggesting in addition to the drift of the MCS across the camera's field of view, the rather tight clustering of successive sprites.

Figure 3-49.

6 August 1994 Sprite Statistics

3096	CG Flashes Detected
7%	Percentage of CG w/ Positive Polarity
22%	Percent of +CGs w/ sprites (0600-0800 UTC)
1/91	Ratio of sprites to CGs (0440-0757 UTC)
100%	Percent sprites associated with visible cloud flash
92%	Percent of sprites with associated +CGs
0%	Percent of Sprites with associated -CGs
30 kA	Average peak current of non-sprite +CGs
81 kA	Average peak current of sprite producing +CGs
32-196	Range of peak currents of sprite +CGs
8	Number of +CGs > 81 kA not producing sprites
1.41	Average multiplicity of sprite +CGs (versus 1.13)
44%	Percent of sprites visible to the naked eye
2-16	Range of number of video fields for sprites
7	Average duration of sprite video fields [115 ms]
92%	Percentage of sprites brightest in field 1 or 2
+39 ms	Average lag between video field and parent +CG
-14 ms	Earliest sprite video - +CG time
+307 ms	Longest lag between +CG and sprite onset
77 km	Average estimated top of sprite (64-88, 5.1 km SD)
50 km	Average estimated base of sprite (31-68, 8.8 km SD)

Figure 3-50.

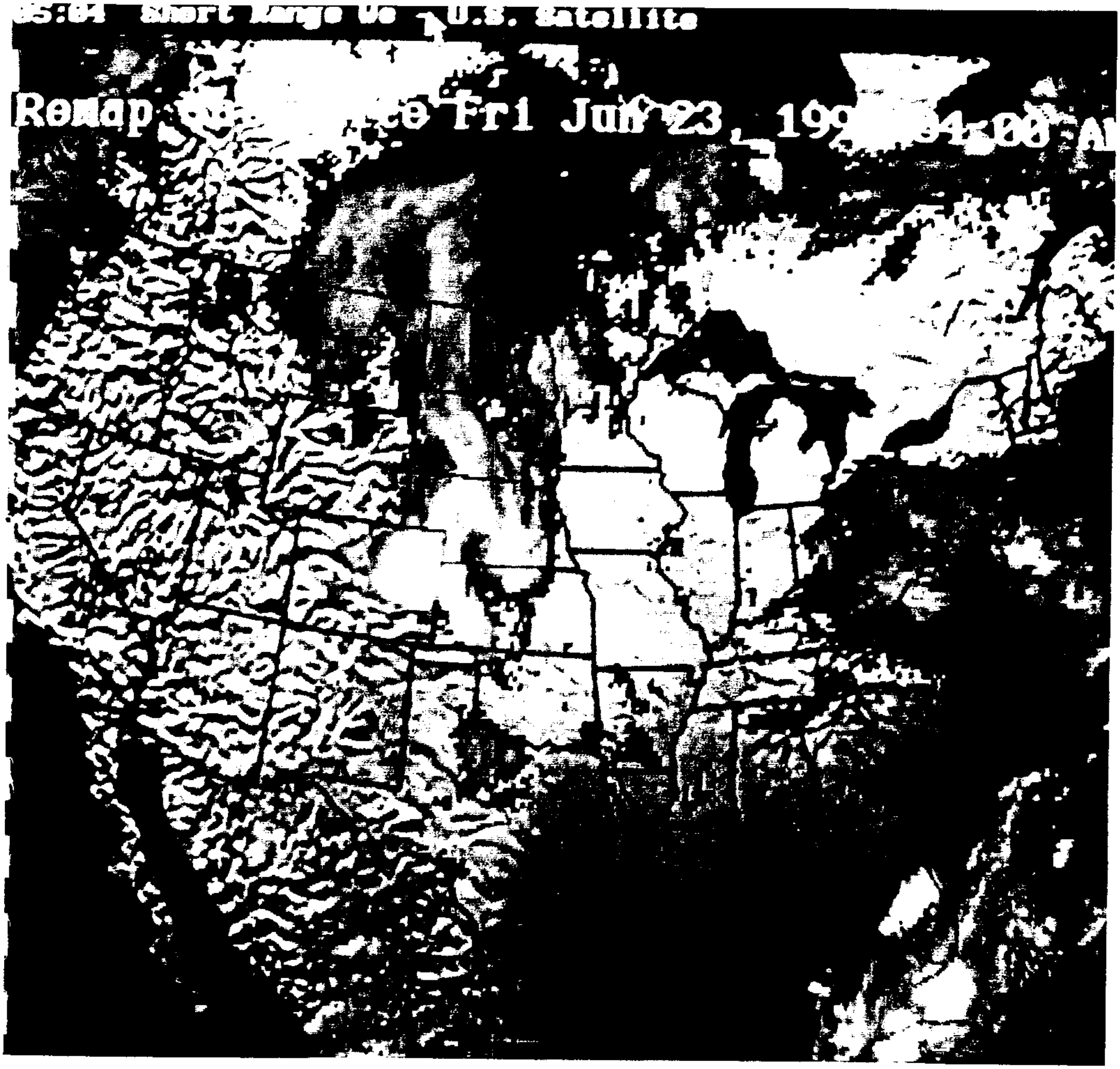


Figure 3-51. IR GOES satellite map, 0900 UTC 23 June 1995.

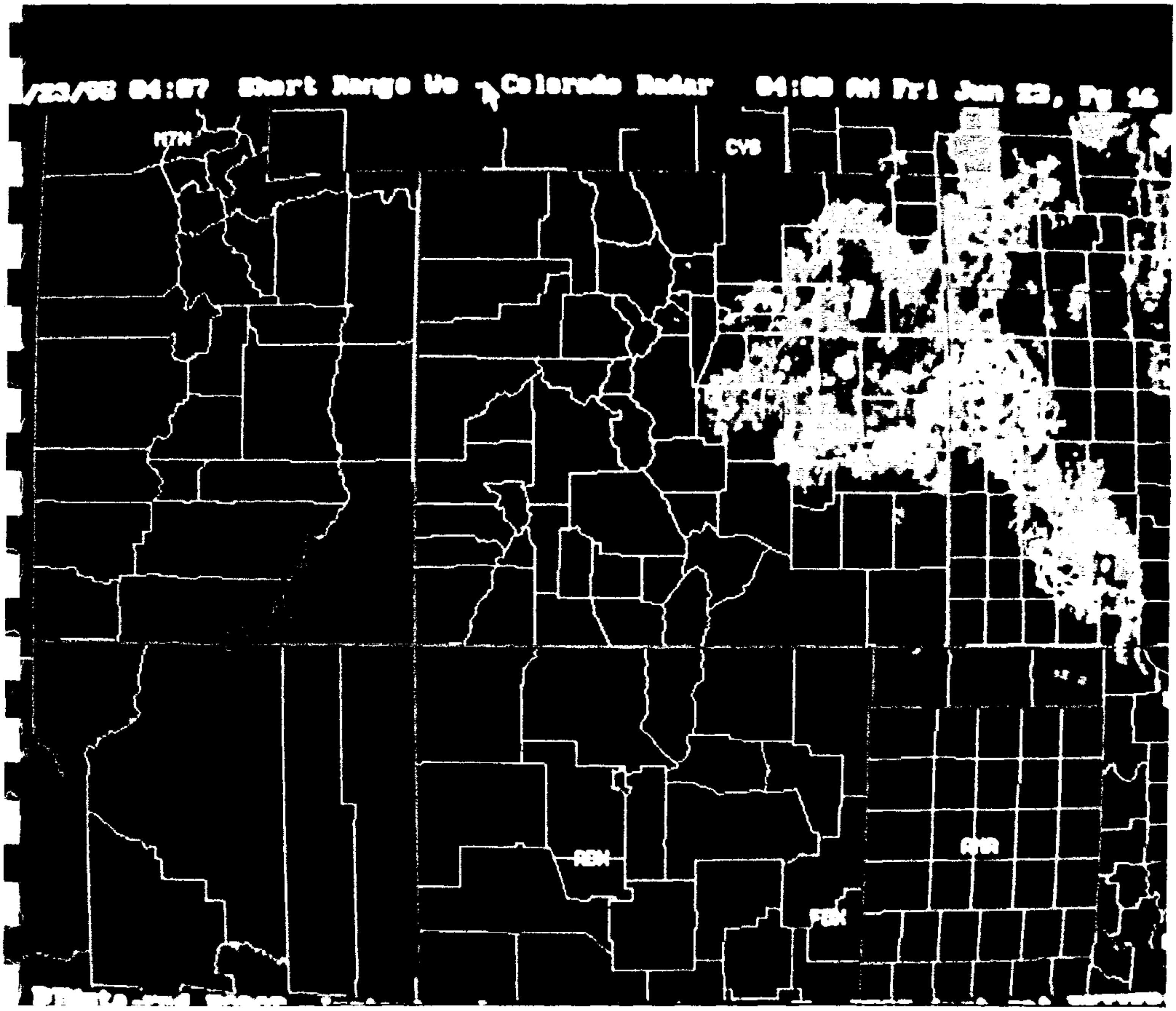


Figure 3-52. Regional radar reflectivity, 0900 UTC 23 June 1995. YRFS is located about 50 km south of CYS.

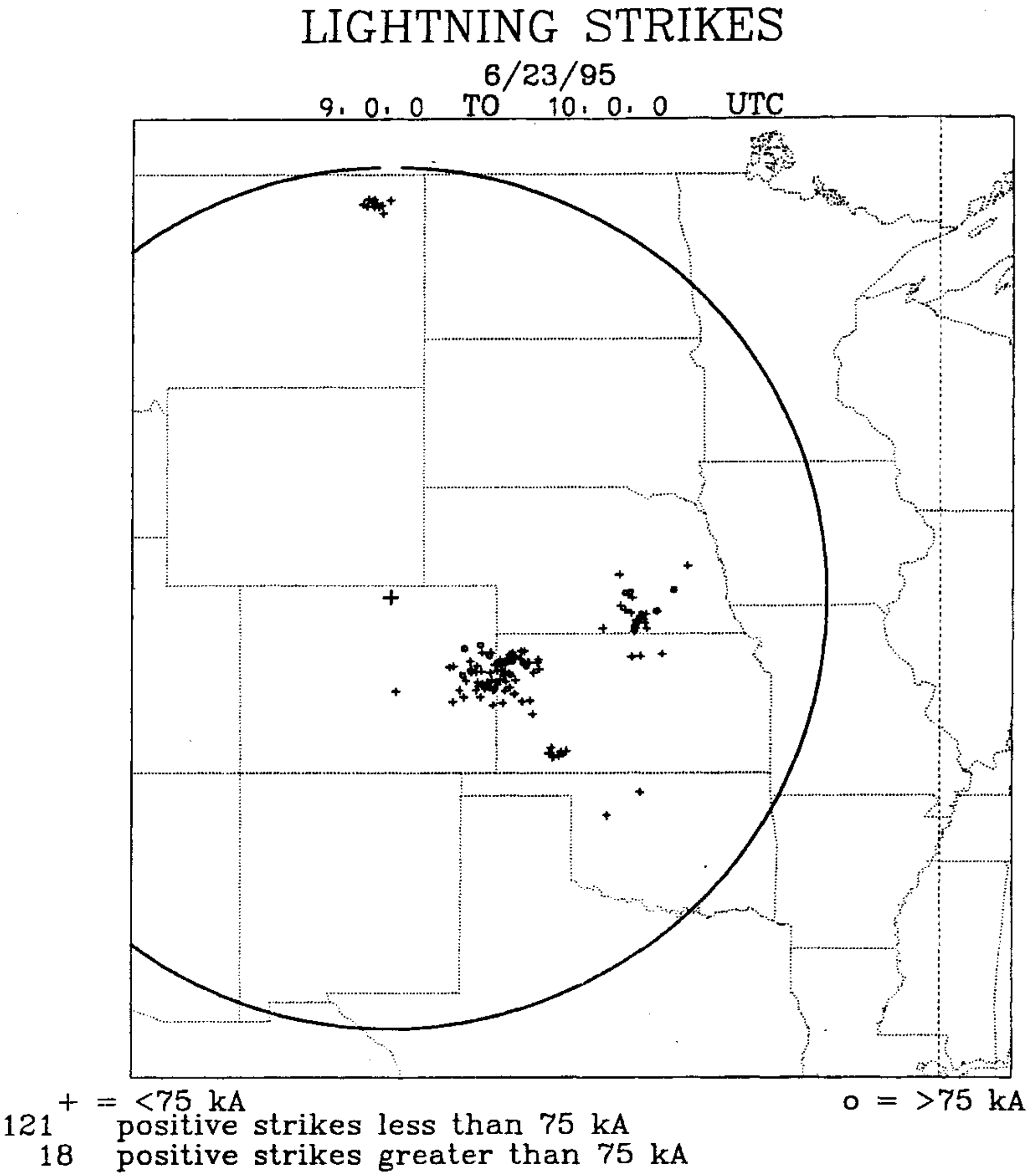


Figure 3-53. Plot of +CG flashes between 0900 at 1000 UTC 23 June 1995.

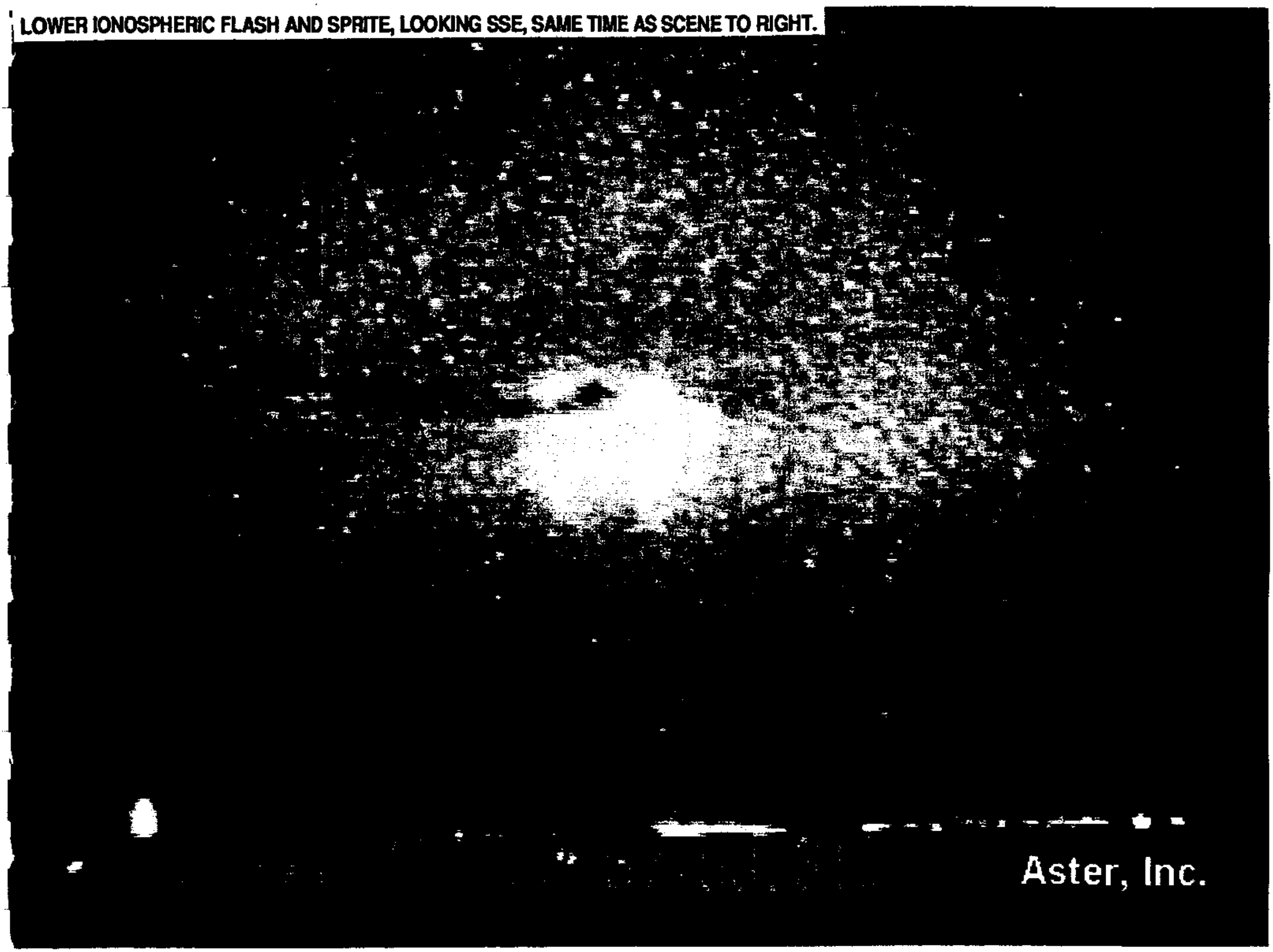


Figure 3-54. LLTV field at 0857.53.318 UTC 23 June 1995 showing both an elve and a sprite.

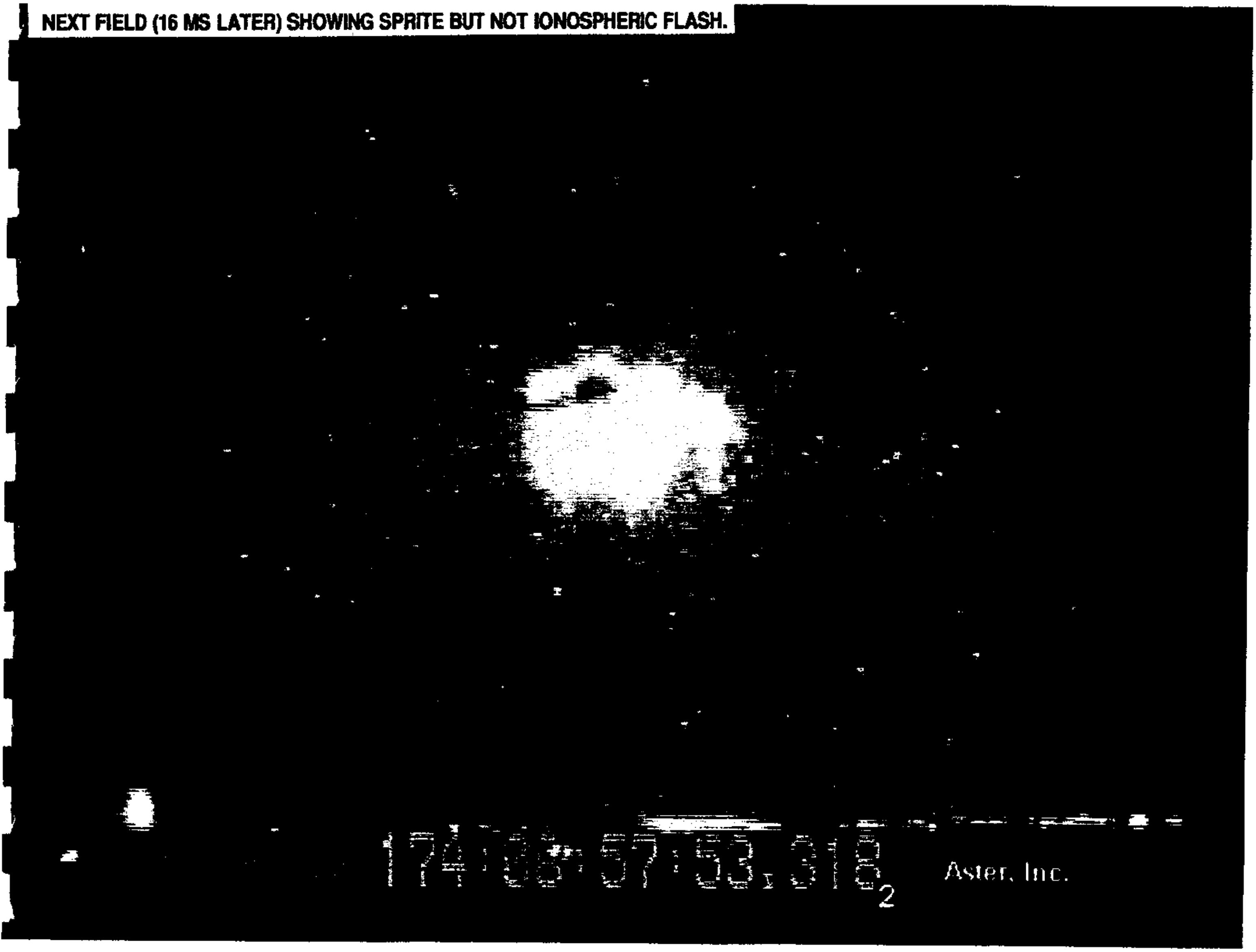


Figure 3-55. The next field taken 16.7 ms after Figure 3-54 showing only the sprite.

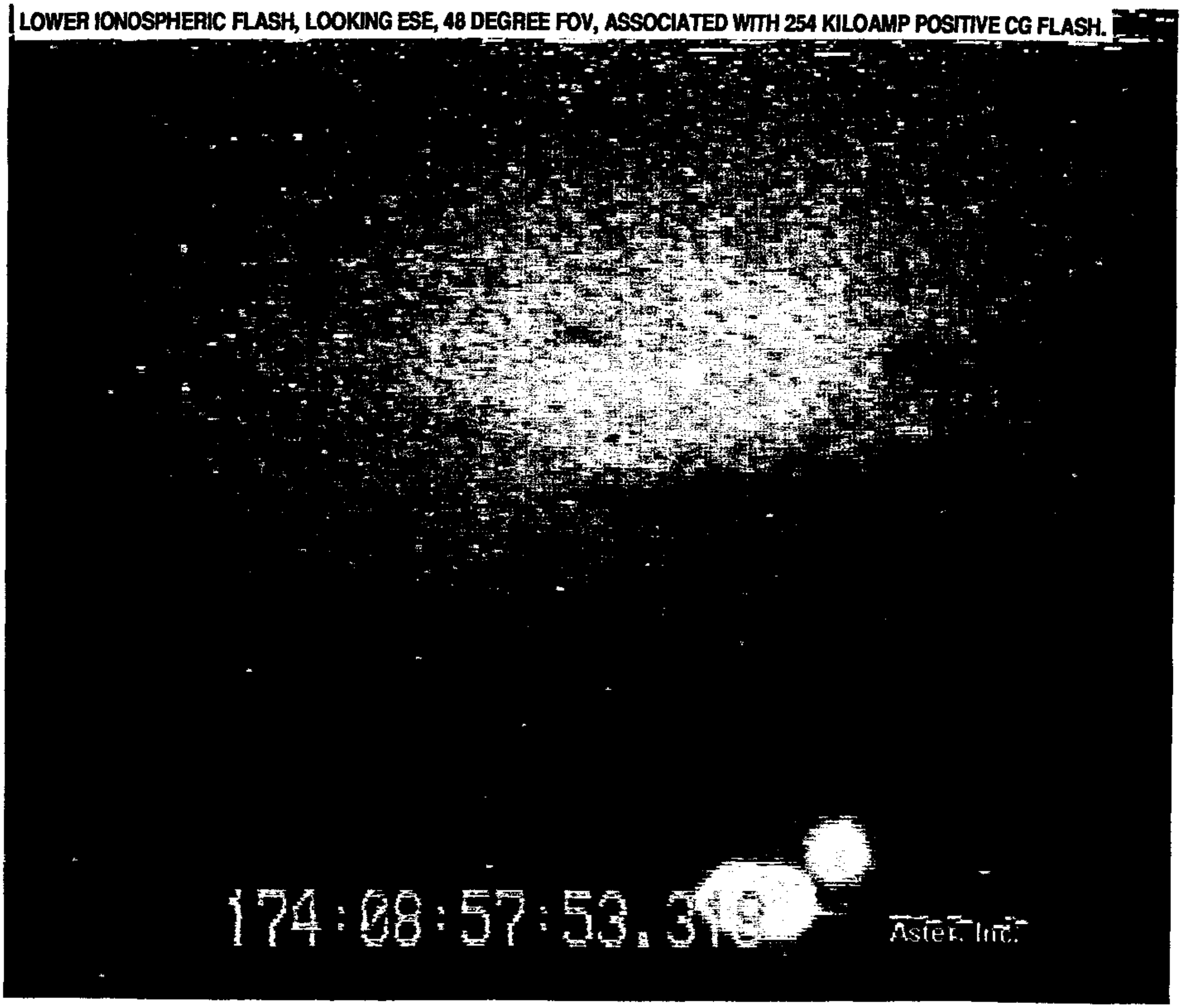


Figure 3-56. The LLTV view at 0857.53.318 taken by the camera panned some 40 degrees counterclockwise from that n Figure 3-54. The elve flow is clearly visible, although the sprite is out of the field of view to the right.

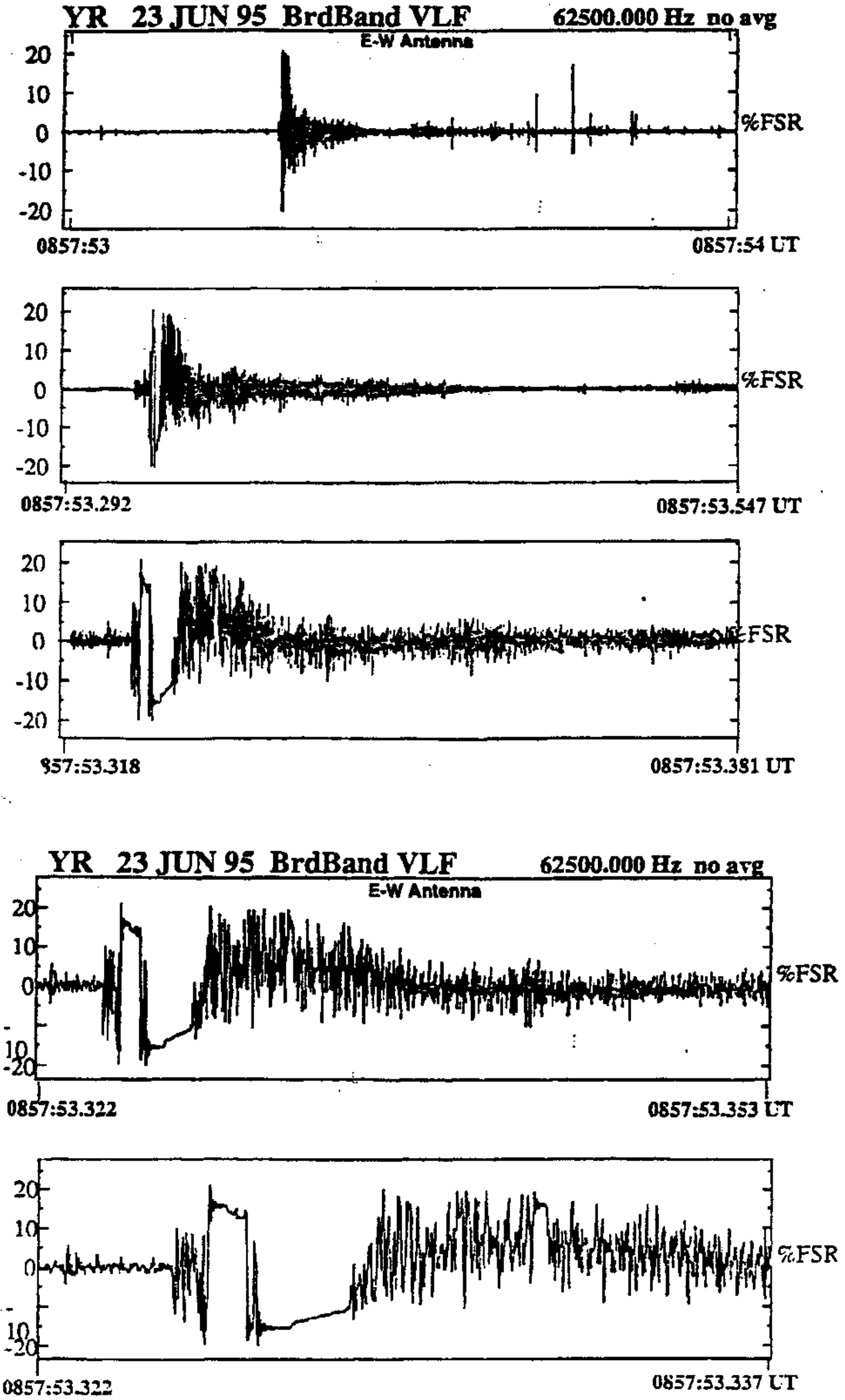


Figure 3-57. Broad band VLF sferics associated with the elve/sprite of 0857.53 UTC 213 June 1995 shown at several time windows. Courtesy STAR Labs, Stanford University.

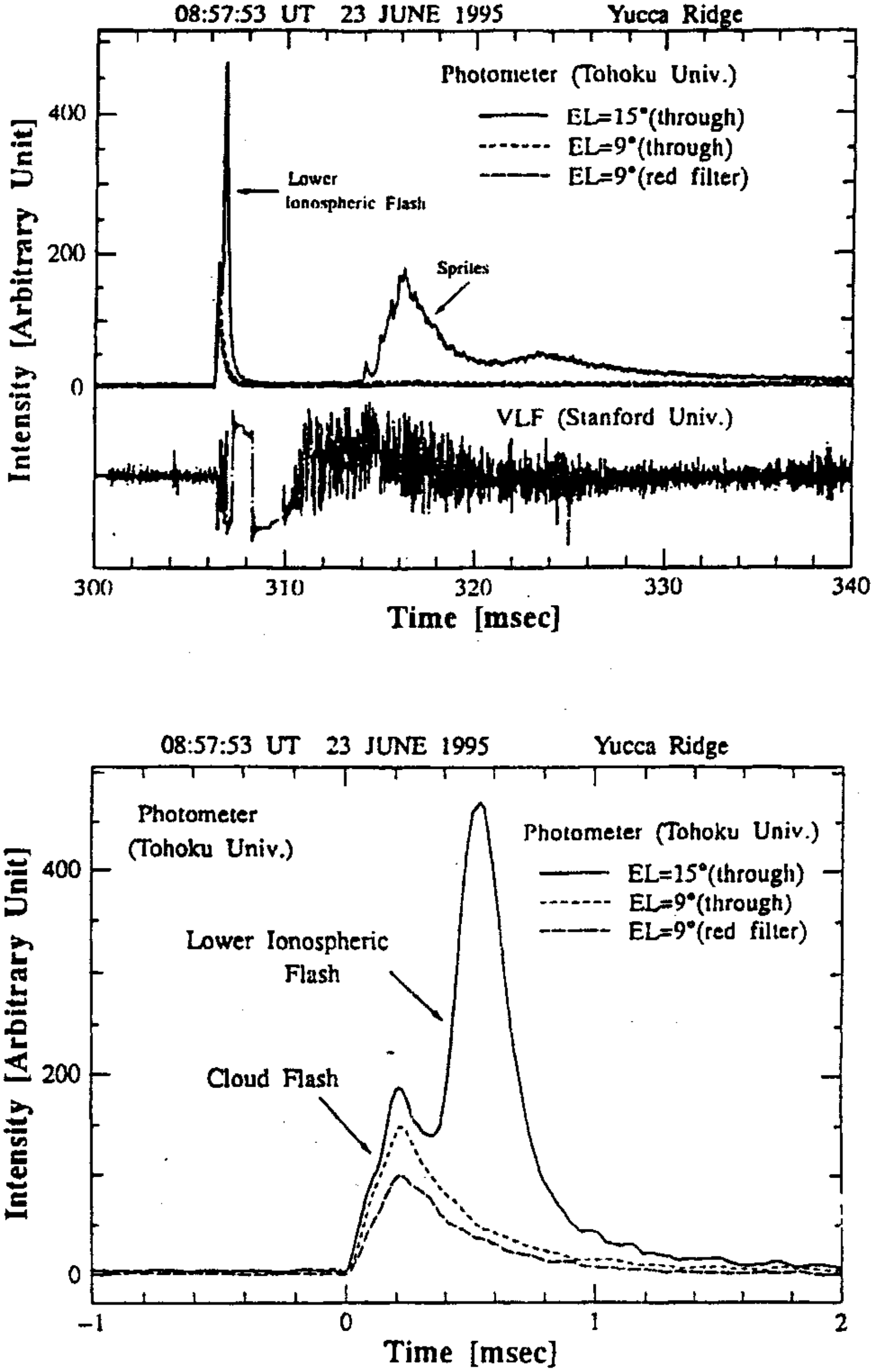


Figure 3-58. Tohoku University photometer traces and STAR Lab VLF record combined. See text and Fukunishi et al (1996) for details. Lower ionospheric flash was the original designation for an elve.

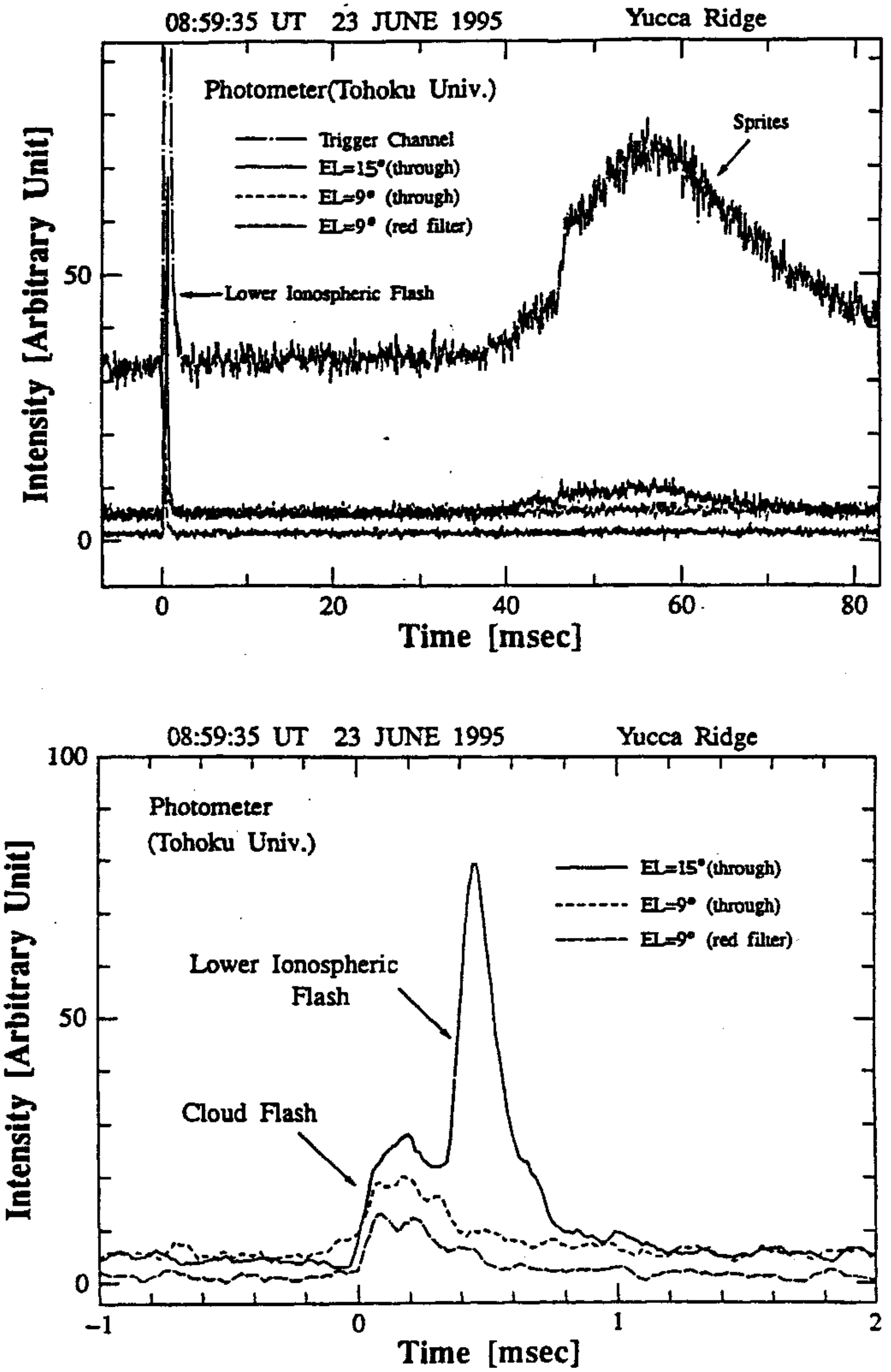


Figure 3-59. An another photometer trace showing both an elve and a sprite. While the elve occurs within several hundred microseconds of the +CG event, the sprite lags by over milliseconds. Fukunishi et al. (1996).

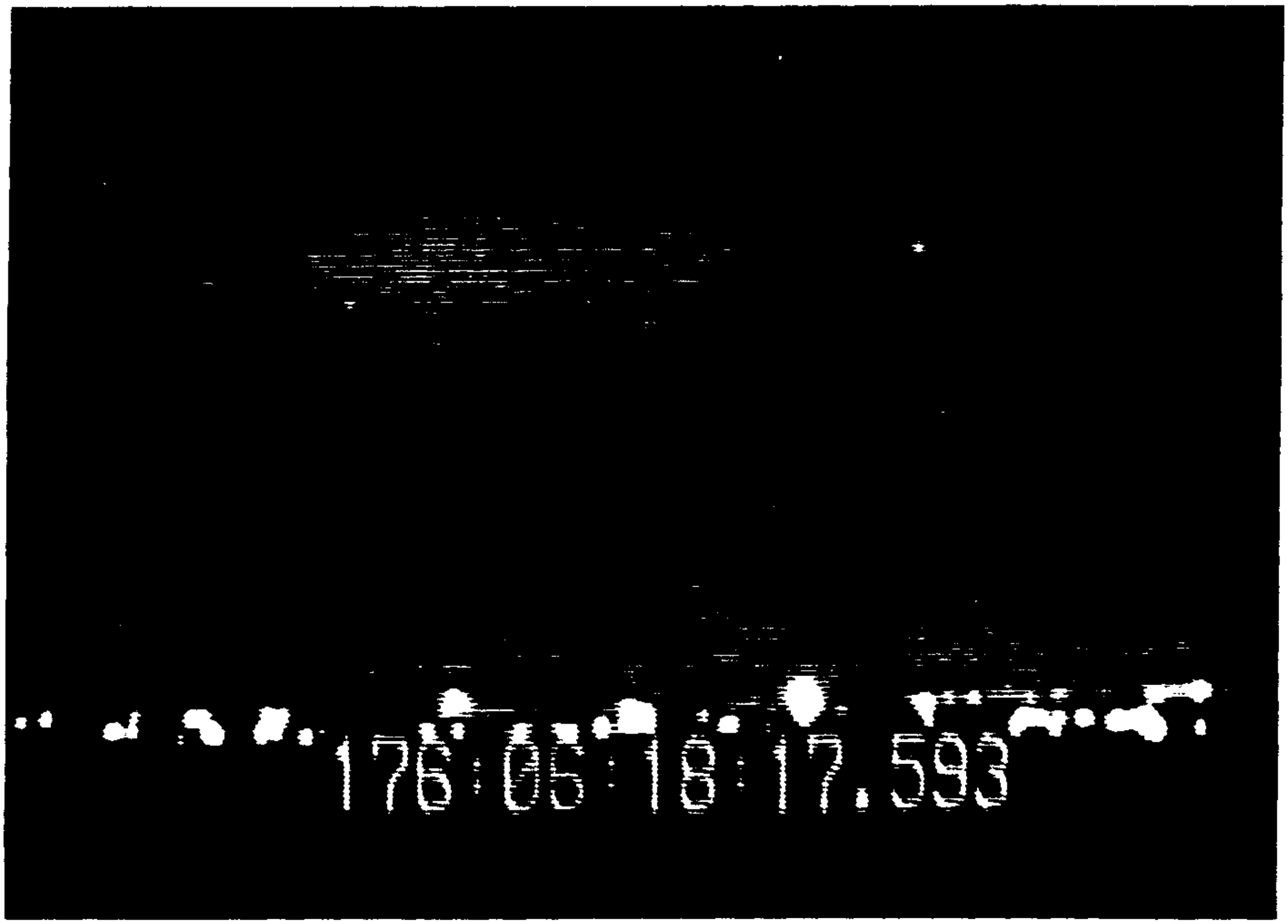


Figure 3-60. An elve associated with a 213 kA +CG over northern New Mexico at 0618.17 UTC 25 June 1995. This elve was not accompanied by a sprite.

Figure 3-61. An elve (top) followed in the next field of video by a bright sprite (bottom). View looking towards north-northeast on 25 July 1995.

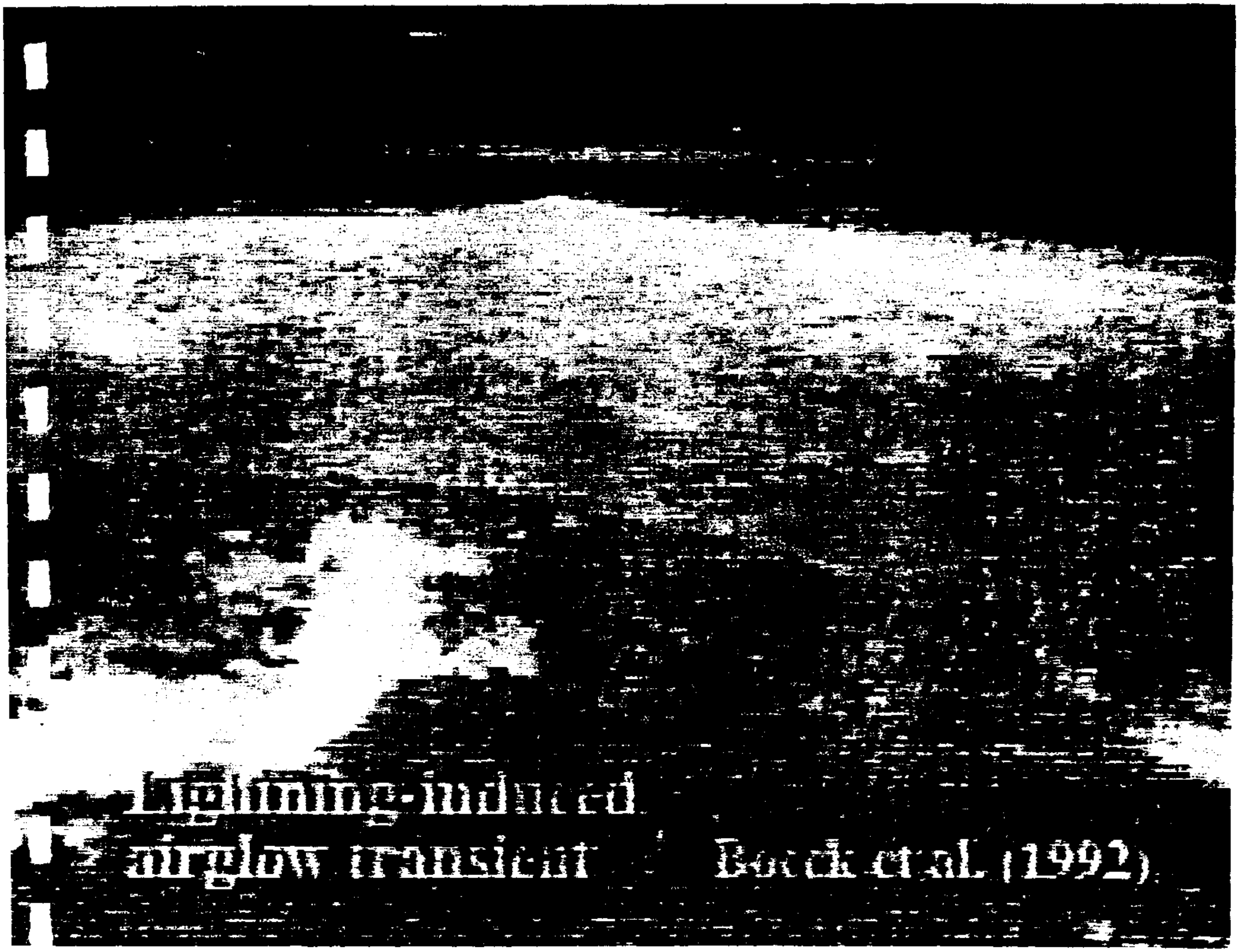


Figure 3-62. Scene from Space Shuttle LLTV showing the broad, disk-like "airglow enhancement" associated with a lightning flash in the cloud below. From Boeck et al. (1992).

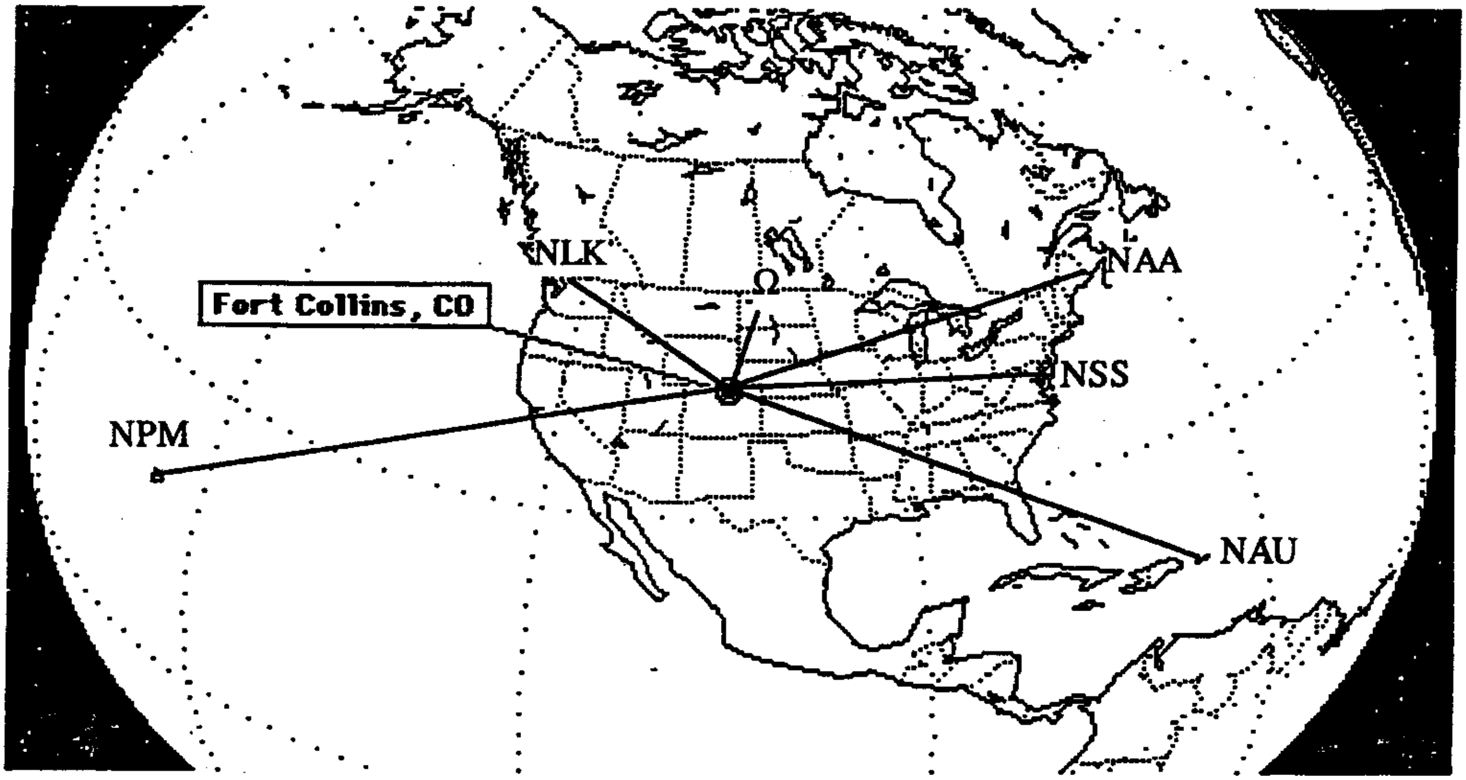


Figure 3-63. Projection onto a plane tangent to the Earth at Ft. Collins the paths from Navy VLF transmitters. Dowden et al. (1995).

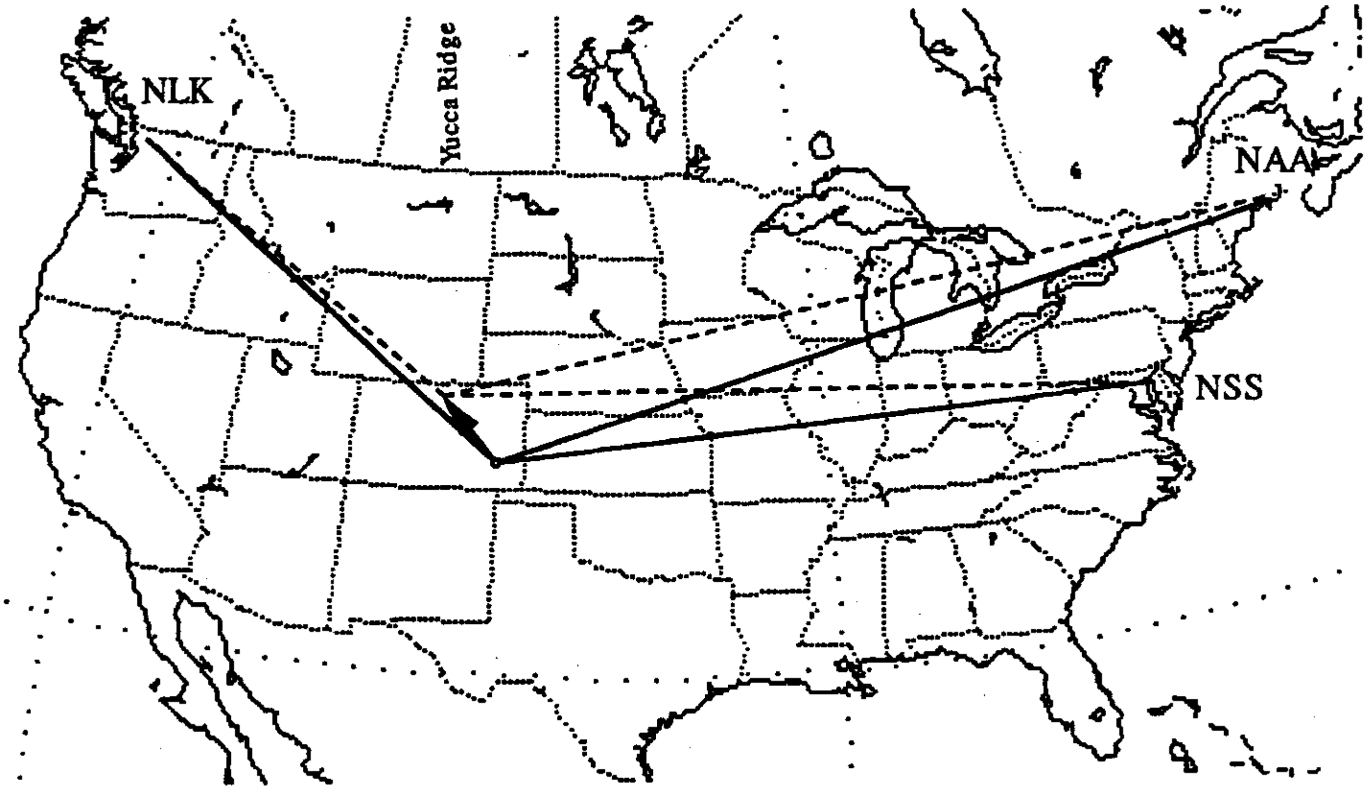


Figure 3-64. Location of the VLF transmitters monitored by OmniPAL. Yucca Ridge is at the point of the arrow. The sprite location for the 0857.53 UTC 23 June 1995 event is indicated by the circle. Note that the NLK wave is scattered almost 180 degrees to produce the perturbation at the receiver. Dowden et al. (1995).

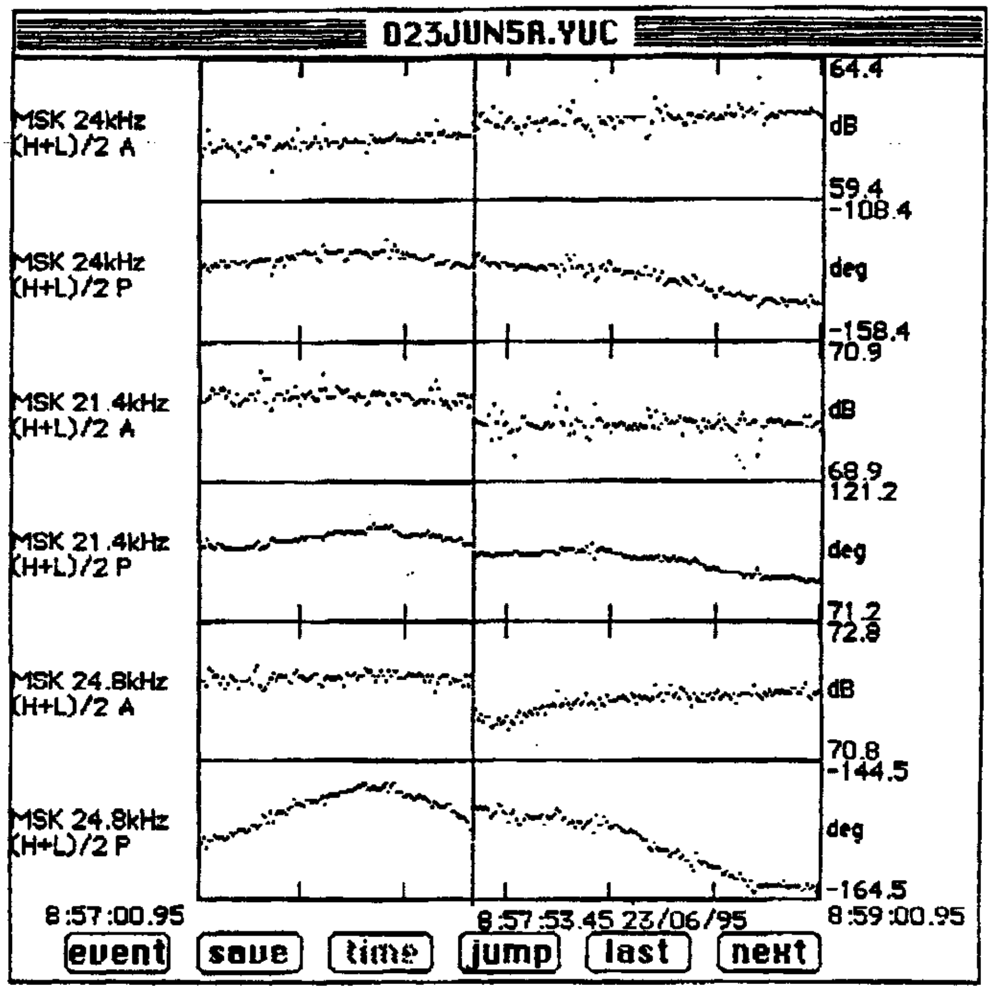


Figure 3-65. Amplitude and phase perturbations on three Navy VLF signals for the 0857.53 UTC 23 June 1005 sprite. Dowden et al. (1995).

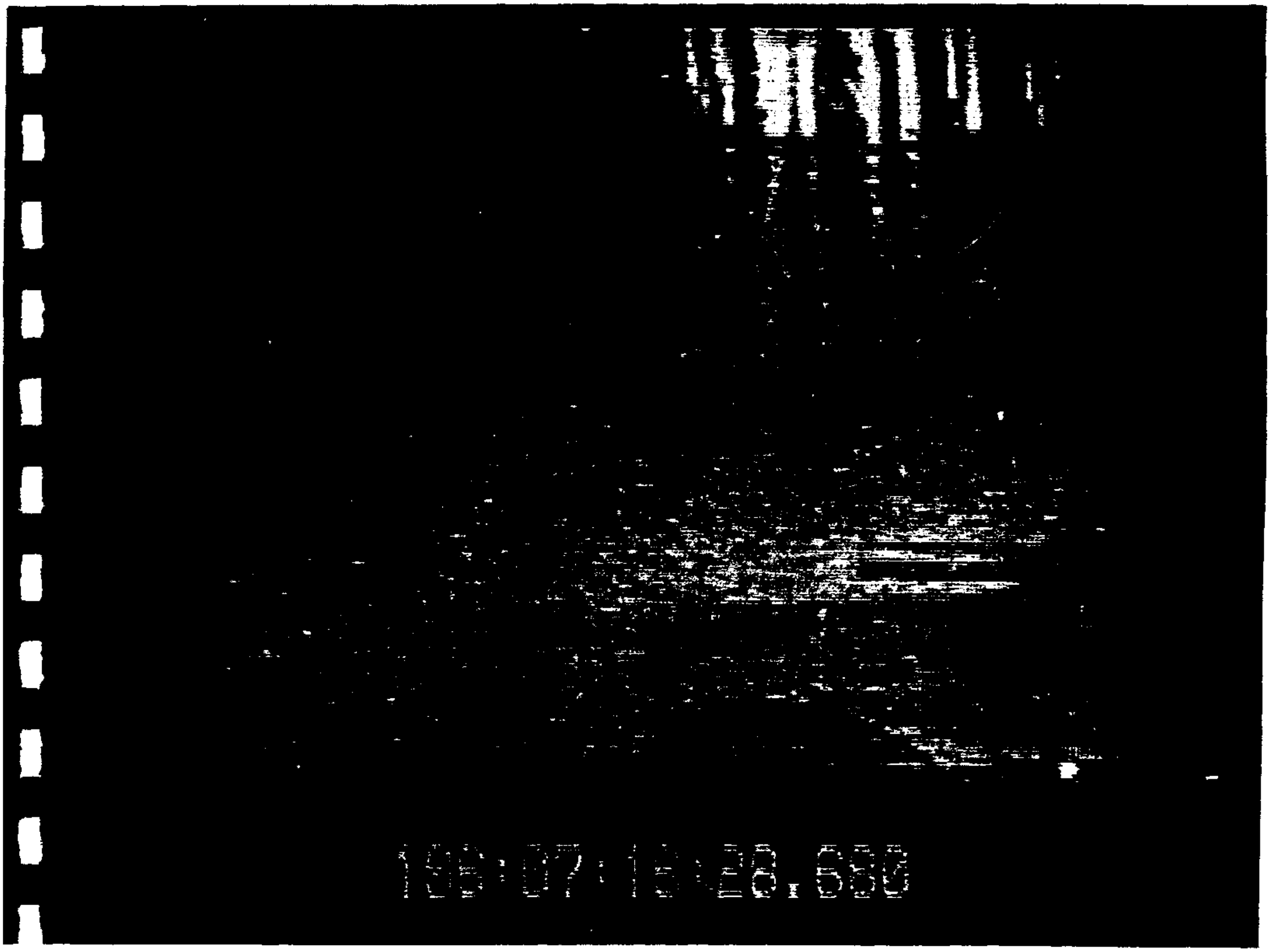


Figure 3-66. The sprite of 0716 UTC 15 July 1995 showing the columnar structure within the sprite more clearly than usual. Light form the CG flash illuminates the cloud obscured horizon. In the foreground is a portion of a satellite receiver dish.

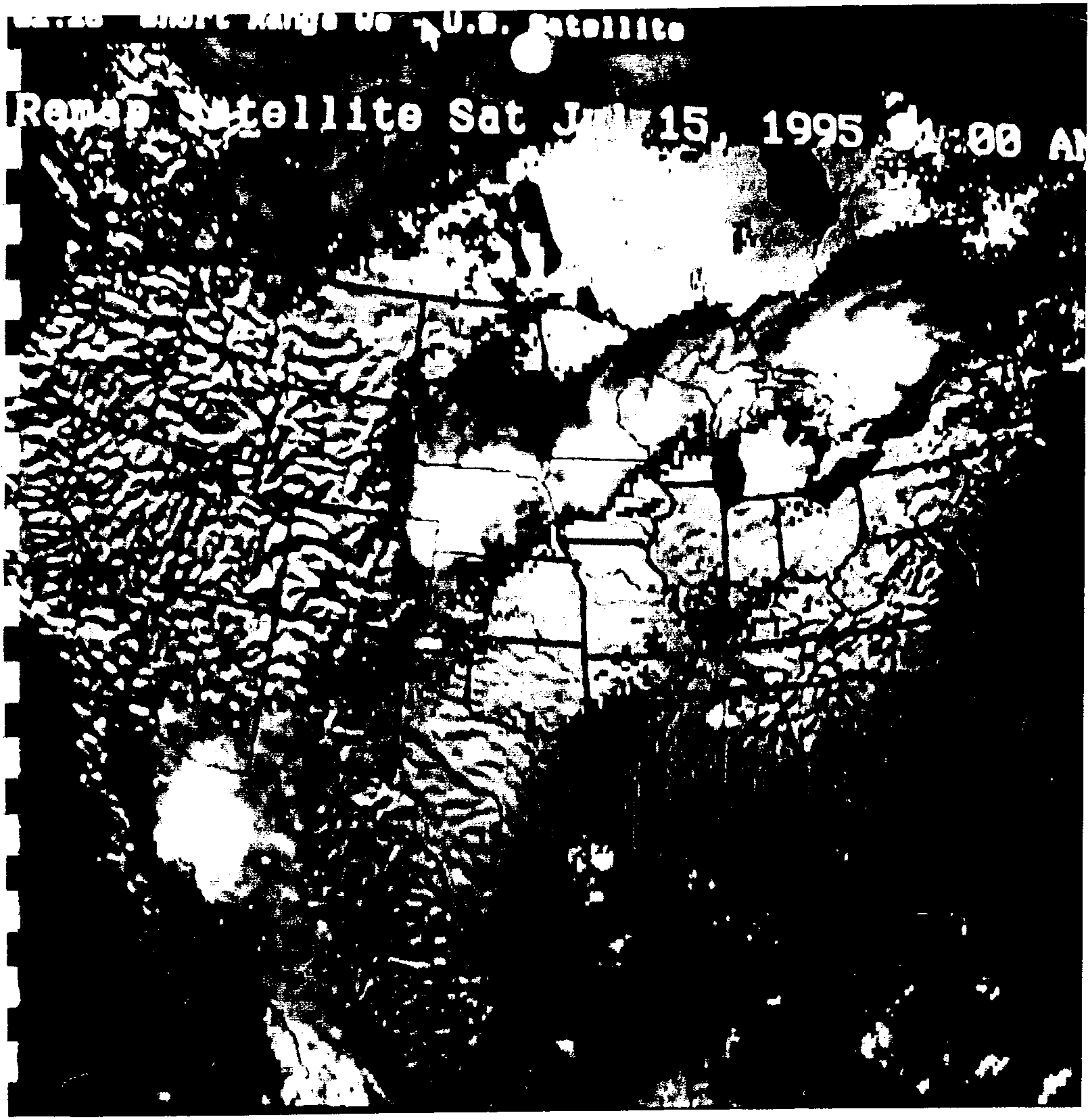


Figure 3-67. GOES IR satellite image, 0600 UTC 15 July 1995.

HQ NASA

4/7/2003

SECTION 3

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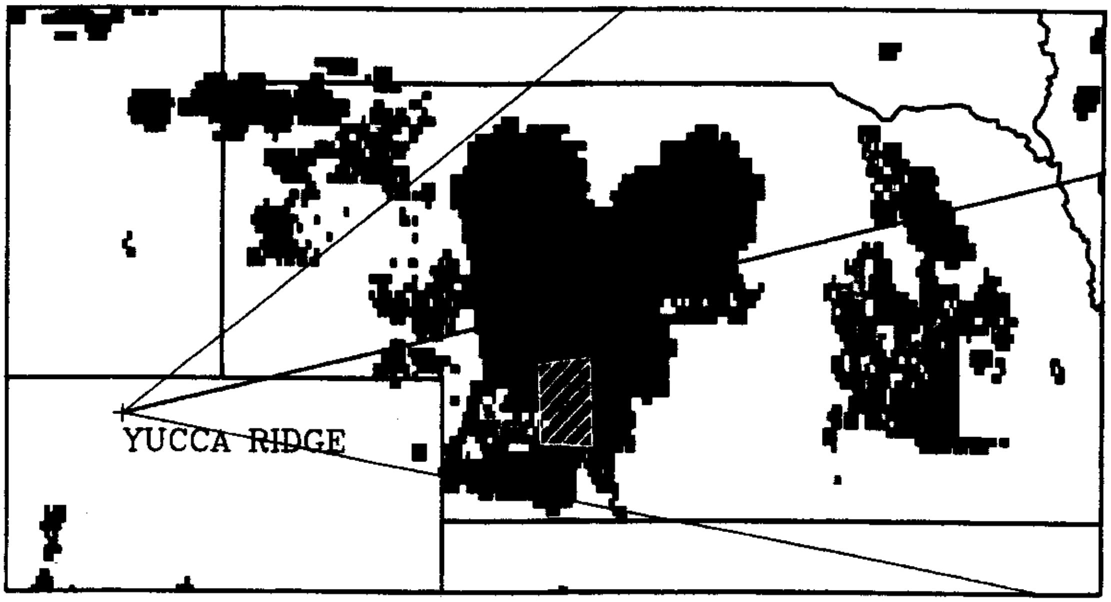
DATE	TIME	LAT	LON	STRENGTH	MULT	AZIMUTH	RANGE	KMEAST	KMNORTH
6/23/95	8:57:46.162	39.946	-97.846	-14.9	3	97.61	606.866	601.528	-80.315
6/23/95	8:57:47.880	40.106	-98.303	-91.4	1	96.35	565.576	562.109	-62.524
6/23/95	8:57:49.717	37.618	-100.802	-25.8	3	133.55	492.321	356.848	-339.175
6/23/95	8:57:51.528	38.583	-102.442	-23.1	3	137.30	315.486	213.932	-231.873
6/23/95	8:57:52.251	38.536	-102.764	-21.6	1	141.82	301.608	186.418	-237.099
6/23/95	8:57:53.306	39.448	-102.742	326.3	1	125.96	231.089	187.057	-135.690
6/23/95	8:57:53.750	38.585	-102.888	-23.7	1	142.82	290.764	175.732	-231.650
6/23/95	8:57:54.142	37.430	-100.662	-18.8	2	134.27	515.871	369.413	-360.079
6/23/95	8:57:55.829	38.489	-102.334	-15.8	1	137.34	329.544	223.333	-242.325
6/23/95	8:57:56.692	40.070	-97.361	-13.6	1	95.92	645.501	642.063	-66.527
6/23/95	8:57:59.664	39.749	-97.812	-21.4	1	99.59	613.862	605.292	-102.220
6/23/95	8:58: 6.489	39.207	-101.714	-29.2	2	120.57	319.444	275.032	-162.488
6/23/95	8:58: 7.554	37.852	-97.918	-22.6	1	117.38	680.845	604.552	-313.155
6/23/95	8:58: 8.837	37.508	-100.710	-16.6	2	133.91	506.715	365.066	-351.406
6/23/95	8:58:11.691	37.215	-100.238	-20.4	1	133.36	559.290	406.645	-383.986
6/23/95	8:58:15.281	41.682	-96.448	-13.2	1	80.99	719.618	710.736	112.717
6/23/95	8:58:15.683	39.184	-101.713	-16.3	1	120.96	320.865	275.163	-165.045
6/23/95	8:58:22.695	39.954	-97.360	-18.2	1	97.04	647.589	642.700	-79.426
6/23/95	8:58:25.782	40.528	-97.820	-13.9	1	91.49	601.326	601.124	-15.601
6/23/95	8:58:26.435	39.207	-101.929	-18.0	2	122.33	303.805	256.701	-162.488
6/23/95	8:58:26.861	39.233	-102.206	-13.8	1	124.41	282.452	233.040	-159.596
6/23/95	8:58:27.357	39.347	-101.873	-15.9	1	119.36	299.692	261.208	-146.920
6/23/95	8:58:27.502	37.196	-100.251	35.3	2	133.59	559.967	405.575	-386.098
6/23/95	8:58:27.694	37.495	-99.967	37.8	1	129.42	555.647	429.231	-352.852
6/23/95	8:58:28.449	38.080	-97.773	-17.5	1	115.04	679.945	616.031	-287.803
6/23/95	8:58:29.060	38.573	-102.410	-40.4	13	137.08	318.175	216.688	-232.984
6/23/95	8:58:32.861	37.621	-100.797	-30.5	2	133.48	492.398	357.271	-338.841
6/23/95	8:58:35.534	38.685	-102.602	-14.6	2	137.78	297.769	200.081	-220.531
6/23/95	8:58:36.620	39.004	-102.298	-27.0	1	129.37	291.773	225.575	-185.060
6/23/95	8:58:37.820	39.302	-101.952	-48.5	1	120.83	296.451	254.563	-151.924
6/23/95	8:58:39.486	38.575	-102.875	-16.7	2	142.77	292.330	176.858	-232.762
6/23/95	8:58:39.589	39.146	-101.769	-27.0	1	122.04	319.065	270.463	-169.270
6/23/95	8:58:42.150	40.452	-98.991	-43.1	1	92.74	503.119	502.543	-24.051
6/23/95	8:58:45.654	39.489	-98.401	-16.1	1	103.26	571.583	556.338	-131.131
6/23/95	8:58:46.289	38.805	-103.001	-21.4	2	141.33	265.354	165.790	-207.188
6/23/95	8:58:47.702	39.751	-98.468	-19.5	1	100.51	558.962	549.577	-101.998
6/23/95	8:58:48.141	39.933	-98.337	-30.8	1	98.31	565.885	559.948	-81.761
6/23/95	8:58:48.325	38.737	-102.795	-61.8	2	139.49	282.467	183.495	-214.749
6/23/95	8:59: 1.696	39.179	-101.727	-17.0	1	121.15	320.138	273.979	-165.601
6/23/95	8:59: 4.753	38.692	-101.647	-36.3	1	127.95	357.352	281.797	-219.752
6/23/95	8:59: 7.072	39.221	-101.188	-18.2	4	116.71	358.048	319.844	-160.931
6/23/95	8:59: 8.233	38.122	-97.704	-22.5	1	114.48	683.205	621.775	-283.133
6/23/95	8:59:11.778	39.185	-101.536	-25.1	2	119.61	333.842	290.253	-164.934
6/23/95	8:59:11.853	39.736	-98.204	-19.9	2	100.27	581.375	572.058	-103.666
6/23/95	8:59:12.122	39.163	-101.758	-21.9	6	121.67	318.836	271.367	-167.380
6/23/95	8:59:13.497	38.650	-102.699	-26.8	2	139.48	295.235	191.829	-224.422
DATE	TIME	LAT	LON	TH	MULT	AZIMUTH	RANGE	KMEAST	KMNORTH

Figure 2-33. Sample of the reprocessed NLDN data including the azimuth and range and northing and easting of the CG event with respect to YRFS.

```
623-1ap.dat
 6 23 95  6 10 46.408 40.447  102.229   130.4   3  95.2  230.90
 6 23 95  6 12 24.147 41.401  100.568   106.9   2  76.1  376.49
 6 23 95  6 37 35.452 39.550  102.390   104.9   2 118.9  250.35

623-2ap.dat
 6 23 95  6 46 10.152 40.323  101.851   125.5   1  97.3  264.63
 6 23 95  6 50 29.834 40.419  101.680    82.3   1  94.7  277.52
 6 23 95  6 57 58.500 40.227  101.790   102.0   1  99.4  271.66
 6 23 95  7  1  8.313 40.519  101.527    83.8   1  92.2  289.36

623-3ap.dat
 6 23 95  7 13 15.788 39.481  102.497    95.8   1 121.5  246.57
 6 23 95  7 17 40.719 39.382  102.838    82.4   1 127.8  229.32
 6 23 95  7 20 52.553 40.361  101.614    76.2   1  95.8  283.91
 6 23 95  7 37 24.610 39.998  101.935    80.2   1 105.3  265.96

623-6an.dat
 6 23 95  8 21 17.083 39.936  101.488   -90.7   2 104.4  304.50

623-6bn.dat
 6 23 95  8 21 17.083 39.936  101.488   -90.7   2 104.4  304.50

623-7ap.dat
 6 23 95  8 57 53.306 39.448  102.742   301.8   1 125.1  231.34
623-7an.dat
 6 23 95  8 34 51.567 38.735  102.821   -82.4   2 139.1  281.23
 6 23 95  8 40 12.907 39.077  102.572   -90.6   6 130.3  268.79
 6 23 95  8 55 18.895 39.127  102.233  -105.2   4 125.6  287.86

623-7bp.dat
 6 23 95  9 11 32.866 39.139  102.978    99.3   1 134.7  238.69
 6 23 95  9 16 16.308 39.708  102.912    79.5   1 121.0  202.95
 6 23 95  9 32 21.470 39.225  102.758   155.0   2 130.0  245.85
 6 23 95  9 36  3.411 39.546  102.247    75.4   2 117.6  261.22
 6 23 95  9 47 22.512 39.428  101.611    82.4   2 114.8  315.66
 6 23 95  9 56 41.624 39.398  101.318    86.4   2 113.4  339.76
 6 23 95  9 58  6.427 39.152  101.668    86.6   1 120.0  326.48
 6 23 95 10  0 52.152 39.167  101.870    88.6   1 121.4  310.89
 6 23 95 10 12 11.786 38.857  101.148    95.1   1 120.5  382.07

623-7bn.dat
 6 23 95  9  9   .605 39.313  101.861  -194.7   1 118.8  302.94
 6 23 95  9  9  4.499 39.413  101.627   -92.4   6 115.2  315.19
 6 23 95 10  1 10.142 38.722  101.451   -87.5   8 124.7  369.07

623-8ap.dat
 6 23 95  9 11 32.866 39.139  102.978    99.3   1 134.7  238.69
 6 23 95  9 16 16.308 39.708  102.912    79.5   1 121.0  202.95
 6 23 95  9 32 21.470 39.225  102.758   155.0   2 130.0  245.85

623-8an.dat
 6 23 95  9  9   .605 39.313  101.861  -194.7   1 118.8  302.94
 6 23 95  9  9  4.499 39.413  101.627   -92.4   6 115.2  315.19

623-9ap.dat
 6 23 95  9 36  3.411 39.546  102.247    75.4   2 117.6  261.22
 6 23 95  9 47 22.512 39.428  101.611    82.4   2 114.8  315.66
 6 23 95  9 56 41.624 39.398  101.318    86.4   2 113.4  339.76
 6 23 95  9 58  6.427 39.152  101.668    86.6   1 120.0  326.48
 6 23 95 10  0 52.152 39.167  101.870    88.6   1 121.4  310.89
 6 23 95 10 12 11.786 38.857  101.148    95.1   1 120.5  382.07

623-9an.dat
 6 23 95 10  1 10.142 38.722  101.451   -87.5   8 124.7  369.07
```

Figure 2-34. Example of sorting NLDN data to show CG events of a given polarity and range within the field of view of he LLTV camera systems.



LIGHTNING STRIKES/RADAR/SPRITES

Box represents calculated sprite location

08/06/94

07:11:42 TO 07:11:42 UTC

CAMERA AZIMUTH 076.0 DEGREES
SPRITE AZIMUTH 083.0 TO 094.0 DEGREES
SPRITE RANGE 318.0 TO 358.0 KILOMETERS

2 positive strikes (+) 0 negative strikes (o)

Figure 2-35. Example of the combination of radar, LLTV and NLDN data. The radar reflectivity at 0710 UTC 6 August 1994 shows the CS. The high reflectivity core is in the southwest part of the system. The field of view of the LLTV systems is shown, along with the angular spread of the sprite at 0711 UTC. The location of the parent +CG of the sprite is shown. The hatched area approximates the area covered by the sprite.

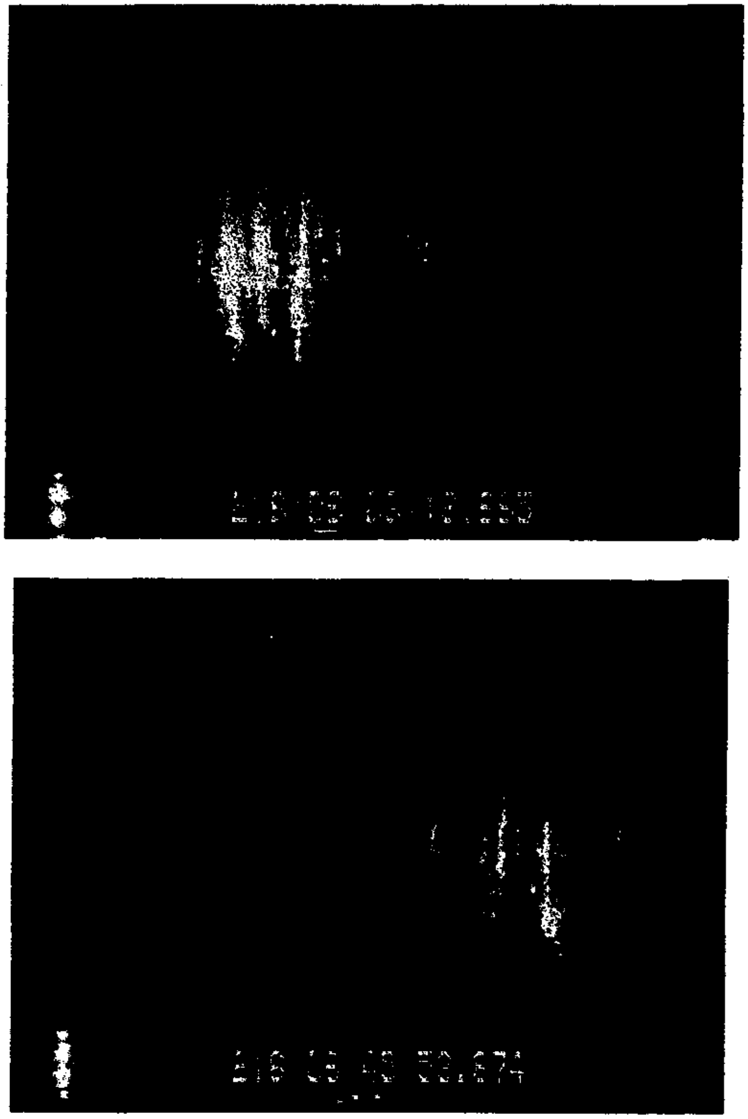
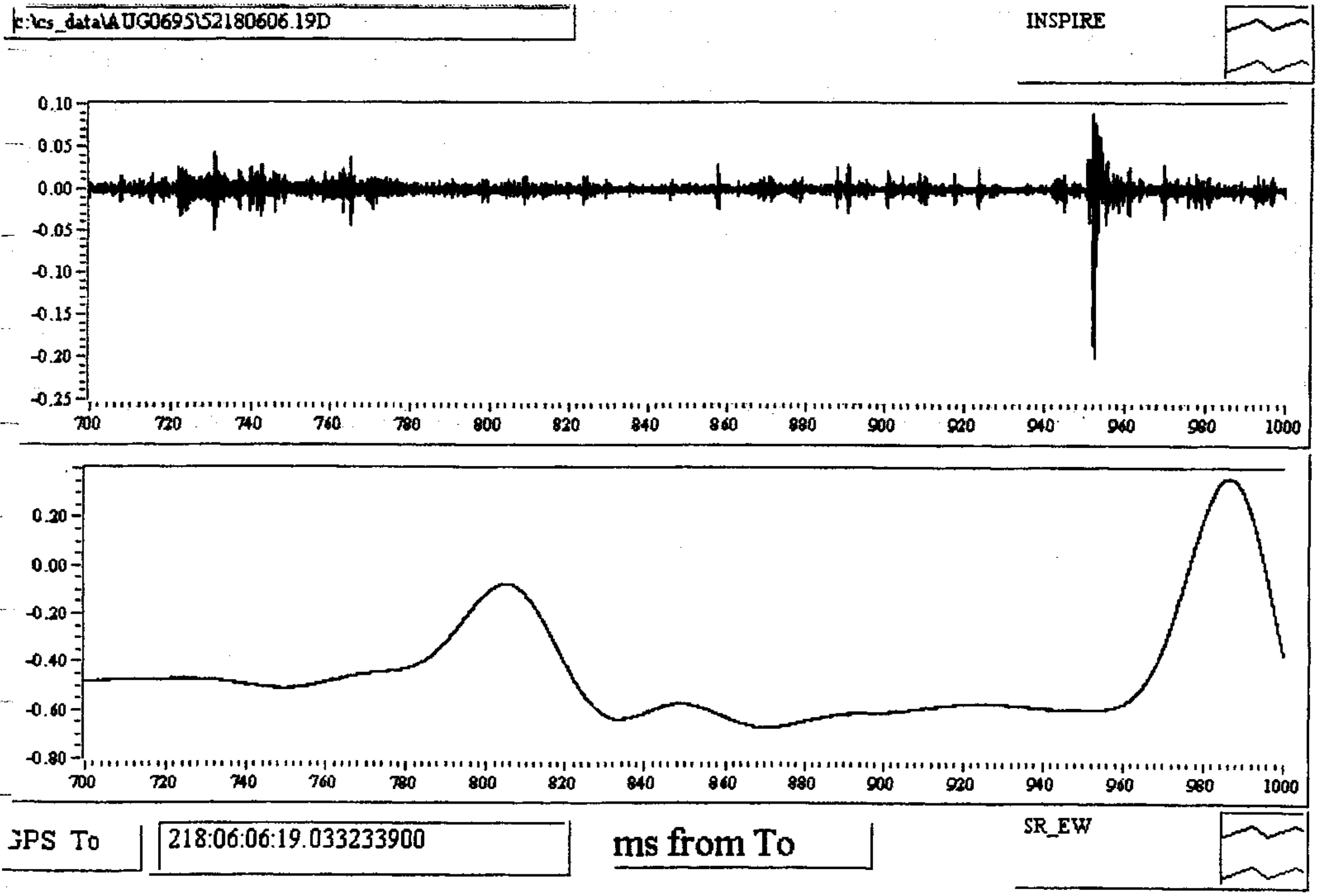


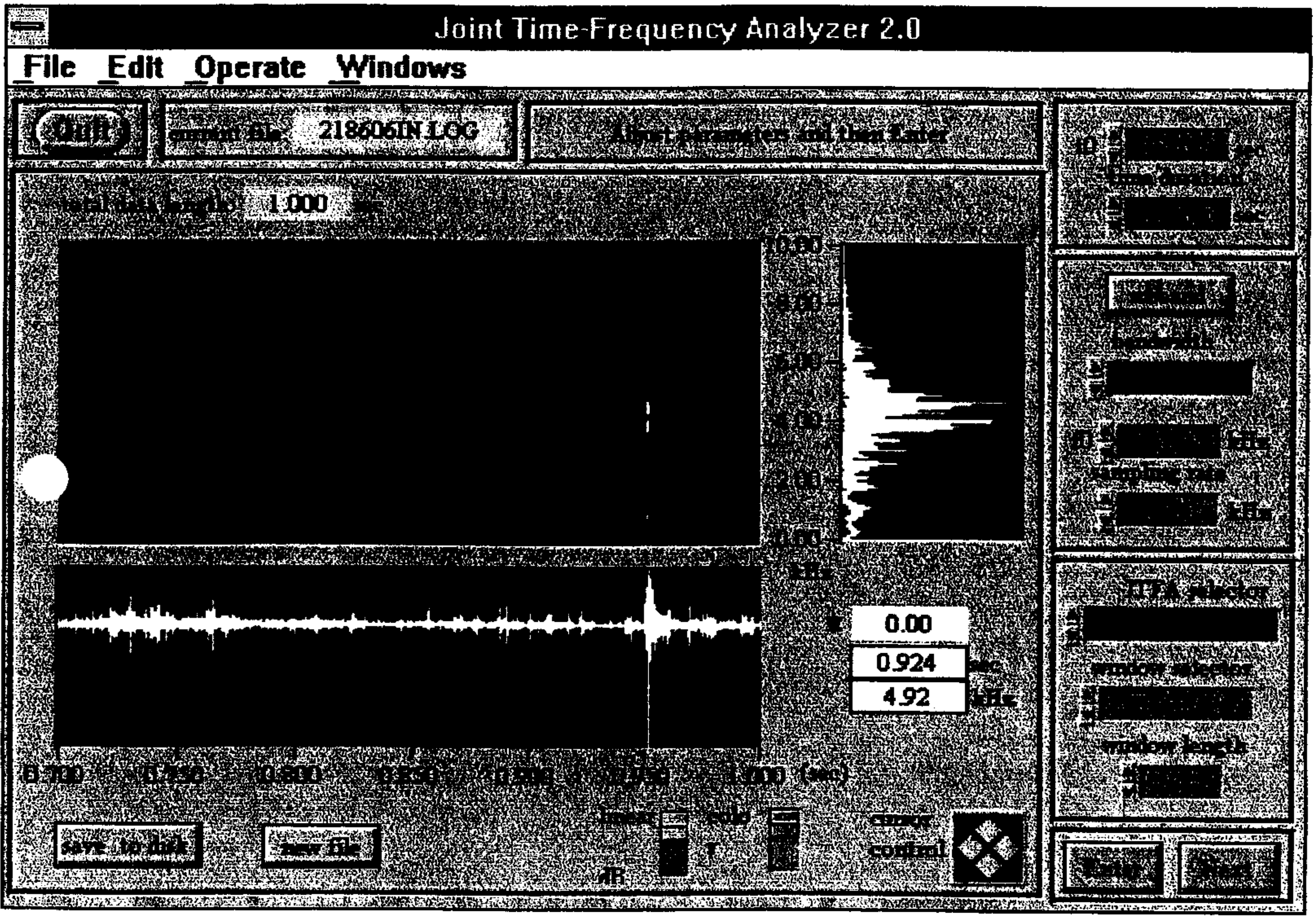
Figure 2-36. Two sprites imaged from YRFS on 6 August 1995, at 0606.19 UTC (top) and 0645.53 UTC (bottom).



c:\cs_data\AUG0695\52180606.19D

GPS To 218:06:06:19.033233900

Figure 2-37. Labview plots of the Inspire and ELF signals for a 300 ms interval containing the 0606 sprite event. This software was created for SPRITES'95 by Robert Nemzek.



current file 218606IN.LOG

total data length 1.000 sec

Figure 2-38. Time-frequency plot of VLF signal intensity for the 0606 UTC sprite.

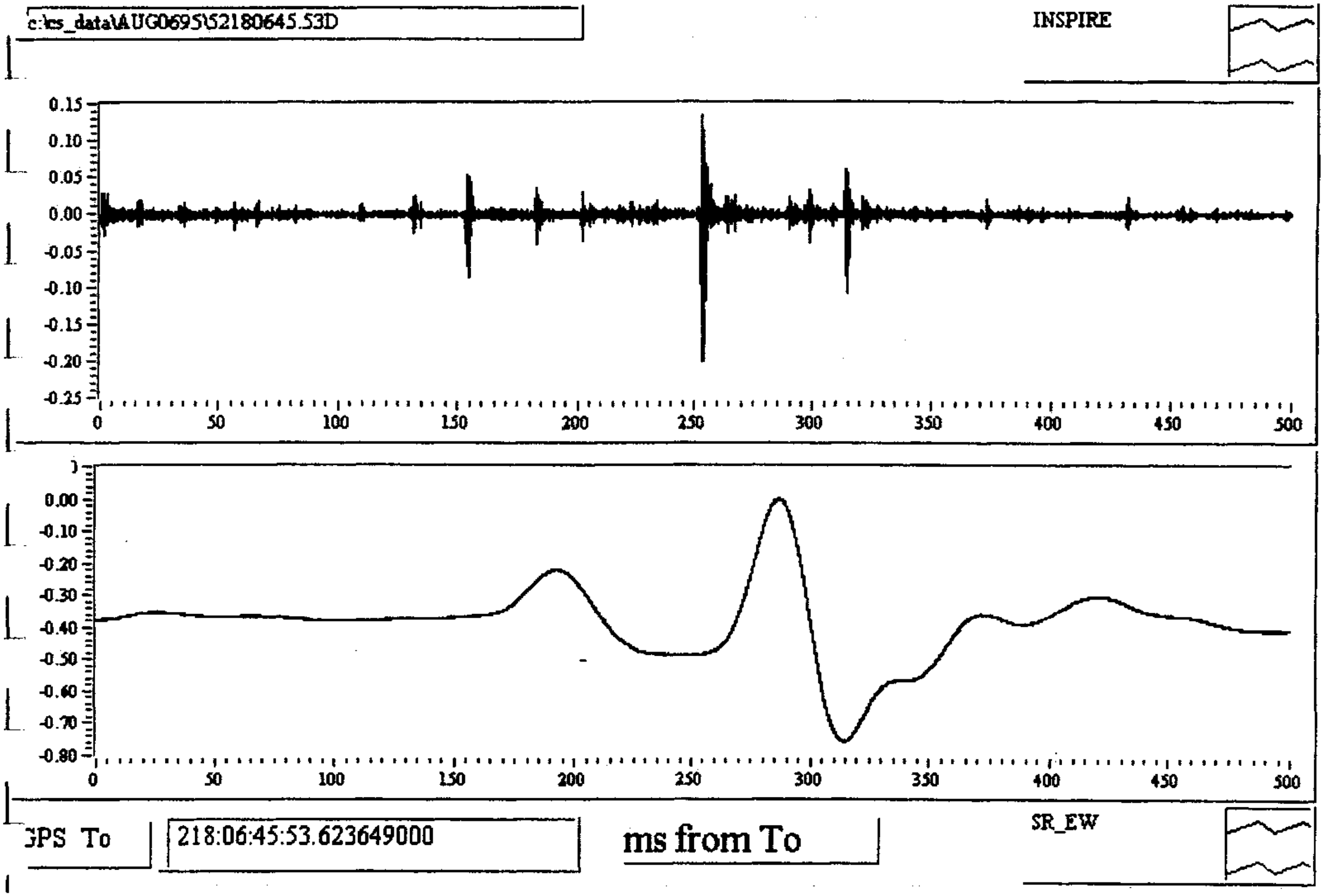
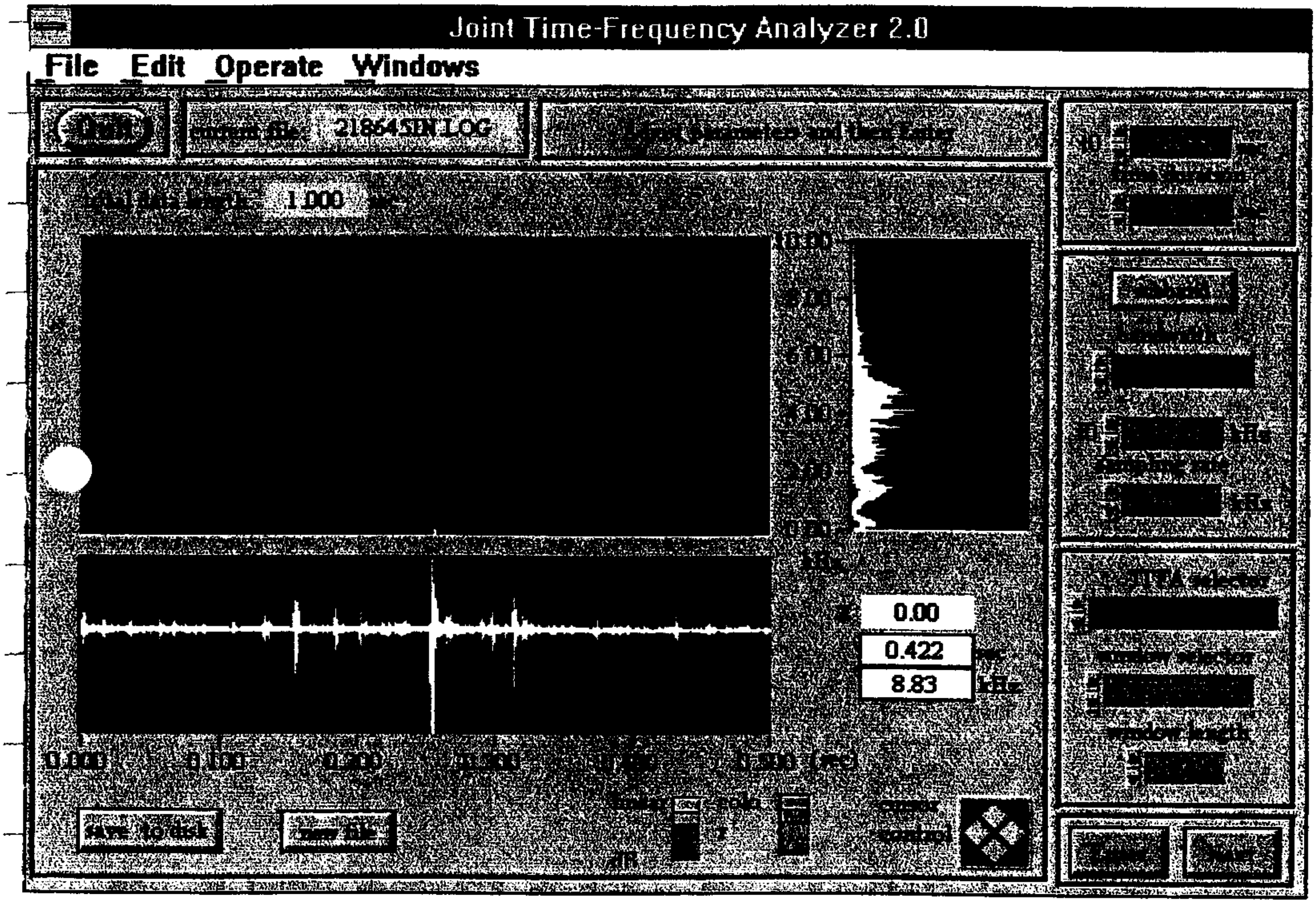


Figure 2-39. Labview plot of Inspire and ELF signals for a 500 ms interval which includes three CG events (A, B, C) visible on the VLF(upper trace)



current file: 21864SIN.LOG

total data length: 1.000 sec

0.00

0.422 sec

8.83 kHz

Figure 2-40. Time frequency plot of VLF signal intensity for the 0645 UTC sprite.

3.0 CASE STUDIES

3.1 Background

During Phase I, detailed literature reviews suggested that what are now called sprites may be found above the anvils of larger than average thunderstorm systems. An initial experiment with low-light television proved the truth of this hypothesis. Sprites were indeed a commonplace occurrence, at least above certain classes of mesoscale convective systems. In Phase II the emphasis shifted to documenting their physical characteristics, developing detection systems, and beginning to understand their overall impact in the geophysical sense, including their potential for interfering with aerospace operations above 15 km. Phase II evolved from a program in which the contractor was to acquire the bulk of the measurements, with occasional cooperation from outside teams, into a full scale international scientific program in which the contractor became facilitator to a large number of participants. This development greatly leveraged the investment of the project by drawing on a vast pool of intellectual and equipment resources. This report, lengthy as it is, only highlights some of what has emerged. In order to put the findings as they are extant to date into some context, we will present a series of case studies. Most of this material is a condensation of scientific papers that have been submitted and in some cases already published in the scientific literature. Most are included with the Appendix materials.

To begin, we review some of the general characteristics of storm systems which produce sprites. at least over the High Plains and central U.S. Figure 3-1 lists the various nights on which operations were initiated during SPRITES'95, the sprite forecasts issued, the number of sprites observed and the times of sprite observations, including their hour of peak occurrence. On some nights more than one MCS was under surveillance. The geographical distribution of the major sprite-generating storms during the 1995 season is shown in Figure 3-2. During this year storms tended to form relatively far from YRFS as relatively dry conditions prevailed over the western High Plains. In other years, one could expect more storms in eastern Colorado, Kansas and Nebraska.

We examined the statistics for the 1995 storms plus five others for which extensive case studies have been conducted (7 July 1993, 10 July 1993, 12 July 1994, 7 August

1994, and 6 September 1994). Figure 3-3 shows the start and end hours for sprite observations at YRFS. This is largely representative of storm behavior but also includes the effects of local cloud obscurations upon sprite viewing. The hour between 0600 and 0700 UTC was most frequently the time of peak sprite activity, though there was a rather broad window between 0500 and 0800 UTC. Once sprites became observable from an MCS, the average duration of activity was slightly over three hours, with a range from a single event to over 6 hours (Figure 3-4). The number of sprites (and elves and blue jets, which are included in these counts) per storm averaged 48, with a range from 1 to 248 (Figure 3-5). The most likely range of sprites per observation period would be between 1 and 25. The thirty storms represented here summarize 5441 minutes of LLTV viewing. With a total count of 1437 sprites that indicates an average rate of 0.26 sprites/minute or an interval of 3.7 minutes between sprites. If only the 1995 storms are used, the interval dropped somewhat to 0.179 sprites/minute with a return period of 5.59 minutes between events.

The Space Dynamics Laboratory of Utah State also conducted parallel LLTV monitoring during SPRITES'95. Their initial count (Figure 3-6) is not the same as ASTeR's since they were using systems with different sensitivities and often pointing in different directions for different intervals of time (M. Taylor, personal communication). A subjective categorization of sprites into bright and faint suggests that on the average about one in three events is noticeably brighter than the others. Their statistics on time intervals between events for a given storm (Figure 3-7) indicate that once a storm begins generating sprites, the reoccurrence intervals are less than five minutes almost 80% of the time. We have also noted, but have not yet quantified, that for extended periods many storms appear to produce sprites at rather regular intervals. After one or two hours, however, the sprites suddenly cease for no obvious reason (based on radar or NLDN activity). After perhaps 30 to 45 minutes, several elves begin appearing, and then gradually elves and sprites become mixed, with a return to the periodic spiriting behavior of the earlier part of the storm. This sequence has been noted informally in several storms and may suggest something about the charge generating processes within the storm.

The massive quantity of data obtained during SPRITES'95 is only beginning to be critically analyzed. This task will extend far beyond the performance period of this contract. The results will, however, continue to be provided to the sponsor as they become available. The following are case studies which highlight some of the initial findings made by the program participants.

3.2 12 July 1994: High resolution optical studies

The XYBION LLTV images obtained during Phase I strongly suggested that the brightest interval of the sprite luminosity occurred within less than one field integration time (16.7 ms). Video could thus not provide any indication as to the rise time of the optical transient or any information about its direction of propagation. A prime task during SPRITES'94 was to gain a better understanding of the relationship between the cloud electrical discharge (as monitored through the NLDN and RF sferics) and the transient luminosity. For this purpose the LLTV system was operated in conjunction with the University of Minnesota telescopic photometer and a 1-to-50 kHz broad band VLF sferics receiver. These results are from a case study conducted on 12 July 1994 presented by Winckler et al. (1996).

On the night of 11-12 July 1994, over 40 sprites were observed above a moderate size MCS over extreme eastern Colorado and western Nebraska and Kansas (Figure 3-8). A considerable number of large +CG events were occurring in this system. Two cameras were used, one in a wide angle mode, the second in a telescopic view (30 mm focal length, 16 x 19 degree FOV) which was co-aligned with the telescopic photometer. A number of sprite events were chosen for detailed analysis. Figure 3-9 shows that the five sprite sequences selected were all associated with +CG flashes with large peak currents averaging above 100 kA. More than half had multiplicities greater than one. The CGs, and thus the sprites, ranged from 252 to 313 km in distance, an ideal range for optical monitoring. Distinct VLF sferics were also recorded simultaneously (within propagation delay) of the +CG detected by the NLDN.

Many of the sprites took on spectacular forms and shapes. One usually bright event has been nicknamed the "angel" and is shown in Figure 3-10. Note the horizon brightening associate with the 106 kA +CG at 266 km distance. The telescopic view of this event (Figures 3-11 and 3-12) reveals a surprising amount of structure, including persistent "hot spots" that last for several fields of video. In other close-ups (not shown), striated and dendritic filaments could also be seen. Many of the wide angle sprite scenes tend to saturate the video system, obscuring some of the fine detail which can be seen in close ups.

The photometer and sferics traces for two of the events are shown in Figure 3-13. The traces for event 1 cover a 30 ms interval. The +CG sferics is coincident with the first rise in the photometer within 1 ms at 0533.28.788 UTC. The photometer trace is double peaked, however. We interpreted the first, smaller peak in the photometer as scattered light from the CG flash and the second peak some 3 ms later as the direct luminosity of the sprite. In Event 4 (the angel) the entire system saturated for close to 10 ms, probably the combined effect of the CG illumination and the sprite.

The photometer traces, however, turned out to be very much at variance with the luminosity as observed on the LLTV system. As mentioned, while the brightest portion of the sprite often only lasts one field, and is typically the first or second in a sequence, there is often a slow decay of luminosity that has continued in some cases for more than 10 fields. Figure 3-14 illustrates the integrated LLTV luminosity (obtained by using image processing software) for an 8 field sequence compared to the photometer trace. Since we know there is virtually no persistence in the LLTV imagery, then either the photometer is malfunctioning or the two systems are sensing different features of the sprite. In fact the latter appears to be the case. Figure 3-15 shows the spectral responses of the photometer and the ISS-255 camera intensifier. As mentioned earlier, the LLTV is essentially red sensitive with no significant response to speak of in the blue. By contrast the RCA 6655A S-10 photocathode is primarily blue sensitive. We note the morphology of the sprites obtained by the GI/UOA airborne color camera missions in 1994 (Sentman et al., 1995) shows the head of the sprite was invariably red but transitioned to blue in the trailing tendrils at lower altitudes (Figure 1-10).

Thus the luminosity indicated by the photometer is likely to be heavily weighted towards the blue tendrils. There is some speculation (see below) that the tendrils in fact represent a separate mechanism (a runaway electron beam) from that which forms the head of the sprite. These are issues which are still unresolved at this time. But they do suggest the need for multi-spectral imaging of TLEs, including the use of CCDs sensitive at the shorter wavelengths. Thus issues about the rise time of the sprite illumination show that it is clearly a sub-field phenomenon but with the possibility that different wavelengths are being excited on different time scales. Also there appears to be a delay of at least several milliseconds between the parent +CG event and the development of sprite luminosity. This will be discussed further below.

3.3 Dual Image Photogrammetry

In both 1994 and 1995 experiments were conducted to obtain long-baseline paired images in order to perform dual image photogrammetry to locate sprites and also determine their relationship to their parent +CG discharge. The GI/UOA group used two aircraft for this purpose in 1994 and the results were reported in Sentman et al. (1995). It was found there appeared to be close spatial correlation between sprites and the parent CG event. Two ground-based programs were also conducted. During 1994, Maj. Perry Malcolm operated a XYBION system identical to those at YRFS from the US Air Force Academy at Colorado Springs, 205 km south of YRFS. The night of 7 September 1994 provided excellent viewing of a storm in Nebraska from both sites. Figures 3-16 and 3-17 show one sprite as imaged by the two cameras. While the video was not time synchronized, the field to field changes in most sprites were small enough so that the center of the sprite could easily be determined from both sites. Using software originally used for multi-site theodolite tracking of missiles, the elevation and azimuth angles to known sprite features were used to back calculate their location. Figure 3-18 shows the calculated location of the sprite centroids compared to the attach point of the parent +CG. The linear separations range from 13 to 111 km, with an average of 42 km. Figure 3-19 shows the distribution of separation distances. These results confirm that the sprite centroid and the parent +CG are closely related in space with separations being no more than the horizontal scale of the sprite itself. This also suggests that the +C can indeed be a reasonable surrogate for the sprite range in single image photogrammetric calculations.

In 1995, a far more detailed dual image study was conducted by Gene Wescott of GI/UOA. An LLTV system was operated, along with a spectrometer, atop 14,000 ft. Mt. Evans, west of Denver. On 19 June, a thunderstorm complex in northeast New Mexico produced sprites that were imaged by cameras at both YRFS and Mt. Evans. Figure 3-20 shows the +CG pattern between 0500 and 0600 UTC. At 0635 UTC a sprite, of the type sometime called a "comb sprite," was imaged at both sites (Figure 3-21 and 3-22). The lower gain in the GI/UOA image permitted seeing a series of at least 15 vertical elements, each on the order of a kilometer across, having relatively uniform tops (around 85 km) and bases (around 77 km). This event was associated with an 84 kA +CG flash. Using the background star field and sophisticated image analysis software, Wescott produced locational data not only for the sprite centroid, but for each element in the sprite (Figure 3-23). The distribution of the sprite elements with respect to the +CG is shown in Figure 3-24 and in close up in Figure 3-25. Of note is the fact that the average distance of the sprite elements from the +CG is only 24 km, although there is a clear concentration of sprite elements to the south and west of the CG. The sprite itself, not an usually large one, is still about 50 across and has a roughly circular aspect.

3.4 12 July and 7 September 1994: Q-bursts, Sprites and Positive CGs

Perhaps the most important development during 1994 was discerning a clear relationship between sprites and +CG events, and in turn with ELF transients known as Q-bursts (Ogawa et al., 1966; Wong, 1996). In the ELF, primary interest has been focused on the Schumann resonance bands (nominally 3 to 120 Hz) first described by Schumann (1954) and studied by many since (Kemp and Jones, 1971; Ishaq and Jones, 1977; Wait, 1992; Nickolaenko, 1995). A detailed theoretical study of ELF wave form propagation has recently been presented by Sentman (1996). ELF Schumann resonance can be thought of as composed of a continuous (background) and a transient mode. The continuous spectra are believed to be driven by the integrated effects of all the global lightning occurrences, with Q-burst events identifiable as transient amplifications of the SR continuous signal by up to 20 dB. These Q-bursts, separated in time by minutes to hours, are thought to be excited by the largest lightning events on the planet (Ogawa et al, 1967; Kemp and Jones, 1971). The magnitude of the background signal has been proposed by Williams (1992) as a surrogate global thermometer, given that there exists a strong relationship between tropical surface layer equivalent potential temperatures and lightning frequency. Sentman (1987) was among the first to note there appeared to be a strong correlation between Q-bursts and especially powerful CG events having positive polarity. Figure 3-26 is an example of Schumann band records showing the background signal interrupted by transient Q-bursts. The interest in Q-bursts comes in part from the fact that they may provide a means for nearly global scale monitoring of large lightning events in which the energy is propagated within the Earth-ionosphere waveguide. Large electrical discharges can in theory detect a half globe away.

Theoretical calculations of the propagation of these ELF waveforms is presented by Sentman (1996) and is illustrated in Figure 3-27. We also note that before sprite observations became routine, Farrell and Desch (1992) had proposed that much of the energy in the "cloud-to-ionosphere" discharge might be concentrated at very low frequencies. Thus as part of the Phase II plan was a goal to determine if sprites and Q-bursts could indeed be related.

On 12 July and 7 September 1994, experiments were conducted in which the sprite events on the LLTV display at YRFS were compared in real-time to the output of the MIT ELF system located at West Greenwich, RI, some 2700 km to the east. It became immediately evident that when sprites were observed, Q-bursts were also very likely to be observed. These results are described in detail in Boccippio et al. (1995) and are summarized in this section. Figure 3-28 shows the experimental design in which a large MCS in Nebraska and Kansas (for the 7 September case) was kept under LLTV surveillance while the vertical electric and the north-south and east-west horizontal magnetic fields were measured. The ELF readings were from a culturally quiet site where long term Schumann resonance background measurements have been made (Williams, 1992). Figures 3-29 and 3-30 show examples of the ELF signals which were sampled at 350 Hz with 12-bit resolution. On the time scale shown in Figure 3-29, a 327 kA +CG event occurred along with a visible sprite which was in turn associated with very large excursions in both the magnetic and electric field at the Rhode Island site on a nearly simultaneous basis. Figure 3-30 shows a similar relationship, along with an apparent reflection of the wave from the antipodal point. Dozens of examples such as these have been collected.

In order to verify that these transients were in fact ELF Q-bursts, spectral analysis of some of the events shows evidence of the entire sequence of SR modes, beginning with the fundamental mode at 8 Hz and extending beyond the power line frequency at 60 Hz, where some distortion is found due to line noise filters. The origin of these transients within the MCS under study was confirmed not only by the temporal coincidence of numerous Q-bursts with large +CG reports from the NLDN, but by applying standard magnetic crossed-loop direction finding methods to the E-W and N-S magnetic signals. For each of nine events, bearings within 10° to 15° of NLDN ground stroke locations (accurate to within 10 km) were obtained.

The common link between sprites and ELF events appears to be the positive CG event. The detection of ELF transients with distant origins requires a large change in the total vertical dipole moment on time scales up to 30 ms (Sentman, personal communication). Thus the sprite related +CG flashes exhibit both unusually large peak currents (as observed by the NLDN) and total charge transfer (as inferred from the ELF signal). This large charge transfer favors an explanation for sprites in which rapid electrostatically induced field changes aloft stress the mesosphere to dielectric breakdown, in the manner proposed by Wilson (1956).

Many of the peak currents in the +CGs reported by the NLDN were unusually large for both days (Figure 3-32). The sprite related +CG peak currents are two to three times the median negative CG peak current and are larger than the peak current of the +CG flashes without sprites (with some overlap). It is clear that sprite formation is favored by large peak currents but this may be neither a necessary nor sufficient condition.

There is rather close agreement between the amplitude of the ELF transients and NLDN peak currents (Figure 3-33). This is to be expected since the two sensors, both crossed-loop magnetic measurements, are observing the same phenomenon at different frequencies (3 to 120 Hz and 1 to 500 kHz).

To achieve dielectric breakdown at altitudes at which sprites are observed, the field change must be fast compared to the relaxation time (which decreases with altitude) in the nighttime mesosphere and should exceed the local breakdown strength which also decreases exponentially with height. Most lightning processes are faster than the relaxation time, which at 80 km is about 10 ms but may vary by an order of magnitude. This mechanism will also be most effective if charge is neutralized over a large region, as a linear or planar charge removal will ostensibly stress a larger region above the storm than a conventional, point-like discharge. This mechanism is consistent with the observed morphology of MCS stratiform regions and many positive discharge events. Electric field soundings have revealed horizontally extensive areas of positive charge in the stratiform precipitation region (Stolzenberg et al., 1994). If such layers are indeed of the same dimensions as the MCS stratiform region, this represents an enormous reservoir of positive charge available to discharges. Moreover, the dendritic network of channels contained in "spider lightning" events is often consistent with propagation through lower positive charge regions (Williams et al., 1990; Mazur and Krehbiel, 1994). The observed charge densities and altitudes and inferred changes in the total dipole moment are evidence that the +CG flashes must be tapping a horizontal region on the order of 100 to 200 km either through long horizontal channels or through spatially extensive dendrites. These scenarios would be favorable for both electrostatically stressing the mesosphere to breakdown and exciting large amplitude ELF transients.

3.5 6 August 1994: Sprites and storm structure

On 7 July 1993, a large mesoscale convective complex in Kansas and Nebraska produced over 25,000 cloud-to-ground (CG) discharges and over 240 sprites (Lyons, 1994). Yet ongoing low-light video monitoring of numerous other storm systems exhibiting extremely high CG rates have demonstrated sprites do not always occur. Why do certain storms generate this phenomenon while others with apparently similar CG activity fail to manifest sprites? Are sprites related to convective storm type or specific CG characteristics, such as polarity or peak current? These and related issues were more completely addressed during expanded, ground-based monitoring over the U.S. High Plains conducted from YRFS during the summer of 1994 (Lyons et al., 1994). There has been found a strong correlation between positive CG flashes (+CG), optical sprites and ELF transients (Boccippio et al., 1995). Additional detailed case studies are now being conducted, of which this is one. This effort is in part directed towards developing methodologies to uncover the relationships between sprites and their parent thunderstorm's electrical activity. The statistics relating sprites to their parent convective storm and its electrical characteristics can provide guidance to the developing and testing of the several theories offered to explain sprite phenomena, of which Pasko et al. (1995), Bell et al. (1995), Taranenko et al. (1993), Rowland et al. (1995) and Milikh et al. (1995) are examples. In addition, such case studies can also be used in the interpretation of laboratory simulations of stratospheric/mesospheric luminous transients such as those of Jarzembski and Srivastava (1995).

On the night of 5-6 August 1994, rather typical of many during the 1994 and 1995 campaigns, a modest-sized MCS formed in southeastern Wyoming around sunset and slowly moved southeastward through Nebraska during the next nine hours. The anvil canopy viewed by GOES at 0700 UTC covered approximately half the state

(Figure 3-35). The radar echo maintained areal coverage of 25,000 to 30,000 km^2 (Figure 3-35). The high reflectivity core was substantially smaller, with the bulk of the radar return being comprised of an anvil-like stratiform precipitation region. The storm was continuously tracked by LLTV from 0310 to 0830 UTC using a 50° horizontal FOV encompassing most of the MCS at any given time. A total of 36 sprites were recorded between 0440 and 0757 UTC. A number of highly structured sprites occurred, such as that portrayed in Figure 3-36, which extends over five video fields. The main morphological features described by Sentman et al. (1995) including the sprite head, dark band, and tendrils are in evidence. The LLTV field of view and the approximate location of the sprite and the candidate for parent +CG are shown in Figure 3-37.

The 2879 negative cloud-to-ground (-CG) and 217 +CG flashes detected between 0440 and 0758 UTC (Figure 3-38) show a tendency toward a bipolar pattern (Orville et al., 1988). The -CGs were largely associated with the high reflectivity core on the western edge of the storm while the +CGs were concentrated further east in the downwind anvil as is typical within an MCS (Rutledge et al., 1990). A smaller storm system over eastern Nebraska did not appear to produce sprites. We note that a plot of the more intense (>75 kA and >100 kA peak current) +CGs shows a rather narrow clustering of the most powerful +CGs in the main stratiform region in central Nebraska (Figure 3-39). This was closely aligned with the corridor of +CGs directly associated with the sprites (Figure 3-40). The large majority of the sprites in this storm occurred above the large region of low reflectivity stratiform precipitation, more than 100 km northeast of the high reflectivity storm core.

A detailed census of the individual sprite characteristics and their associated CG events is displayed in Figure 3-41 with half-hourly synopses exhibited in Figure 3-42. It is immediately apparent that 34 of the 36 sprites were temporally associated (within 500 ms) with a +CG. Only a half dozen -CGs occurred within 1000 ms of any sprite, with time intervals usually being seconds or more. Given that the estimated detection efficiency of the NLDN for +CGs is about 90%, this strongly supports the contention of Lyons et al. (1994) and Boccippio et al. (1995) that sprites may be almost uniquely associated with +CG events. Moreover, as summarized in Figure 3-43, the sprite +CG had an average peak current 2.7 times that of the other +CGs within this storm system (81 kA versus 30 kA). The highest sprite +CG peak current was 196 kA, the smallest 32 kA. In fact, 32% of the sprite +CGs had peak currents of under 50 kA, suggesting that unusually large +CG peak currents may not be a necessary condition for sprite formation. There is also a discernible tendency for the sprite +CG flashes to have multiple strokes (35% versus 11%) and higher flash multiplicity (1.41 versus 1.13) than non-sprite +CGs (figure 3-43). This may imply that the discharges associated with sprite producing flashes are comparatively complex.

With no moon, clear skies and a compact storm system only 300-350 km distant, viewing conditions were excellent on this night. All of the sprites were associated with visible cloud flashes in the video, as compared to only 39% during the 7 July 1993 (Lyons, 1994 a,b) in which a much greater horizontal path length through the deep cloud system obscured the lightning flash. Furthermore, 16 of the 36 sprites were detected with the dark-adapted naked eye by observers scanning the region above the parent storm. The airborne campaigns of the University of Alaska using color cameras have substantiated that sprites are uniquely red in color (Sentman et al., 1995), as have recent spectral measurements (Mende et al., 1995). It is curious to note that on 6 August 1994 the human eye perceived 37.5% of the sprites as green, 25 % as orange, and only 37.5% as red or salmon pink. This is most likely an artifact of the poor color response of the human eye at low light intensities. It may, however, explain the rather large variance in the colors found in the historical reports of sprites (Lyons and Williams, 1993). While Malan (1937) described sprites in his eyewitness account as being salmon red in color, Wilson (1956) perceived green flashes above thunderstorms. Those +CGs that produced visible sprites tended to have higher peak currents (89 kA) than those in which visible sprites were not noted (66 kA), perhaps suggesting a link between +CG charge transfers and the intensity of the optical emissions.

The duration of the sprites on 6 August 1994 ranged from 2 to 16 video fields (33 to 267 ms), with a mean of 7 fields (117 ms). Some of the longer events were in fact clusters of sprite elements forming and dissipating, possibly in response to long lasting in-cloud electrical discharges manifesting themselves as "spider" or dendritic lightning in the anvils. The first field was the brightest (estimated by qualitative inspection of the video) in 65% of all cases (75% if the sprite was visible to the naked eye), and the brightest was either the first or second field 92% of the time. Most sprites probably attain their maximum brightness within the first 1-10 ms, then gradually decay in luminosity as suggested by Winckler et al. (1995) and Fukunishi et al. (1996). Figure 3-41 shows a very close temporal correlation between the start of the 16.7 ms video field containing the first sprite luminosity and the parent +CG time. In all but three of the 36 sprites the +CG time preceded the sprite start time, but never by more than 1 video field (average 7.3 ms), implying that the sprite always lags the +CG. High speed photometer readings of CG flashes and sprites during the SPRITES'95 field program confirmed that the sprite luminosity can lag the cloud flash by up to tens of milliseconds (see below). The sprite illumination most likely begins shortly after the brightest part of the cloud flash and often terminates before the cloud illumination does. This characteristic was noted in the analyses of sprite videos taken by the Space Shuttle low-light camera (Lyons and Williams, 1993; Boeck et al., 1995). In this storm, the average sprite onset lag was 39 ms, 67 % occurring within 17 ms of the reported +CG time. A few cases showed lags as large as 307 ms. This could imply an earlier +CG causing the sprite was not detected, or that extensive horizontal in-cloud components of the discharge, some of which can extend over 500 ms in a large MCS, were also involved in the sprite-generating process.

Using the +CG location to fix the distance and the elevation measured from the video sprite image, the vertical extent of the sprites was estimated (Figure 3-44). The mean top was 77 km (5.1 km standard deviation) with a range from 64 to 88. The mean detectable lower limit was 50 km (8.8 km standard deviation) with a range from 31 km to 68 km. These estimates are believed to be generally accurate within 10 km. They are somewhat lower than the mean upper limit of 88±5 km obtained by Sentman et al. (1995) from triangulated airborne images. The generally lower values may reflect either a bias in the estimation technique or perhaps some storm to storm variability in sprite heights. There are no clear cut cases where the tendrils could be seen attached to the cloud top. This in part stems from obscuration due to blooming of the image in the bright glow above the illuminated cloud as well as the fact that at lower altitudes the tendrils are likely to have a higher proportion of blue light to which these cameras are not sensitive. The maximum altitude of the sprites showed little trend with time and was relatively insensitive to the magnitude of the peak current (Figure 3-45) though a slight positive correlation can be discerned. The sprite aspect ratios (angular width divided by angular height) varied from 5.0 to 0.28, with a mean of 1.84 (standard deviation 1.04). This suggests that for this storm the typical sprite was almost twice as wide as it was high. Initial experience suggests this characteristic may vary considerably from storm to storm. There was a discernible tendency toward aspect ratios increasing with time during this storm.

As in Figure 3-37, the angular dimension of the sprite was plotted and the range estimated by the +CG location for each event. In fully 50% of the cases the +CG azimuth was contained with the angular breadth of the sprite. Assuming the range of the sprite center and the +CG to be coincident, we measured the lateral distances of the +CG location to the estimated center of the sprite and found the displacement to average 35 km. This supports the previously estimated average displacement of 42 km. For this storm the +CG location was directly beneath or south of the sprite center in all but one of the 36 cases. This is suggestive of large horizontal channels of "dendritic" or "spider" lightning radiating outward away from the storm's interior, a frequently noted observation by High Plains storm watchers.

The sprite frequency was not evidently correlated to the overall CG rate in the storm, which shows a modest peak about an hour before the maximum number of sprites (Figure 3-46). Between 0300-0850 UTC there was a total of 4670 CGs of both polarities, of which 7% where positive. The +CG flash rate remained relatively constant throughout the period and did not appear strongly correlated with the number of sprites. As in a number of other storms, the sprites did not begin until one to two hours after the MCS reached critical size and developed significant numbers of +CGs. This could mean that some sort of pre-conditioning of the mesosphere above the storm is required before sprites can occur. While frequent +CGs seem to be a necessary condition for sprite formation, it may not be a sufficient one. This aspect will be investigated in future studies.

During the peak sprite period (0600-0800 UTC), 22% of the detected +CGs produced sprites (Figure 3-47). This percentage is known to have been both considerably lower and higher in other storms, the exact range awaiting documentation from the 1994 and 1995 data sets. Once the sprites did commence at 0440 UTC, as mentioned, 92% were associated with +CGs. All sprites were +CG related in the three hour period starting 0500 UTC. During the 0310-0850 UTC observation period, 1 CG out of 137 (of either polarity) resulted in a sprite, with the ratio increasing to 1 in 91 during the active sprite period. One interesting aspect of this storm was that the peak current of the +CG producing sprites rose steadily with time (Figure 3-48), reaching a maximum of 196 kA on the final event. This trend was not duplicated by the non-sprite producing +CGs (Figure 3-48). Large amplitude +CGs did not necessarily result in observable sprites. At least eight +CGs with amplitudes greater than 81 kA (the average sprite producing value) occurred without producing a sprite. The question of the VLF and ELF signatures associated with sprites is being treated elsewhere in this report and in other papers (Boccippio et al., 1995; Inan et al. 1995; Dowden et al., 1995). We do note, however, that on 6 August all but four of the sprites had a distinctive audio signature coincident with the visible sprite as recorded on the video tapes.

Another feature of the 6 August 1994 MCS seen previously and subsequently is the tendency of sprites to concentrate in a relatively small portion of the storm. Despite the storm filling virtually all of the 50° FOV of the low-light camera, sprites would typically be bunched in a very narrow (5-10 degrees) range of azimuths (Figure 3-49). While this window would translate across the FOV as the storm traveled, more than 50% of the sprites were within 5° azimuth of its predecessor. This suggests that a relatively small portion of the large stratiform region generates sprite conducive conditions.

Sprites (as well as elves) appear to be uniquely related to +CG events, usually with large peak currents and a greater probability of multiple strokes than the remaining +CG population in a storm. Yet all large +CGs do not generate sprites or elves. Why? Some have proposed meteors as possible triggers, but this is easily disproved by viewing hundreds of meteors during sprite episodes which show no correlation to TLEs whatsoever. While the possible role of secondary cosmic rays serving as a trigger has been suggested (Bell et al., 1995), they are likely to be relatively ubiquitous. While the evidence is still circumstantial, we propose that the sprite generating +CGs are associated with unusually large charge transfers resulting from intracloud "spider" or "dendritic" lightning known to accompany many +CG events and contributing to the large continuing currents known to occur under these circumstances. The stratiform precipitation region of large MCS storms is favorable to horizontally extensive and layered regions of positive charge generation due to in situ charging mechanisms within the anvil system (Rutledge et al. 1993; Stolzenburg et al., 1994). Our knowledge of these events is severely limited as the NLDN only detects the return current of a CG strike and not the remainder of the electrical discharge within the cloud. The Lightning Detection and Ranging (LDAR) System operated at the Kennedy Space Center (Lennon and Maier, 1991) can map the entire lightning channel within the cloud as well as the CG component. Horizontally extensive discharges on the order of 100 km have been noted in connection with large +CG events (L. Maier, personal communication, 1995). Charge transfers in excess of 200 C during such events have been postulated (E. Williams, personal communication, 1995). Since a large anvil region is by definition required for such long horizontal discharges, this may well explain the minimum size requirement for sprite storms discussed below (typically one dimension is in excess of 150 km). Figure 3-50 summarizes a number of statistics that can be derived from an analysis of this kind.

3.6 23 June 1995: Elves and VLF holography

On the night of 23 June 1995 a moderate sized MCS developed over eastern Colorado. Its cloud canopy and radar reflectivity size and pattern along with the NLDN lightning reports suggested conditions would be favorable for sprites (Figures 3-51 to 3-53). Equipment including the LLTVs and the Tohoku University pointing photometers were trained on the volume above the thunderstorm. Twenty three TLEs occurred at ranges between 200 and 300 km from YRFS.

At 08857.53 UTC an unusual image was obtained (Figure 3-54). In its center was an apparent sprite, but that structure was surrounded by a large diffuse glow. A single field later (Figure 3-55) saw the sprite remaining but little sign of the glow. The same glow was noted in the LLTV image that was positioned to look about 40 degrees counterclockwise, one in which the sprite was outside the field of view. This transient luminous event was associated with a very powerful (326 kA) +CG event located at 232 km and 126° azimuth. There was also a very powerful broad band VLF sferic recorded on the STAR lab system at this time (Figure 3-57).

Several previous experiments had observed transient luminosity increases in the night sky using photometers (Nemzek et al., 1989; Winckler et al., 1993) many of which were short (less than 1 ms) events, although some were of longer duration (20 ms). The source of the short events, always coincident with sferics, was speculated to be the Rayleigh scattered light from distant lightning, whereas sprites were proposed as possible sources of the longer events (Winckler et al., 1993). These images suggest another phenomenon might be responsible.

The multichannel high-speed photometer output was combined with the STAR Lab sferic record (Figure 3-58). The upper panel shows the luminosity variations measured by the photometer over a 40-ms interval, with one photometer channel without a filter, set at 15° elevation, while the remaining two channels, one without a filter and the other with a red filter set at 9° elevation. There are clearly two luminous transients, an initial short duration burst and a longer duration event starting some 6 or 7 ms later. In the enlarged display of the initial 3-ms burst, the two channels at 9° elevation exhibit a single peak with a rise time of 200 μs and decay time constant of 300 μs, while the upper channel shows a double peak structure consisting of the same first peak but also a second burst with a rise time of 200 μs and a decay time constant of 170 μs. Based on the VLF recordings, the first peak is nearly coincident in time with the onset of VLF sferics. It is estimated that one unit of the unfiltered channel response equals 10 kR of light intensity.

The two bursts of luminosity were clearly distinct phenomena but occurred sufficiently close in time to be contained within the single 16.7 ms field of video (Figure 3-54). The sequence apparently shows the scattered light from the cloud flash, followed within 350 μs by what was initially called a lower ionospheric flash. This time difference is essentially the speed of light assuming the altitude of the flash to be between 75 and 100 km. This strongly suggests the flash is a response to the electromagnetic pulse (EMP) of the energetic lightning discharge. From this analysis arose the name elves: emissions of light and VLF perturbations from EMP sources. The singular is elve, to avoid the obvious confusion resulting from the use of elf.

Elves are extremely brief (<1 ms) and very bright, reaching a peak luminosity of up to 10 mR, which is substantially brighter than most sprites. This indicates that the lower ionosphere is heated significantly during these events. This response in fact had been previously predicted by Inan et al. (1991) and Taranenko et al. (1993) and most recently modeled by Inan et al. (1996). These observations in fact closely resembled the original theoretical predictions.

Figure 3-59 shows one of many additional cases. The elve again appears within the propagation time of the EMP from the +CG flash. A sprite appears, but this time is delayed by over 40 ms. This delay lends further credence to the concept that sprites are a quasi-electrostatic response to the transport and/or rearrangement of large quantities of charge by the complex cloud discharge marked a NLDN-detected +CG event. The tendency for sprites to lag to the +CG time has been noted above.

Elves can appear either in isolation or as part of a sequence which includes a sprite. Figure 3-60 shows a large elve which appeared at 06187.17 UTC on 25 June 1995 from a 213 kA +CG within a storm in northern New Mexico some 500 km to the south southeast of YRFS. The glow at the bottom of the picture is from the city lights of Denver. No sprite followed the elve. Figure 3-61 (top) shows two successive video fields in which an elve appears above the upwelling scattered light from a +CG flash over South Dakota which is then replaced within 16.7 ms by a very bright columnar sprite (bottom).

Now that elves have been identified as a separate phenomenon with its own morphological characteristics, it is clear that these events have been noted before. It was commented by Lyons et al. (1994) in the AGU video presentation that "airglow enhancements" may often accompany sprites. The much discussed "airglow brightening" (Figure 3-62) seen in a Space Shuttle video and discussed by Boeck et al. (1992) appears in retrospect to be an elve. If the physical mechanisms postulated by Taranenko et al. (1993) are in fact correct, than it is a misnomer to refer to this phenomenon as an "airglow" effect.

On 23 June as well as many other dates the OmniPAL VLF receivers installed by the University of Otago monitored strong perturbations in the phase and the amplitude of the various US Navy VLF transmissions. Figure 3-63 shows the paths from the various Navy transmitters (NLK, NPM, NAA, NSS, NAU and the North Dakota Omega station). For the event at 0857.53 UTC on 23 June, an intense perturbation was noted on the NLK signal, which originates northwest of YRFS. Since the elve/sprite was located to the southeast of YRFS, this strongly implies the NLK wave was back scattered almost 180° to produce the perturbation recorded (Figure 3-64). Figure 3-65 shows the perturbations in several VLF signals as recorded by the OmniPAL receiver at YRFS. By the time of the 15 July case, two OmniPAL VLF receivers had been established, the original at YRFS and the second at the JILA Tower at the University of Colorado in Boulder. Distinct and different perturbations were recorded at both sites for the various sprites. Previous use of a closely spaced (wavelength/2) array of VLF receivers lead to the discovery of wide angle scattering (to at least 50°) by lightning-induced plasma of VLF waves traveling in the Earth-ionosphere waveguide (Dowden and Adams, 1993). This implied that such plasma has narrow lateral dimensions and/or is highly structured (scale ≈1 km) but possibly of considerable vertical extent. Such a stalactite structure is suggested in the sprite shown in Figure 3-66. Such wide angle scattering means that sprites occurring in any direction and within 500 km or so of the receiver can be detected and roughly located even using a single low-cost receiver. By using an array of such receivers, including some spaced less than wavelength/2 apart, would greatly increase the ability to detect and local sprite events (Dowden et al., 1996). During 1996 this theory will be tested along the Front Range.

3.7 15 July 1995: VLF disturbances and a blue or red jet?

The 15 July 1995 case was among the more interesting of the SPRITES'95 campaign. During the early evening, cloudy skies along the Front Range had obscured the view of a large MCS system to the east over Nebraska, but by 0600 UTC skies had begun to clear (Figure 3-67). The MCS had a large stratiform region (Figure 3-68) and was producing a steady stream of +CG events (Figure 3-69). The storm was oriented so that the family of sprites, elves and a possible blue jet that it produced were in the direct line of the Navy transmitter at Annapolis, MD (NSS).

VLF perturbations on signal propagation along great-circle-paths (GCP) through electrically active midwest thunderstorms have been found associated with sprites observed from aircraft and at YRFS (Inan et al., 1995). These constituted some of the first evidence that the physical processes leading to sprites also alter the conductivity of the lower ionosphere. These perturbations were suggested to signify ionization changes resulting from the heating of the lower ionosphere by EMP from lightning (Inan et al., 1991) or ionization columns associated with sprites (Dowden et al., 1994). Heating of ambient electrons by quasi-electrostatic thunderstorm fields due to massive charge transfer in clouds was suggested to produce both sprites and large ionization changes (Pasko et al., 1995). During the 12 July 1994 episode discussed above, several of the sprite-associated +CGs were within ±50 km of the GCP path between the NAA receiver in Maine and the STAR Lab receiver in San Diego. There were distinct amplitude fluctuations induced in the 24 kHz NAA signal. These results suggested that VLF fluctuations would be detected although apparently only if the disturbed ionospheric regions were within ±50 km of the GCP being monitored.

On 15 July 1995 an entire series of VLF amplitude perturbations on the 21 kHz NSS (Annapolis) signal were observed in conjunction with specific sprites and elves by STAR Lab (Figure 3-70 and 3-71). In the broad band VLF signatures were also noted (Figure 3-72). These data are still undergoing extensive analysis by the STAR Lab team.

This date was interesting from another standpoint. Within a single 11 minute period there was a spectacular display of sprites, elves and what may be the first ground-based video of a blue jet. One of the more spectacular sprites was discussed in Figure 2-8. Figure 3-73 shows a combined elve and sprite associated with a 185 kA +CG some 326 km distant from YRFS. Figure 3-74 shows a six video field sequence of what may be a blue jet. It was not associated with any apparent CG event of either polarity. It rose at a slight angle from the vertical from behind a bank of clouds. It had a bright head and a dimmer tail. If it was at the same distance as the sprite activity in the storm, its rate of ascent was about 140 km/sec and rose to a height of around 50 km, which is close to the values of a typical blue jet computed by Wescott et al. (1995). In the fifth video field, the jet was momentarily surrounded by what appeared to be a ring of small sprites. A close up of this scene is presented in Figure 3-75.

What remains puzzling about this event is the fact that Wescott (personal communication) has reported that blue jets imaged by the GI/UOA airborne missions were in fact almost exclusively blue when analyzed using the R, G and B signals from their color video. The XYBION LLTVs have very little response in the blue. Thus this could be a "green" or a "red" jet. It also resembles the "rocket lightning" event seen by the Space Shuttle analyzed by Boeck et al. (1995). That event was the only in the 20 or so TLEs from the Shuttle that appeared to exhibit some detectable upward propagation. The possibility remains that the "blue jet" of 15 July 1995 may in fact be yet another type of transient luminous event.

3.8 16 July 1995: Spectra and photometric

In June 1995, the GI/UOA group obtained the first optical spectra of sprites from their Mt. Evans site in Colorado (Hampton et al., 1996). These spectra showed the dominance of the N_2 1PG band. A group from Lockheed Martin was able to confirm these findings by a series of spectrometer measurements made from YRFS during the following month (Mende et al., 1995; Rairden and Mende, 1995).

On the night of 16 July 1995 a small but active thunderstorm near the Black Hills in South Dakota produced about 24 sprites and elves. The small cluster of +CGs associated with his storm are shown in Figure 3-76. The sprites and elves on this night were unusually photogenic as can be seen from Figure 3-77, which also shows the anvil of the distant thunderstorm along with the upwelling light from the in-cloud discharge. [Images from this night were used in the widely distributed Lockheed Martin false color sprite poster which is hanging on meteorologists' office walls across the country.]

The instrumentation used for spectral measurements was a copy of the transmission grating spectrometer used in Shuttle-borne aurora and airglow investigations. It resolves from 450 to 800 nm. Figure 3-78 shows a typical spectra obtained. The N2 1PG system was the only emission detected. Taranenko et al. (1993) predicted the N2 1PG system would be the brightest emission to occur in lightning-stimulated upper atmosphere emissions. However this result also implies that the electrons in the sprite had insufficient energy to efficiently ionize the nitrogen. Energies would thus be substantially less than 100 eV. If so this casts doubt on the prediction of Chang and Price (1995) and others attempting to explain the observations of energetic electrons (gamma rays) above thunderstorms as observed by the Compton Gamma Ray Observation (Fishman et al., 1994).

On the same night, another series of optical measurements were conducted by Russ Armstrong (MRC) which lead to a potentially conflicting opinion (Armstrong et al., 1996). Armstrong deployed a narrow band pointing photometer system specially filtered for the 427.8A nm band. The system had a 3° half angle field of view, an 80 ns time constant and a quantum efficiency at 427.8 nm of 17%. It was sampled at 750 Hz by a PC based system. On 16 July 1995 the photometer was aimed at the same series of sprites from which the spectra were obtained. Very strong signals above background were obtained for both sprites and elves (Figure 3-79). By contrast to the spectrometer results (which do not reach to this shorter wavelength) this provides a contrary indication of potentially significant ionization in either part of the sprite structure or within an elve.

3.9 24 July 1995: Elves and sprites

Many other case studies are now in progress. A few highlights are included. One of the best viewing nights was 24 July 1995 when exceptionally clear skies allowed imaging over 200 TLEs associated with a large MCC in central Oklahoma. Figure 3-80 shows the +CG distribution during the hour of highest TLE counts. This storm produce large numbers of sprites and elves, along with numerous excellent Q-burst transients recorded at the MIT Rhode Island site. Of current interest is the characteristics of the CGs associated with both sprites and elves. Analysis of data from this storm continues to indicate that elves, like sprites, are exclusively the product of CG flashes which lower positive charge to ground. They also are consistently more powerful than those responsible for sprites, which are in turn possessed of peak currents greater than non-TLE producers. In 69 +CGs that were sprite parents, the average peak current was 58 kA with the largest being 113 kA. For 14 +CGs associated with elves, the average peak current was 104 kA with the peak being 200 kA. A compilation of sprite and elve CGs characteristics from the 23 June, 15 and 16 July 1995 cases (Figure 3-81) shows an even larger disparity between the peak currents of +CGs producing sprites versus elves. Also while the weakest +CG to induce a sprite was 18 kA, the smallest associated with an elve was 42 kA.

3.10 27 June 1995: Long distance sprite monitoring

It had been estimated at the beginning of Phase II that the maximum practical range for sprite detection using optical means from YRFS was on the order of 1000 km. During 1995 several nights of viewing proved this assertion. Figure 3-82 shows a cluster of +CGs associated with a sprite producing storm system approaching Lubbuck, TX, some 950 km distant from YRFS. Over 80 TLEs were logged that night. Some actually appeared to emerge from below the horizon (Figure 3-83). This capability is of potential value since line of sight optical and RF emissions from the parent thunderstorms are effectively blocked, allowing investigations of only those emissions from the sprite/elve zone itself. Figure 3-84 shows an example from the Tohoku photometer of an elve and sprite detected at this great range.

3.11 Gnomes: other unexplained transient luminous events

At the beginning of Phase I, we were confronted with a bewildering variety of reports of strong luminous events above active thunderstorms. With the finding that sprites are relatively commonplace occurrences, much of the mystery began to fade. But the totally unexpected discovery of blue jets by Wescott et al. (1995) and the imaging of the theoretically predicted by heretofore unseen elves began to indicate that stratospheric and mesospheric phenomena may be very complicated indeed. It is now expected that as more and varied types of sensors are applied to monitor the volume above thunderstorms that additional "creatures in the mesospheric zoo" will be identified. Somewhat in jest, these yet-to be identified phenomena have been informally (and not for public release) termed "gnomes," signifying "goofy nocturnal optical mesospheric emissions from something." There already exist a number of candidates.

A local resident volunteered that in August 1990 she twice saw thin, straight lightning bolts discharging to great heights from a pinkish glowing region atop a rapidly building MCC moving east into the Plains. Her uncoached illustration is shown in Figure 1-7. It resembles some of the reports quoted in Vaughan and Vonnegut (1989). This phenomenon was also seen by project technical manager Thomas Nelson while flying on a commercial jet between Denver and Minneapolis in July 1994. Near sundown, while the plane was circumnavigating a large MCC, a brilliant, long lasting (≈500 ms) lightning-like column shot from the cloud top to at least twice the height of the parent cumulonimbus (Figure 3-85). This could be thought of as a true upward traveling cloud-to-stratosphere lightning discharge. There has been no systematic monitoring above the tops of thunderstorm during the daytime to record such a phenomenon. There are no known recordings of this phenomenon.

On 6 June 1989 NASA research balloon flight 1482P experienced a premature flight termination and unplanned impact of its valuable instrument package west of Ft. Worth, TX. The altitude of the system at the time of failure was 110,000 feet. The failure occurred while overflying a large thunderstorm complex containing active lightning. Analysis of the singed components in debris from the $1 million electronics package indicate the premature release was caused by an electrical discharge in the flight termination electronics package which was induced by lightning activity in the area. A blue jet or an upward superbolt is at least a plausible explanation for this still largely unexplained event.

The growing public awareness of TLEs has resulted in a flood of stories from persons previously unwilling to divulge their observations. One recent letter was received from a man in South Australia who provides highly credible descriptions of what could only have been red sprites that he had been able to repeatedly observe with his naked eye. This region is thought to have numerous sprites based upon the VLF research of Dowden and Adams (1993). Yet another observation published in the 1996 Weather Guide Calendar (Figure 3-86) is more problematic. The report discusses a discharge from an active tropical thunderstorm in which an enormously powerful discharge shot from the ground, completely through the cloud mass, and out the top in a purple helix that appeared to stretch upward into space. While the writer believes he witnessed a blue jet, there are too many details which suggests this may be yet another type of phenomenon.

A letter received from a former USAir pilot, Air Force ECM officer and amateur radio ham is quoted below. It is clearly not the work of a crackpot (though many such letters have been received by ASTeR). An accompanying sketch is shown in Figure 3-87.

> "We saw the fountain-jet about spring 1984...somewhere between Oklahoma City and Midland, TX, southwest bound and at an altitude of 39,000 thousand feet. The sun was already set and the sky and thunderstorm tops were bright and distinct....the captain nudged me soon after I noticed it. My first perception was of a decorative water fountain, circular planform, and parabolic trajectory of the individual drops...overshooting hail was my second perception. This did not last long. No movement or imperfection in the shape could I see and the whole shape turned off for a fraction of a second. My perception settled on a glowing corona discharge. Most of the time it was lighted and flickered off something like an aged florescent lamp. Mostly it was on. The flickering had no movement to it...I believe I remember a column or stem. The general arrangement reminded me of an umbrella as well as a fountain. The color was white as is lightning, not as bright however.......I have made an estimate of the height of the protuberance as between one and five thousand feet....It passed off

> to our right side....the top of the thunderstorm was 45,000 to 50,000 feet...."

There is simply no category under which to file such a report. The same holds true for the following observation made by the PI himself.

The author visually observed a brief but brilliant, plume-like column during the night of 6 July 1992 from the YRFS. Thus conditions were ideal for viewing of events near the horizon. A few minutes before 0500 UTC, a very brief (<100 ms?) fountain of brilliant, blue-white (lavender?) light was noted at about 20° azimuth. It extended only a short distance (less than one solar diameter) above the horizon. It flashed rather than pulsed. It had an apparent tilt from the vertical of perhaps 25° and appeared to be somewhat bifurcated. This was a singular event. Also no distant "heat lightning" or other signs of convection were apparent. An infrared GOES image at 0500 UTC suggests that the plume emanated from the anvil region of a mesoscale complex in extreme southwest North Dakota. This is a distance of approximately 725 kilometers. Simple geometric calculations show that the entire cloud was below the horizon and only the upper portion of a plume extending some 40 km above cloud top could be visible at that range. The effect of atmospheric refraction does allow an observer to see somewhat over the horizon (by approximately an additional half degree), but even accounting for this it is fairly certain that the event was one of great vertical extent, on the order of 50 to 100 kilometers. This phenomenon was clearly neither a sprite nor blue jet and has not been noted since in three years of video monitoring.

Other unusual events have been imaged on the LLTV system. On the night of 12 August 1994 a strange pillar of light moved from left to right (about 20° of azimuth) across the top of the video screen during a sprite monitoring session. The translation took approximately 350 ms (Figure 3-86), gradually increasing, then dimming in intensity. It was clearly not a sprite. Had it been at the same location as the sprites under surveillance that night it would have been over 200 km high. This night was also unusual because it was the only night in two years that whistlers were recorded using the Inspire receiver. At the time of the moving luminous column, there were no unusual sferics, whistlers or CG events.

An even stranger display occurred during sprite monitoring on 7 September 1994. This time the pillar light blinked on and off at 1.3 second intervals, while moving from left to right across the screen (Figure 3-89). There were no whistlers, CG events or sferics that were coincident. There is no evidence that these were reflections of any kind. These images have been widely shown to the space physics community but no hypotheses as to their true nature have been forthcoming.

At least one luminous phenomena been explained. On one night during the SPRITES'95 campaign, in the direction of the MCS that was being kept under surveillance, it was possible to see on the LLTV, and indeed with the dark adapted naked eye, a series of greenish striations emanating from below the horizon (Figure 3-90). These in fact represent local enhancements in the airglow above 90 km as the result of local density variations from upwelling gravity waves from the sprite generating thunderstorm (Taylor and Hapgood, 1988). It has been speculated that some of the structure of the sprites might in fact be due to the modulation of local density by upward propagating gravity waves of this type (Alexander et al., 1995).

It is clear that the stratosphere, mesosphere and ionosphere regions above thunderstorms are directly influenced by tropospheric electrical processes. This area of the atmosphere once thought to be electrically rather quiescent is, in fact, home for a growing number of transient luminous events. While three major classes have already been identified, it seems almost inevitable that more await to be discovered. It is important for researchers to keep an open mind in the interpretation of their newly arriving data sets. Attempts to explain all reports in terms of the three TLEs currently agreed upon could prove inappropriate. Future measurement program plans should be open to the possibility of detecting as yet unknown phenomena and be alert to this in the processing of data.

THE 1995 SPRITE CAMPAIGN - OPTICAL MEASUREMENTS AT YRFS

JULIAN DAY	DATE	SPRITE FORECAST	NUMBER OBSERVED	SPRITE START-END TIMES	PEAK HOUR (UTC)
170	19-Jun-95	N/Y	(0) (9)	0356-0711	05-06
171	20-Jun-95	Y	4	0647-0737	06-07
172	21-Jun-95	Y	17	0752-1011	09-10
174	23-Jun-95	Y	23	0639-0956	09-10
176	25-Jun-95	Y	2	0522-0700	06-07
178	27-Jun-95	Y	85	0444-0856	06-07
185	04-Jul-95	Y	51	0509-0832	07-08
188	07-Jul-95	Y	14	0405-0750	05-06
189	08-Jul-95	N/Y	(0) (50)	0551-0927	08-09
190	09-Jul-95	N	0		
192	11-Jul-95	N	0		
193	12-Jul-96	Y	1	0700-0800	07-08
194	13-Jul-95	Y	13	0421-0617	04-05
196	15-Jul-95	Y	38	0528-0731	06-07
197	16-Jul-95	N/Y	(0) (24)	0438-0632	05-06
200	19-Jul-95	N	0		
201	20-Jul-95	Y	46	0340-0921	08-09
202	21-Jul-95	Y/N	(5) (0)	0431-0551	04-05
203	22-Jul-95	Y	6	0434-0642	05-06
204	23-Jul-95	Y/Y	(3) (4)	0621-0729	06-07
205	24-Jul-95	Y	225	0311-0929	07-08
206	25-Jul-95	Y/Y	(18) (11)	0335-0639	05-06
207	26-Jul-95	Y	53	0347-0717	06-07
208	27-Jul-95	Y	91	0429-1035	07-08
212	31-Jul-95	Y	29	0501-0622	05-06
213	01-Aug-95	N	0		
215	03-Aug-95	Y	52	0323-0709	05-06
216	04-Aug-95	Y	51	0307-0817	06-07
217	06-Aug-95	Y	50	0315-0711	06-07

Figure 3-1. Summary of sprite observations and forecasts during the 1995 season.

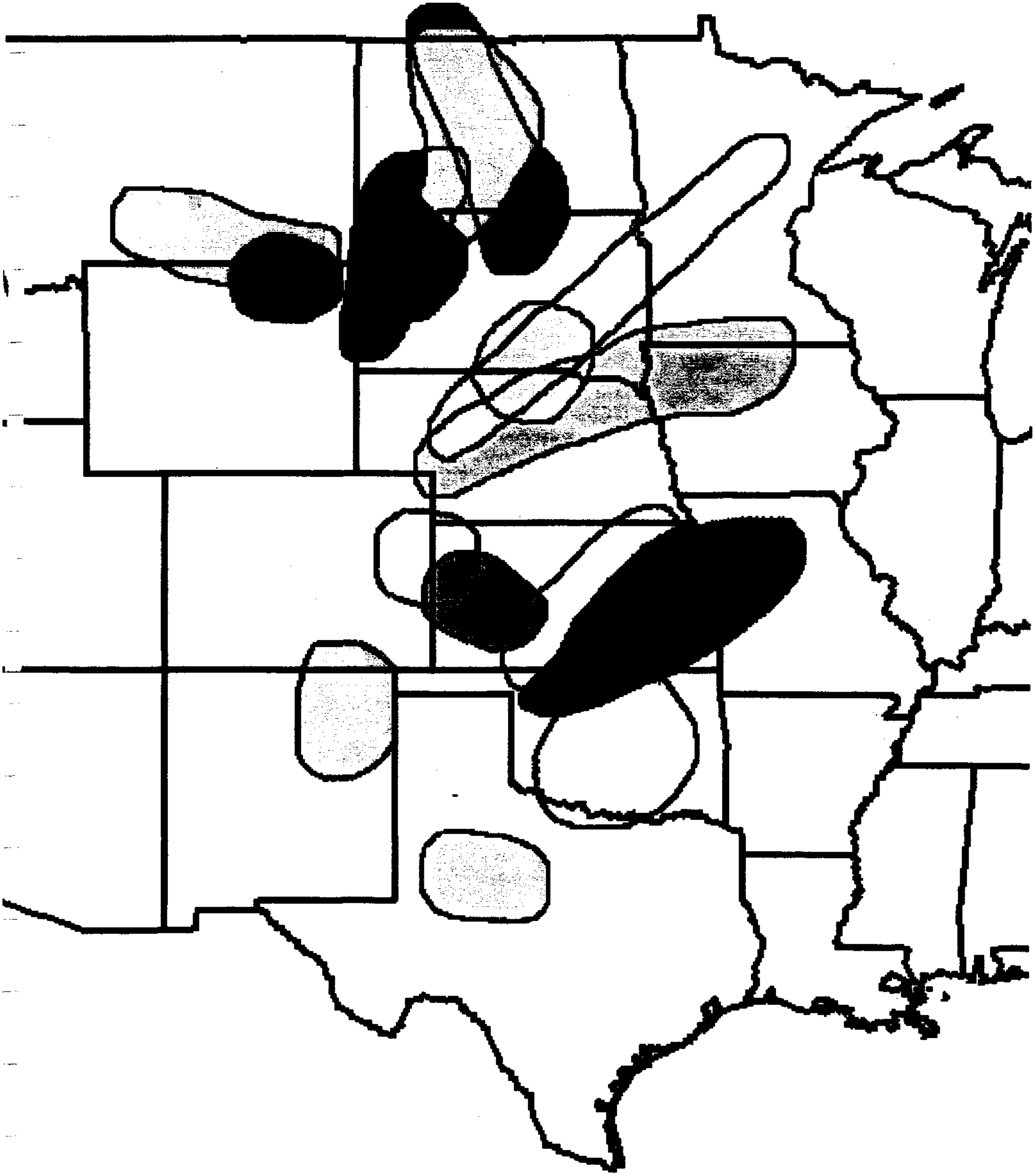
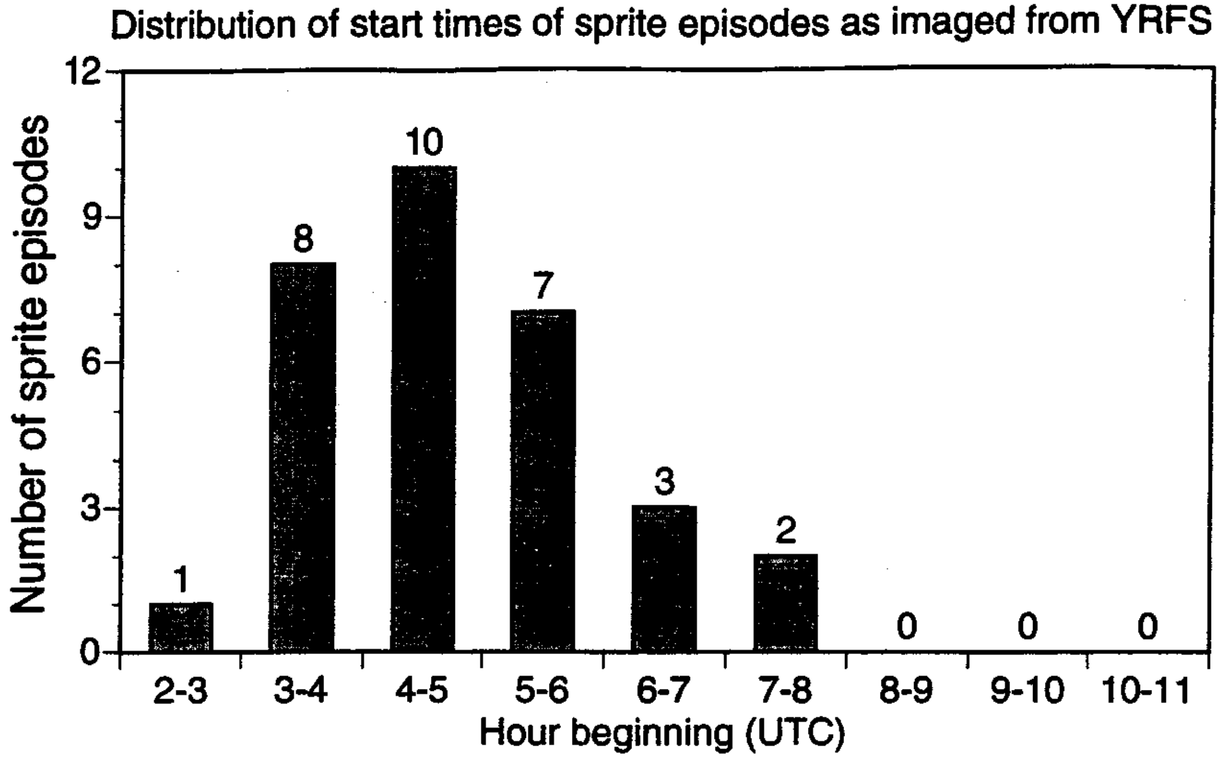


Figure 3-2. Areas of major sprite generating storms during the 1995 season



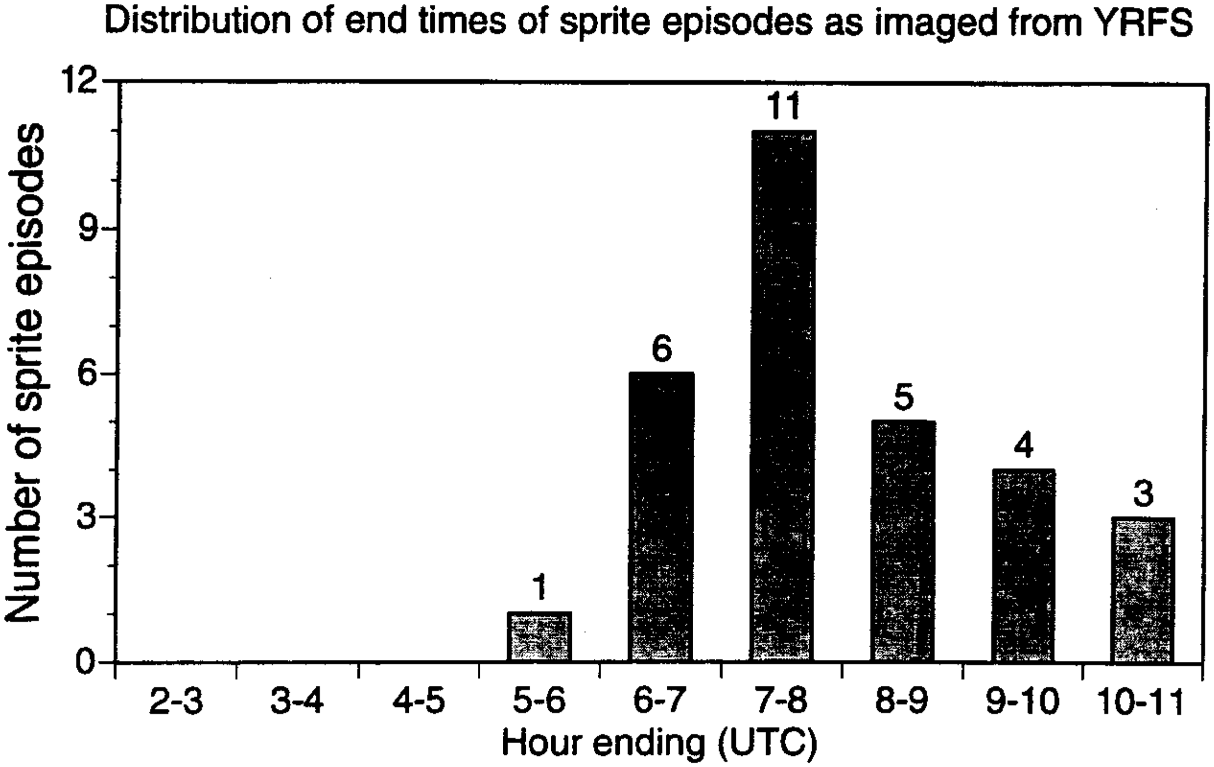


Figure 3-3. Distribution of starting and ending times of sprite imaging in 1995.

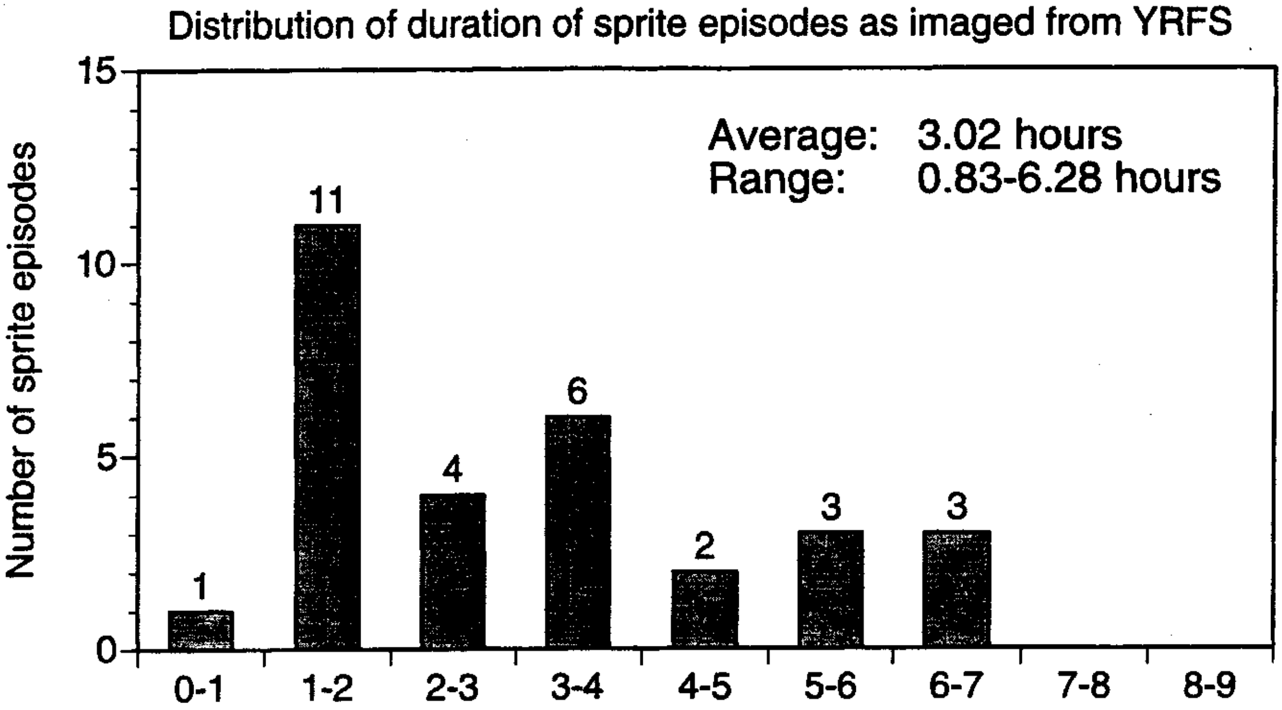


Figure 3-4. Distribution of duration of sprites imaging periods during 1995.

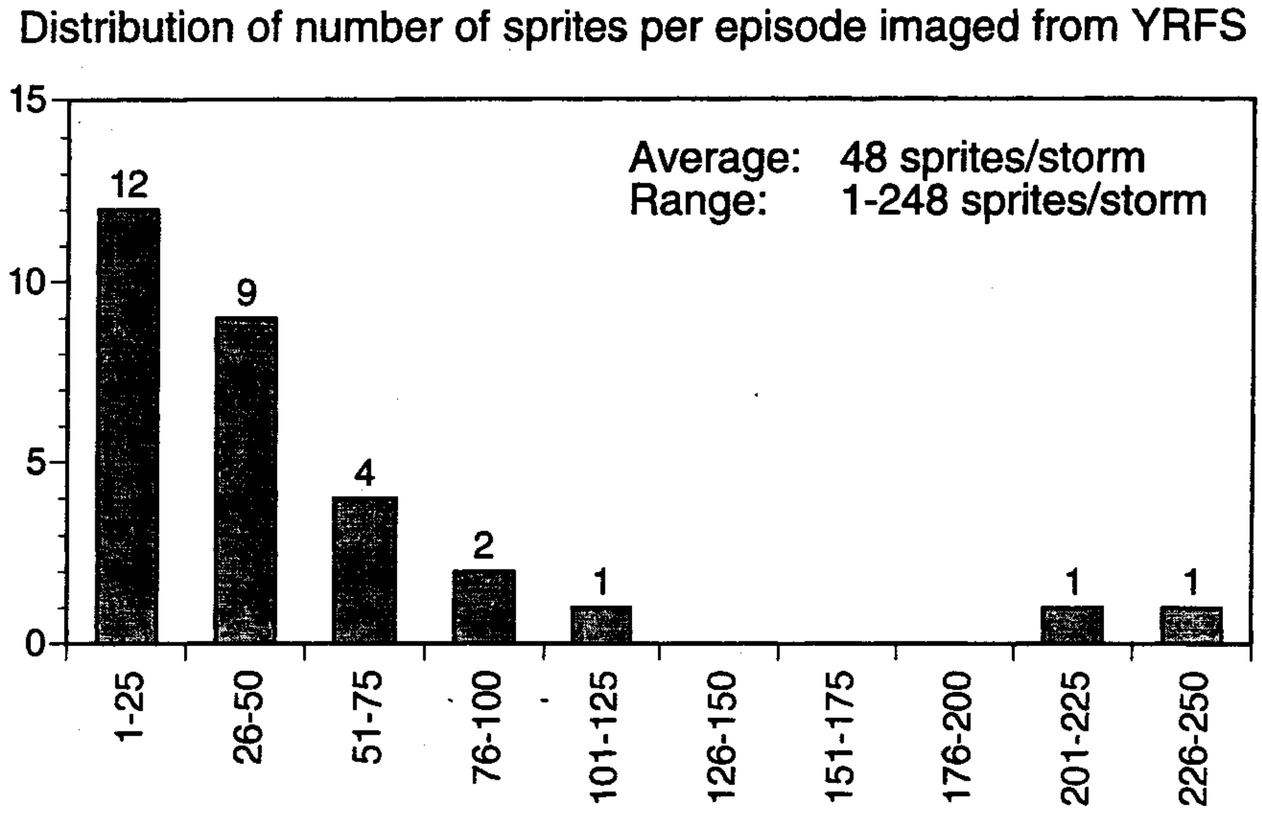


Figure 3-5. Number of sprites per episode during 1995.

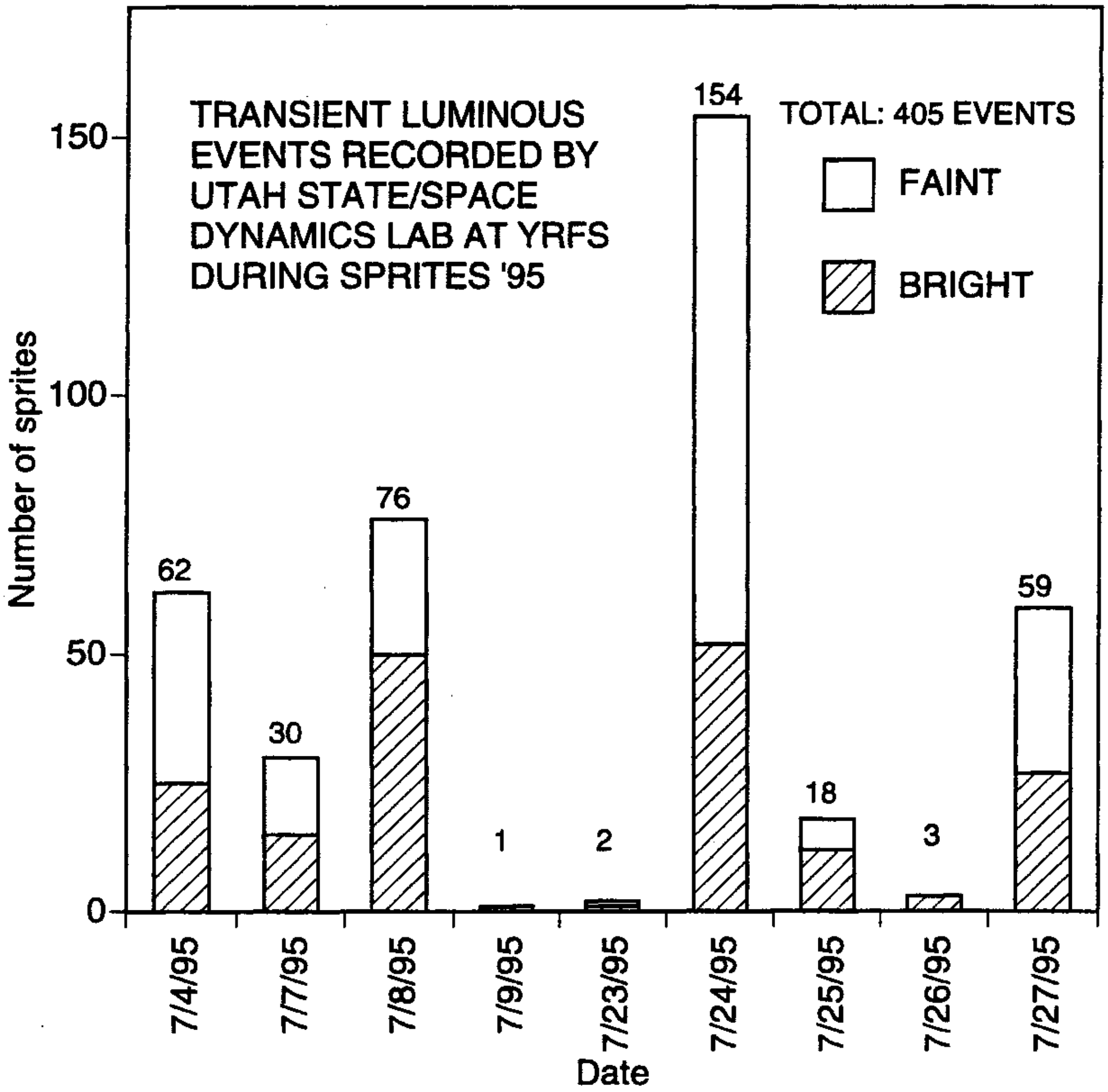


Figure 3-6. Distribution of bright versus faint sprites for selected storms. Courtesy M. Taylor, Utah State University.

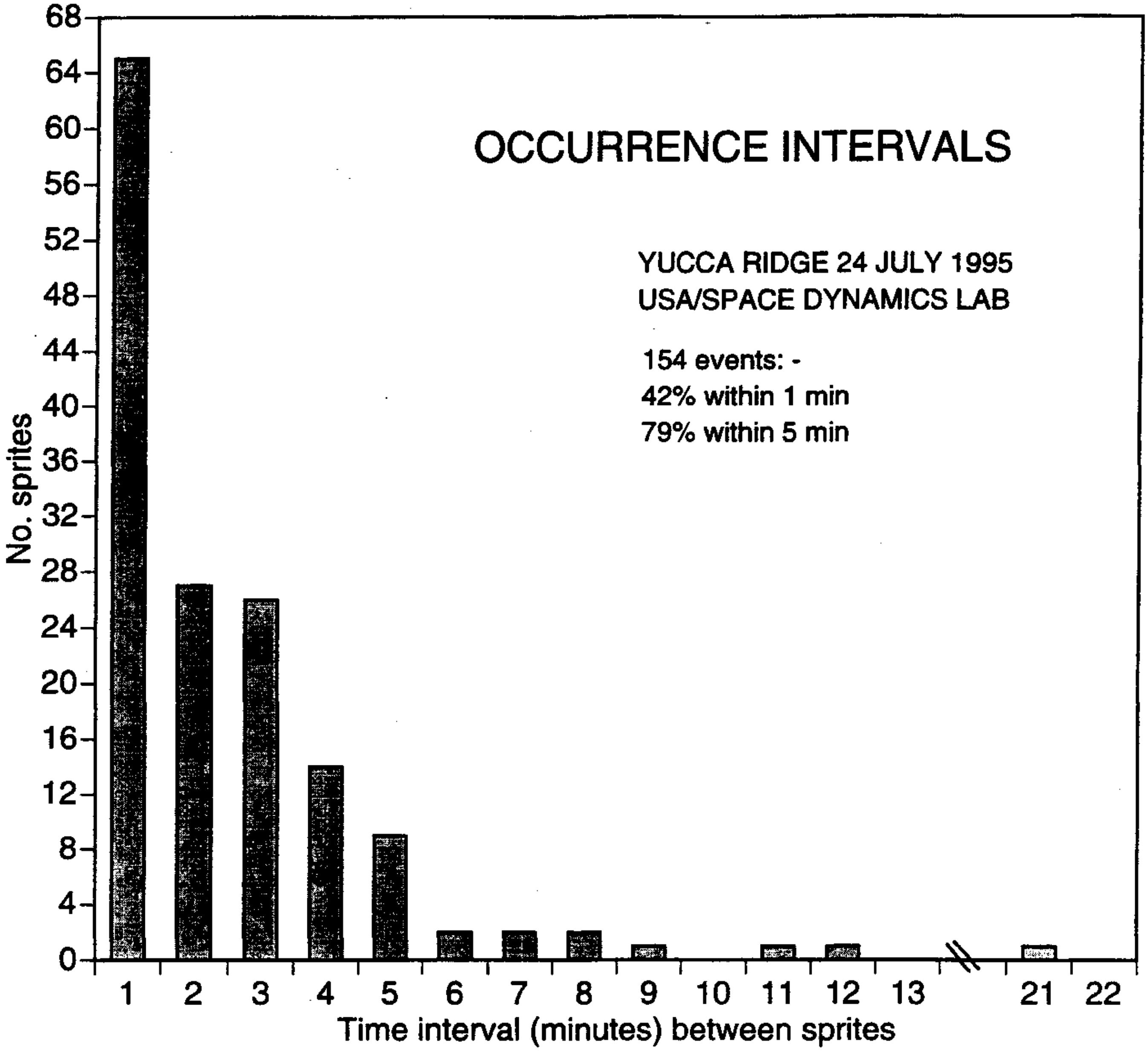


Figure 3-7. Distribution of time intervals between successive sprites for 24 July 1995. Courtesy M. Taylor, Utah State University

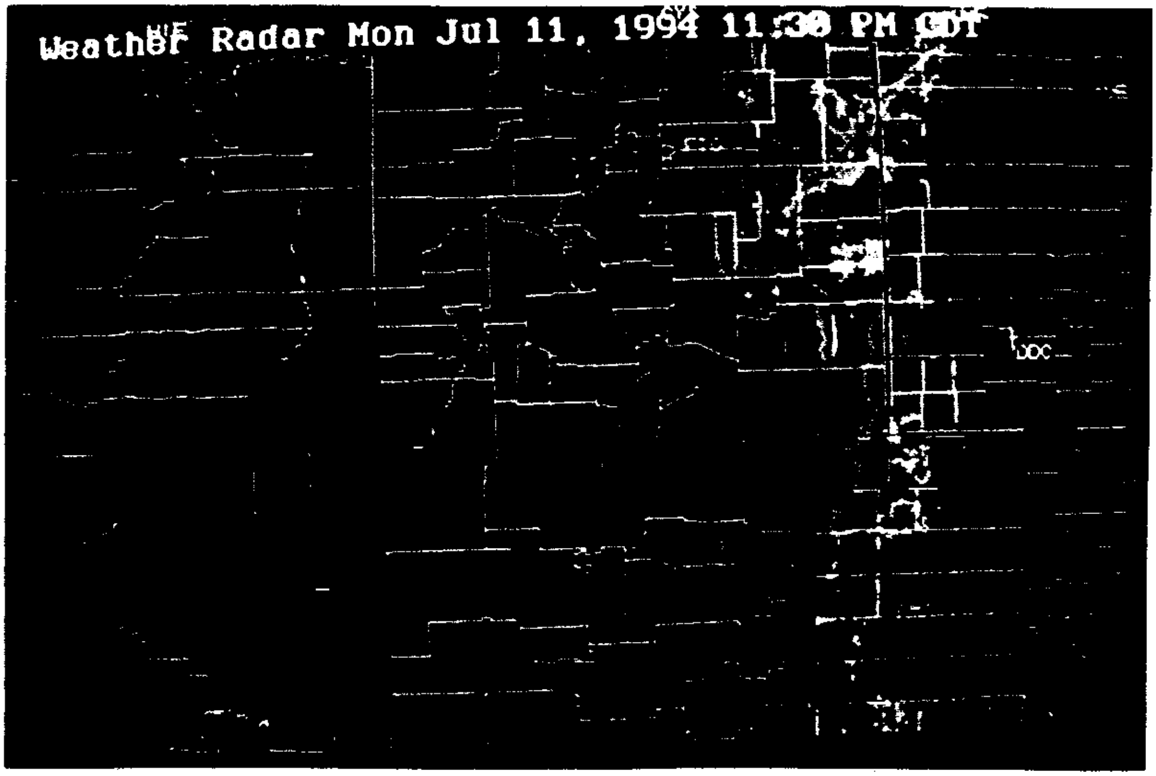


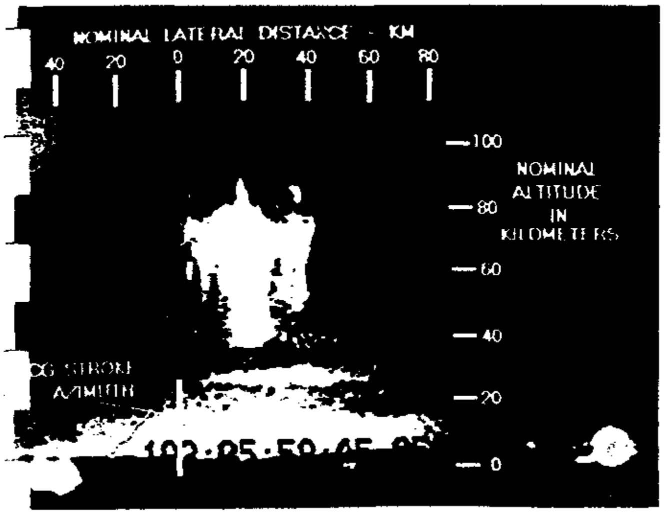
Figure 3-8. Radar reflectivity pattern, 0530 UTC 12 July 1994.

Comparison of National Lightning Detection Network (NLDN) Cloud-To-Ground Stroke Times With Yucca Ridge VLF-Sferic Start Times, July 12, 1994

Event	Observer	Universal Time	Current, kA	M	Bearing, deg	Range, km	Comment
1	NLDN	05:33:28.788	+50.5	2	117.5	266.4	sprite
	Yucca	05:33:28.788					
	NLDN	05:33:28.921	+41.5	1	124.0	262.7	small
	Yucca	05:33:28.973B	(timing from TV)				striated sprite
2	NLDN	05:37:27.435	+232.2	1	116.6	270.5	sprite
	Yucca	05:37:27.436					
	NLDN	05:45:36.781	+216.7	2	91.6	252.1	cloud
	Yucca	05:45:36.788B	(timing from TV)				light-up
3	NLDN	05:45:56.197	+165.2	3	115.8	268.5	sprite
	Yucca	05:45:56.198					
4	NLDN	05:58:45.104	+76.7	2	105.9	291.3	cloud-sky
	Yucca	05:58:45.106					light-up
	NLDN	05:58:45.371	+105.5	2	119.5	266.8	begin
	Yucca	05:58:45.372					sprite
5	NLDN	06:07:35.370	+92.4	2	103.0	313.9	tiny
	Yucca	06:07:35.371					sprite
	NLDN	06:07:35.919	+35.7	1	110.4	265.9	cloud
	Yucca	06:07:35.920	(.922B TV timing)				event + sprite
	NLDN	06:07:36.074	+21.4	1	126.1	284.5	"carrot"
	Yucca	06:07:36.074					sprite

Average Current is 110.7 kA. M designates stroke multiplicity

Figure 3-9. Source: Winckler et al. (1996).



TV1 (wide angle) image of the bright sprite of event 4, annotated in the manner of Figures 3a and 4. In this case, the CG stroke location was laterally 20 km to the left of the sprite center.

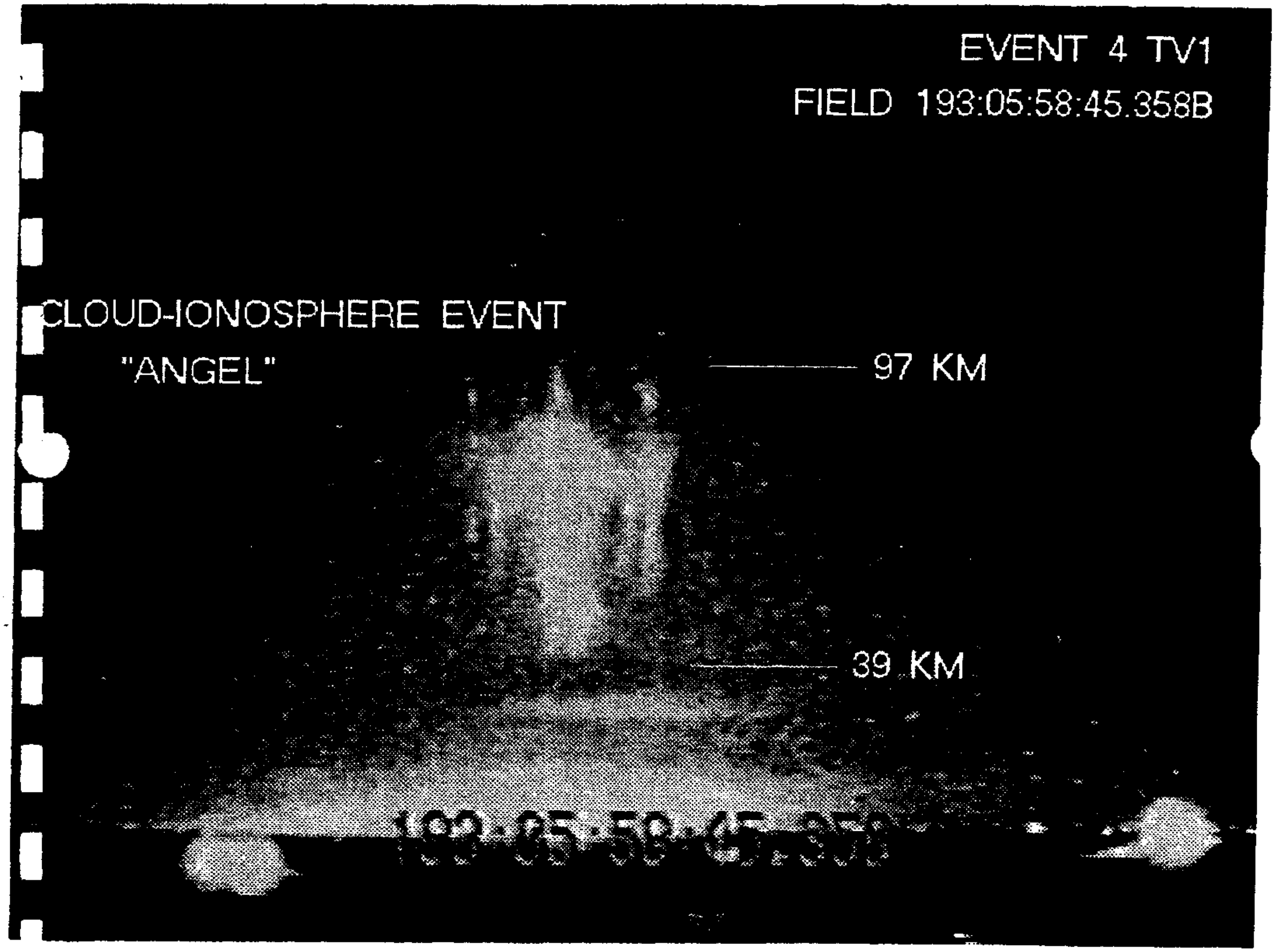


Figure 3-10. Wide angle LLTV view of sprite of 0558.45.358 UTC 12 July 1994. Source: Winckler et al. (1996).

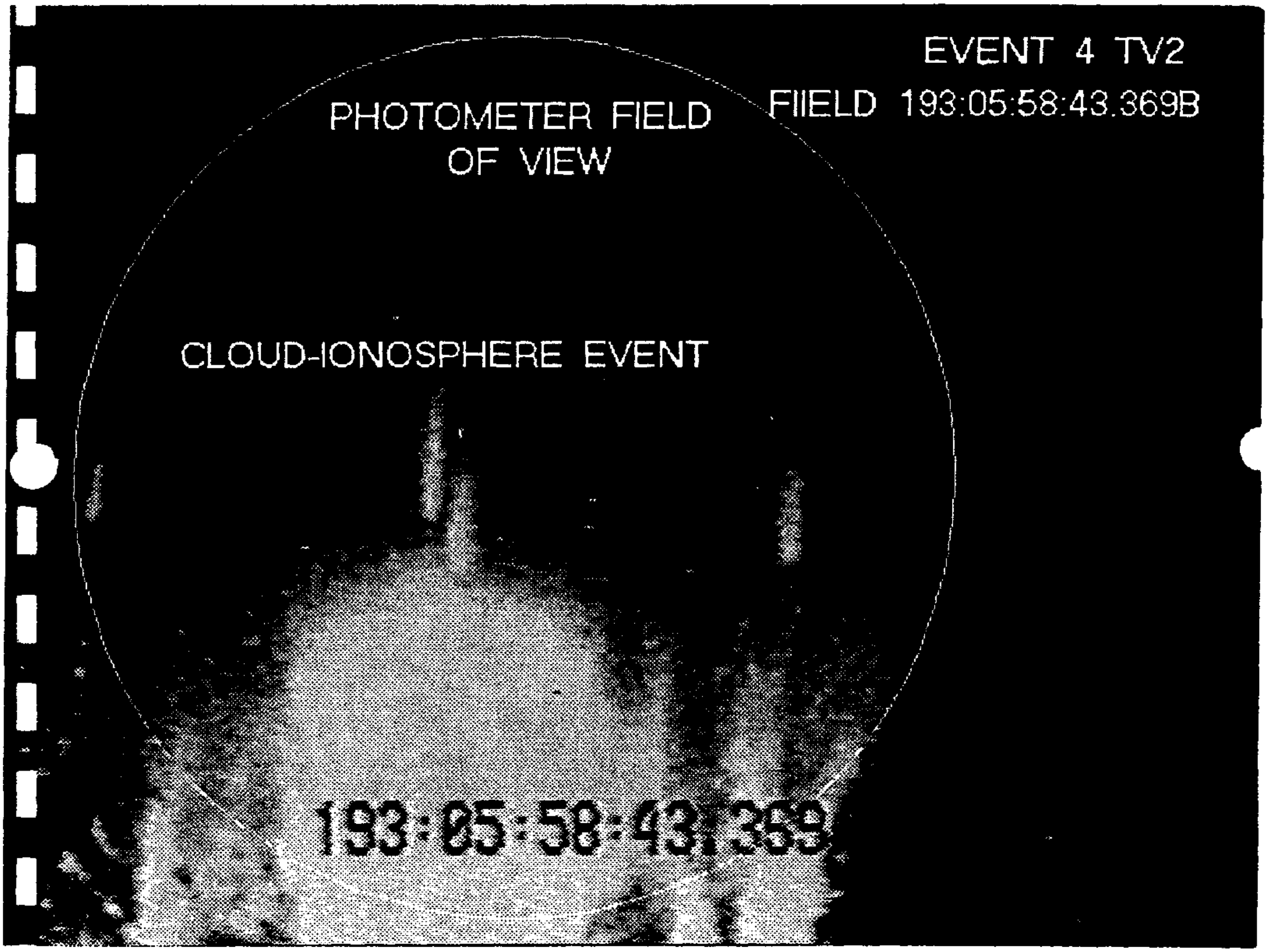
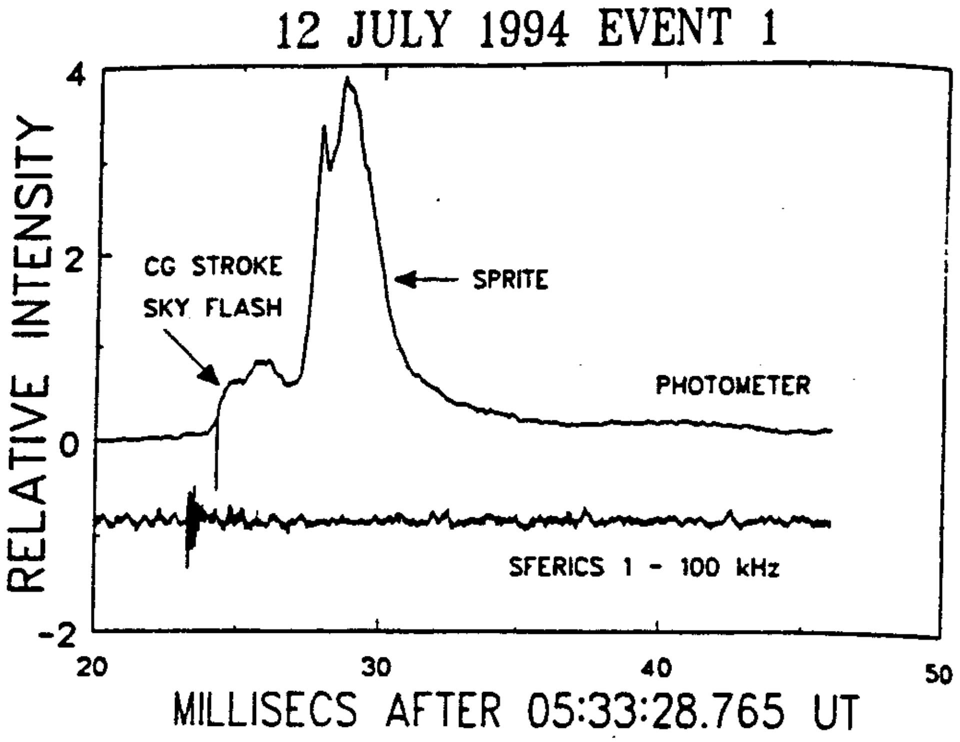
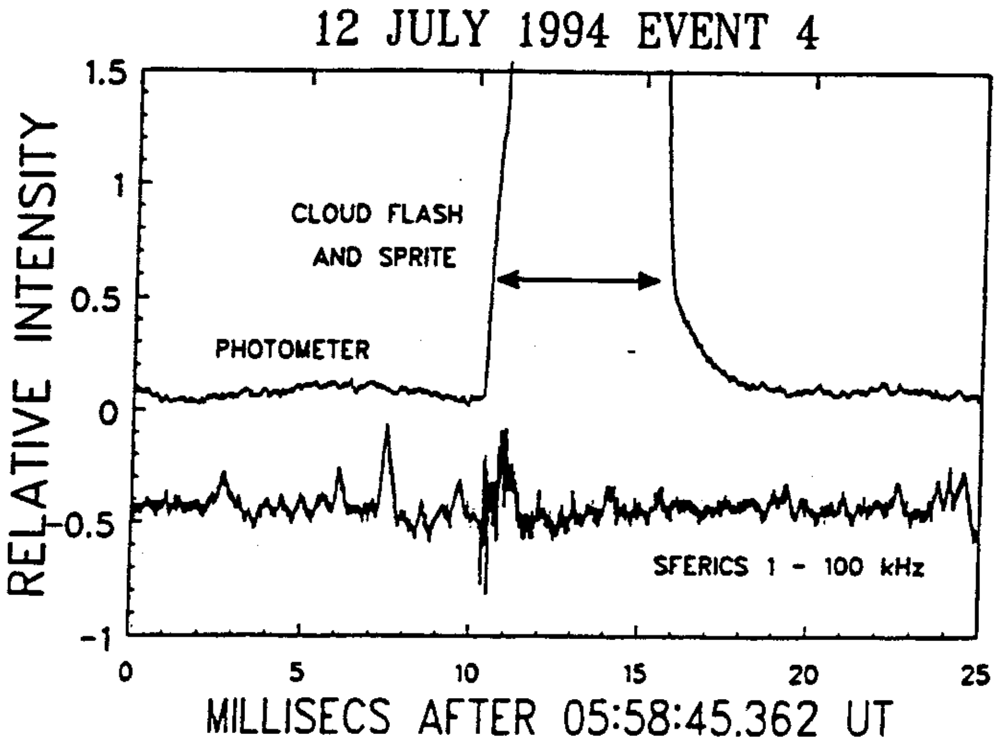


Figure 3-11. Telephoto view of sprite shown in previous figure, showing details including a number of hot spots. Source: Winckler et al. (1996).

Figure 3-12. The same scene as the previous figure, but one field (16.7 ms) later. Note the several hot spots still remaining. Source: Winckler et al. (1996).

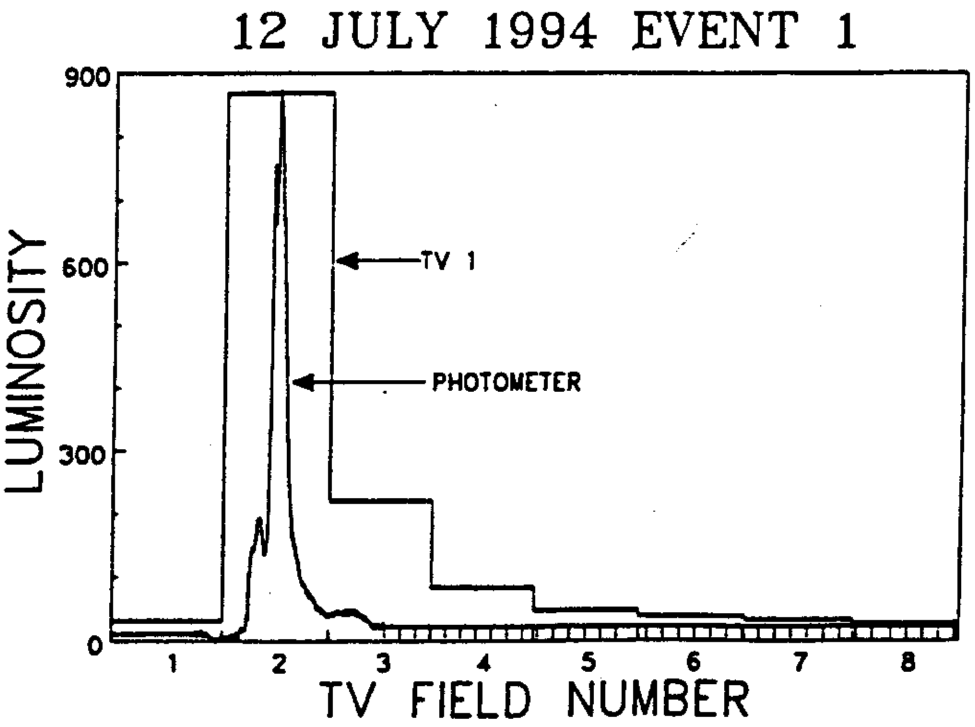


Photometer and sferic traces for the sprite of event 1. Note the initial photometer response within 1 ms of the sferic, followed by a small maximum due to the flash from the CG stroke, and a large maximum due to the sprite.



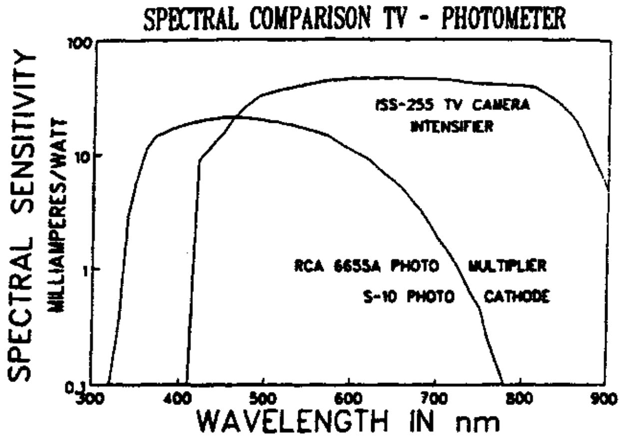
Photometer and sferic traces for the sprite of event 4. The photometer went off scale at the start of the sky flash and returned after the sprite, and thus no relative response was obtained.

Figure 3-13. Source: Winckler et al. (1996).



Comparison of photometer and TV time responses to event 1. The longer response of the TV camera seems due to its substantial red response compared with the photometer, coupled with the natural spectral decay of the sprite.

Figure 3-14. Source: Winckler et al. (1996).



Spectral responses of the photometer and TV cameras.

Figure 3-15. Source: Winckler et al. (1996).

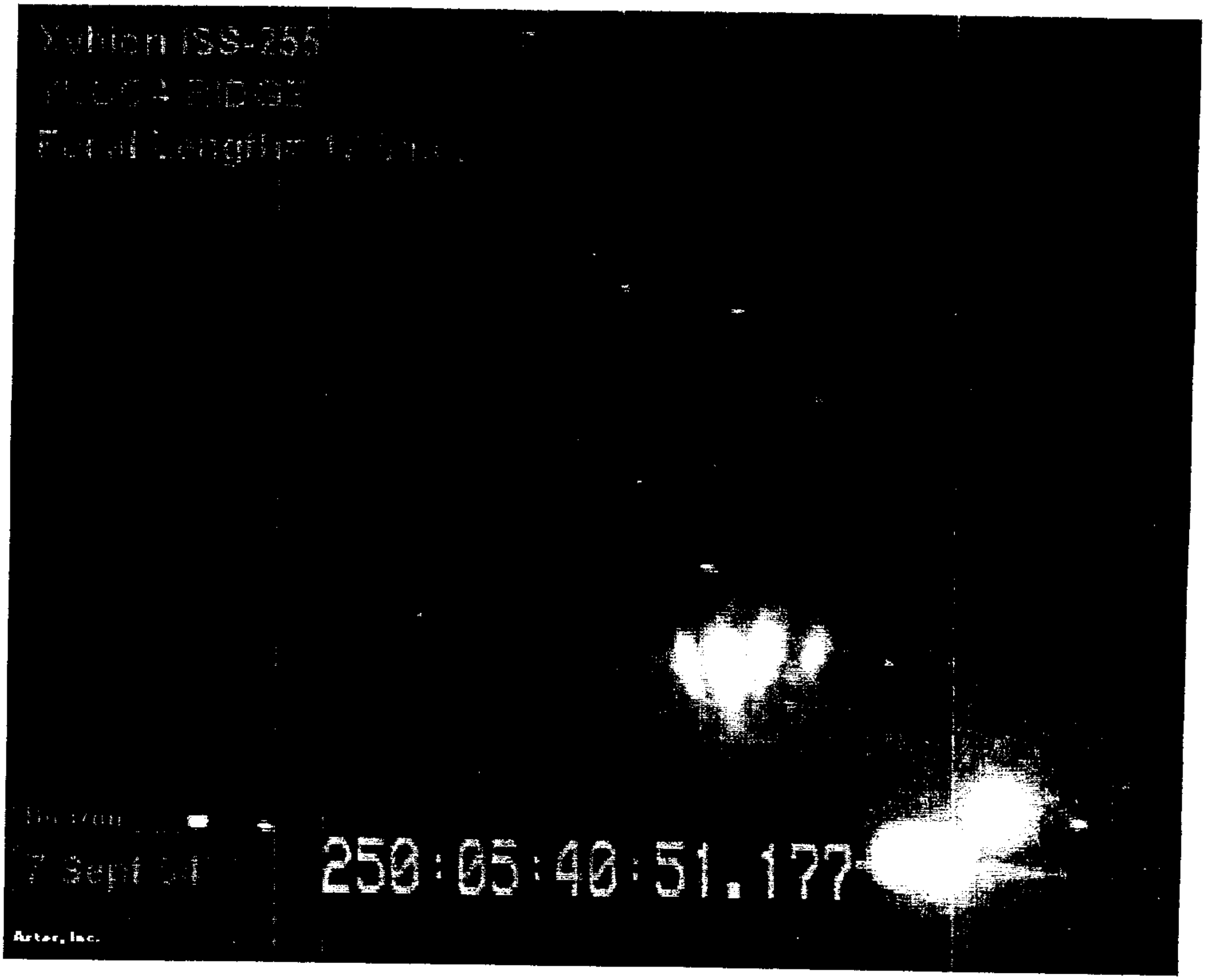


Figure 3-16. Sprite at 0540.51 UTC 7 September 1994 as viewed from YRFS.

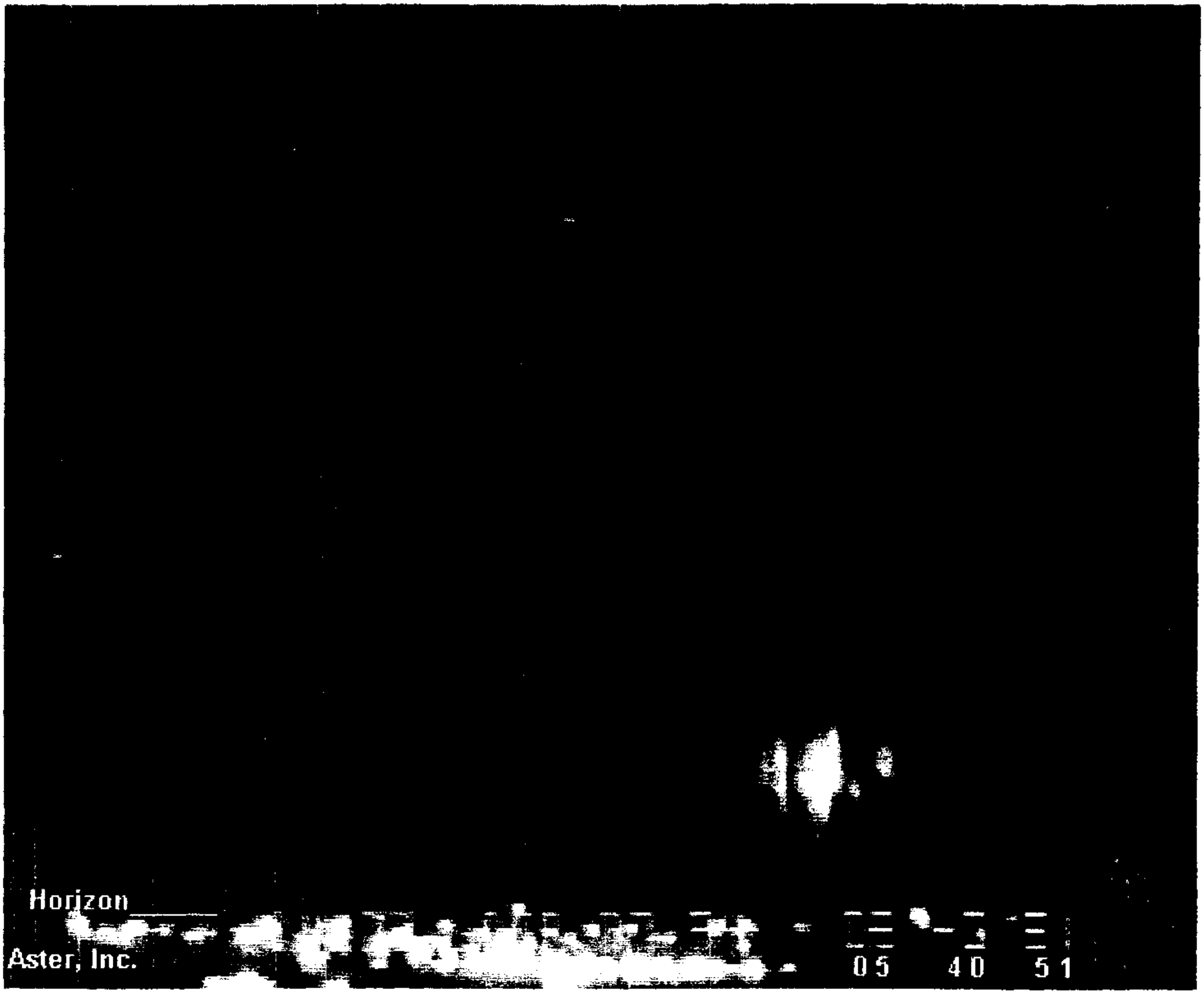


Figure 3-17. Same sprite as previous figure but as imaged from the US Air Force Academy in Colorado Springs.

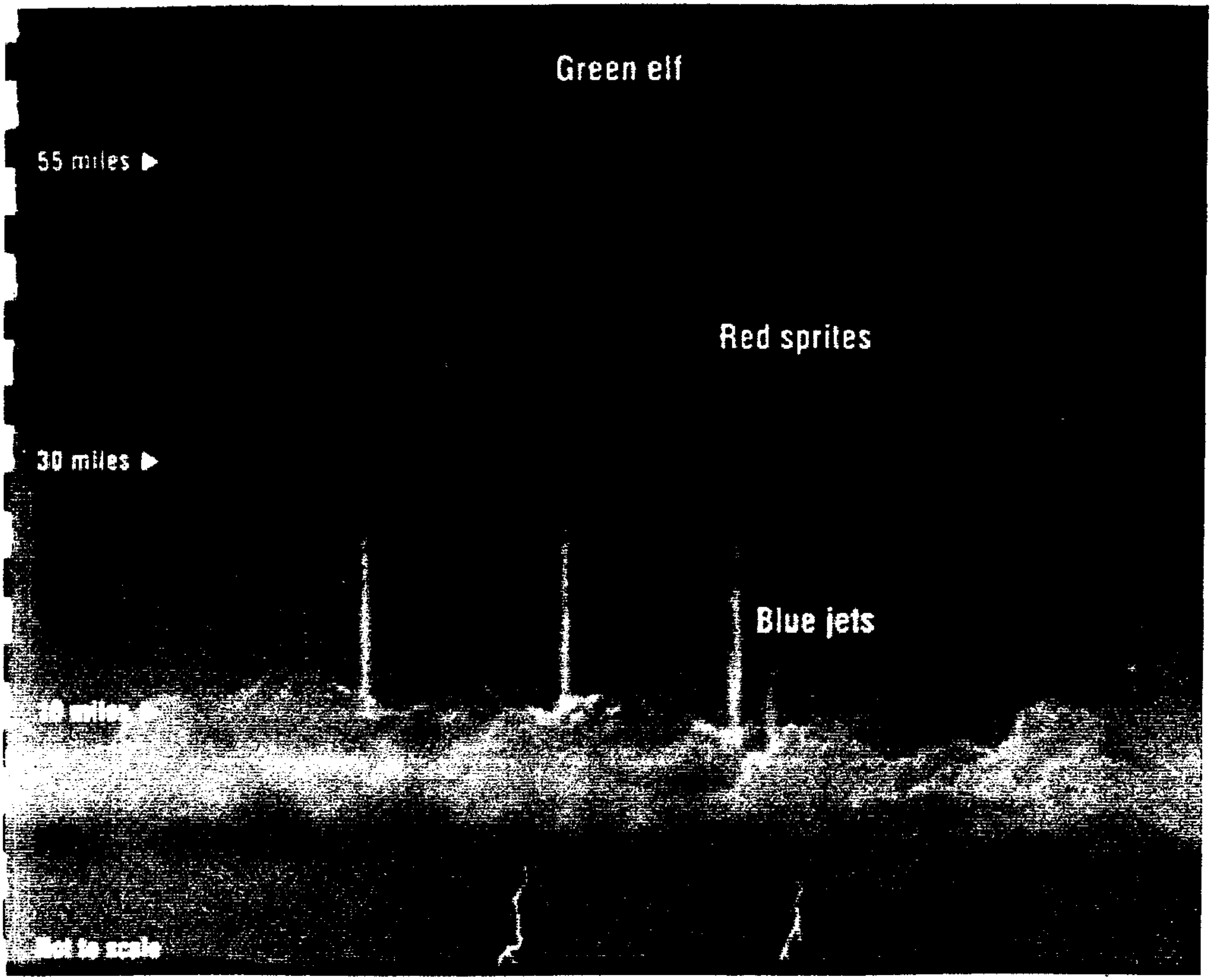


Figure 1-19. Illustration from Earth Magazine Story, June 1996.

2. THE 1994 AND 1995 SPRITE FIELD PROGRAMS

2.1. The Yucca Ridge Field Station and Florida

The centerpiece of the Phase II effort was a series of observational campaigns conducted during the summers of 1994 and 1995. They were held both at the Yucca Ridge Field Station (YRFS) and at Melbourne, FL, covering the Kennedy Space Center facilities.

The YRFS summer programs have since became known as SPRITES'94 and SPRITES'95. The Yucca Ridge Field Station is an 80 acre site located approximately 20 km northeast of Ft. Collins, CO at (104°56'24"W and 40°40'06"N) at an elevation of approximately 1690 m MSL. This rural site is the highest point for about 25 km radius and possesses a commanding view of the High Plains as well as the Front Range to the west. Figure 2-1 shows a DMSP picture of the U.S. The arrow indicates the approximate location of YRFS, which is on the western edge of a sparsely inhabited region. There are very few lights in the broad arc sweeping from north-northwest through southeast, making the site ideal for optical measurements. This is aided by the general clarity of the atmosphere in the western U.S. due to low mixing ratios and (sometimes) lesser amounts of anthropogenic aerosol loading than found in the eastern U.S. YRFS, located at the edge of the Front Range conurbation, is also relatively quiet from the point of view of RF. As will be discussed, the site is sufficiently clear of cultural electrical noise to be useful for a variety of RF measurements. The High Plains east of YRFS also has a well-known summertime maximum of nocturnal thunderstorms and lightning, often reaching the size of mesoscale convective complexes (MCC). The lightning from these systems can often be seen with the naked eye for a distance of several hundred kilometers or more, and with low-light television even beyond that range. As spring yields to summer, subsidence in the lee of the mountains often produces cloud free lines of sites from the Front Range to the mesoscale convective systems (MCSs) further east. It was estimated that under ideal conditions sprites could routinely be viewed at ranges of 500 km, and indeed to a limit of 1000 km from YRFS and from the US Air Force Academy, which was a second camera site during 1994 (Figure 2-2). This provides an effective optical viewing region of sprites of about 400,000 km^2.

In order to facilitate optical measurements, elevated platforms were built during both 1994 and 1995. Figure 2-3 shows the platform used for the various optical sensors during SPRITES'95. From here an unobstructed view of the horizon was available from 340 degrees clockwise through 170 degrees (Figure 2-3). While the view to the western semi-circle was blocked, there were rarely any storms present in that region during the nighttime hours and, for reasons that will be explained below, if there were, they would be unlikely candidates for sprites.

The SPRITES'94 campaign was conducted as a test for new data acquisition systems and also for developing forecasting techniques. As plans progressed, several other organizations expressed interest in taking coordinated measurements. SPRITES'95 was a full fledged field measurement program that was opened to all interested parties in the scientific community. By the completion of SPRITES'95, over 45 scientists had participated either on-site or remotely. They represented 16 organizations and four nations. A plethora of diverse data emerged from SPRITES'95, only the smallest portions of which have been analyzed. Even given that, several key discoveries have been made.

The Florida component of the observation programs was aimed at documenting the presence of sprites and related phenomena in the vicinity of the Kennedy Space Center. This component of the program did not live up to expectations. Dual LLTV systems were installed atop a 14 story hotel facility located on the beach near Melbourne, FL some 60 km south of the KSC launch facilities. Lightning, radar and satellite data were available from commercial services using dial-up communications. Coordination with the LDAR system at KSC (1995) was arranged. Unfortunately, no transient luminous events were observed. The reasons are several fold. Ambient light was, however, not one of them. While the lights from the beachfront communities did present some glare, there would have been no difficulty in seeing sprites. But in both years, during 10 day periods, there were severely depressed frequencies of thunderstorms, especially during the nighttime hours. The August 1995 experiment endured one week of drought conditions, during which severe haze caused by industrial pollution drifting over Florida from the northeastern U.S. also limited visibility and even prevented attempts at long range monitoring. Regional visibilities were often below 7 nm. The second half of the program was disrupted by persistent cloud cover associated with the passage of tropical storm systems. Several nights of viewing were undertaken, however. On none of those nights did storms have large enough size and significant numbers of positive cloud-to-ground flashes (see below) to be likely candidates. We will not further discuss the Florida program. However, we wish to point out that the null results should not necessarily be interpreted as proving that TLEs do not occur over Florida. While there are reasons to suspect that sprites are less common than over the High Plains, the characteristics of lightning in the region (see below) suggest that other phenomena such as blue jets may be present. Remote sensing techniques, based upon the use of ELF transients, may in the long run prove a more fruitful approach to monitoring mesospheric disturbances over Florida.

2.2 Sensors

The guiding principles of the YRFS campaigns was (1) coordination, (2) cooperation and (3) collaboration. The goal was to obtain as much multi-spectral information as possible from a common volume of atmosphere during identifiable TLEs. Given the known short lifetimes of the phenomena, it was essential that precise timing be utilized by all participants. With only a few exceptions, highly accurate GPS time tagging with millisecond precision was applied to optical and RF measurements. The cooperation involved the various teams training their instruments on a common volume of the atmosphere upon receipt of predictions or observations of sprite occurrences. Collaboration was essential after the data acquisition effort so that as many of the data sets as possible could be intercompared. Especially during 1995, data taken during the previous night was often retrieved, displayed and preliminarily analyzed within 24 hours. Thus results could be checked on the spot, and changes made to system configurations or data acquisition scenarios.

ASTeR, Inc. was charged with providing a base line suite of optical, RF and meteorological measurements. Cooperating science teams brought a varied suite of instruments. The 1994 configuration is shown in Table 2-1. This will be outlined below.

2.1.1 ASTeR Base Line System

The key measurement system provided by ASTeR, Inc. was dual XYBION ISS-255 low light television (LLTV) cameras (Figure 2-5). This sensing system has a face plate illumination sensitivity of 10^{-6} foot-candles. Uncalibrated gain and black level adjustments can be made. Most brighter stars can be seen during clear sky, no moon conditions. The EIA RS/170 video was recorded on S-VHS tape. The cameras were strapped to provide successive, independent 16.7 video fields. A True Time GPS system (nominal accuracy 2 microseconds) provided digital time information and also drove video date/time stamping cards using IRIG-B format. Each field of video was time stamped to the nearest .00 second at the end of each 16.7 ms data integration period. WWV audio was also recorded on one of the four channels as backup in case of loss of the GPS signal (not used since GPS proved exceedingly reliable). Several lenses were used. Two Fujinon zoom lenses were employed during part of 1994. Later, faster Cosmicar f/1.8 zoom (12.5 mm to 50 mm) and f/1.4 fixed focal lengths (12.5 mm) were used. No filters were employed. The XYBIONs were equipped with a GEN2 Red photocathode which had a broad response from 400 to 900 nm, but peak from above 480 nm to about 850 nm and thus could be said to be essentially red sensitive (Fig. 2-6).

Figure 2-7 shows successive 16.7 ms duration fields of a sprite event. The tendency in many observations is for the sprite to suddenly appear in the first field, often at its brightest intensity, and then gradually fade thereafter, sometimes lasting 10 fields or more. This has been interpreted by some as a characteristic of the imaging system. It is not. There is virtually no image persistent between fields. This can be evidenced from inspection of video of airplane and tower strobes, lightning channels, and the sprites themselves. Figure 8 is an image of an extremely bright and large sprite taken on 15 July 1995 above a lightning event some 280 km east of YRFS. The sprite is so bright as to be actually visible through portions of the thin altocumulus cloud in the foreground. This sprite appeared in only a single video field. There was absolutely no evidence of the structure in the following video field. Thus the apparent decay in sprite luminosity in the LLTV images is indeed real. The fact that the fine structure also changes from field to field during the dimming processes is further evidence.

The XYBION cameras were deployed in several modes. Commonly one was employed in a "patrol mode", using the wide angle lens to view the entire storm. On those few occasions where the storm system was wider than the nominal 50 degree FOV, the cameras would be in panoramic mode, with a slight overlap of the two images. Most of the time the second camera was nested inside the field of view of the patrol camera to allow close up views of TLEs to be obtained. A log of the azimuth and elevation of the cameras was maintained. The two LLTV systems were frame synchronized to assure that the sprites imaged in two fields of view began their integration at the same instant.

Two RF systems were deployed by ASTeR. The first was a broad band magnetic VLF receiver, operating from about 10 kHz to 100 kHz. The second was the NASA-developed Inspire receiver, operating in the 1 kHz to 10 kHz range. It has been widely used for, among other things, detecting whistlers. The audio output from both systems was recorded on individual sound channels of the LLTV tape decks. The fourth channel was used for recording observer comments. Dual wireless microphones were used to collect observations from ASTeR personnel.

A fast response photometer was designed and built by Prof. J.R. Winckler of the University of Minnesota (Winckler et al, 1996). The photometer had a 12° circular field of view and was often run co-aligned with the close up LLTV system. The photometer was sampled at 100 kHz sampling rate by a computerized data acquisition system. This system used an RCA 6655A two-inch photomultiplier, whose cathode response was S-10, peaking at 450 nm and thus very blue sensitive. This created some problems in comparing the results to the red sensitive LLTV images. The optical system was initially designed to self trigger. It was found however, that the flash that caused the sprite itself often caused false triggers. A manual system, was devised in its place. The appearance of a sprite on the TV monitors in the control center prompted the system operator to push a button. A circular buffer n the data acquisition system allowed sampling the last 1000 ms. While response time lags did sometimes prevent the sampling from being acquired, a substantial fraction of the desired samples were obtained.

The digital data acquisition system was a PC-based system using National Instrument's A/D cards and the Labview Software environment. As mentioned the University of Minnesota photometer and magnetic VLF receiver were sampled at 100 kHz, while the Inspire system and an alternate HP variable frequency VLF receiver were sampled at 40 kHz. Files were time stamped using GPS. The sampling duration was adjustable, but most were taken over 1000 m periods.

Meteorological data acquisition systems involved several components:

(1) Video: additional time lapse video of daytime clouds was used to characterize the cloud systems that became sprite producers; a KY19 lolux system also obtained video of lightning from storm systems that were sufficiently close to YRFS

(2) DTN: direct satellite downlink of national and regional reflectivity mosaics provided near real-time monitoring of storm systems. Archival was by 35 mm color slides of the display

(3) WSI: dial-up access to the WSI data base permitted downloading at 14.4 bps products such as regional radar, satellite images, and plots of NLDN lightning products. These have been archived on Syquest disks

(4) NLDN: at the end of each storm season, the entire national ground flash lightning data base was obtained from Geomet Data Services, Inc. (GDS) on 8 mm tape. In 1995, a CD-ROM version was also provided. These data included full millisecond timing resolution.

(5) GOES Animation Loops: by arrangement with the Department of Geography at Mankato State University we obtained continuous animated loops of GOES infrared satellite imagery to aid in visualizing storm behavior.

(6) Ancillary weather information such as the monthly Storm Data reports from the National Climatic Data Center were obtained for case study analyses.

2.1.2 Cooperating Science Teams

During 1994, several small scale cooperative measurement programs were attempted. By far the most productive was coordinated optical sprite measurements with he logging of ELF transients called Q-Bursts by the Massachusetts Institute of Technology team lead by Earle Williams. The results of this collaboration are described in a following section and in an article by Boccippio et al. (1995) published in Science (see Appendix C).The operation was actually straightforward. While sprites were being monitored using LLTV, a telephone link was maintained with an operator of the ELF system in Rhode Island. Voice communication quickly determined that when a visible sprite was imaged, a strong ELF transient was also apparent. This system was now largely been automated, but it illustrates the benefits of real-time intercomparison of disparate data sets.

A second cooperative program in 1996 was conducted with Maj. Perry Malcolm of the US Air Force Academy. On several nights, a third XYBION camera, graciously provided by J.R. Winckler of the University of Minnesota, stationed in Colorado Springs, some 205 km to the south was operational. When storms were in the common field of view, LLTV were obtained for several hours. One night provided excellent targets for triangulating the position of the sprites and establishing their relationship to the parent cloud-to-ground (CG) flashes.

During the first portion of SPRITES'94 the GI/UA team was airborne in two business jet aircraft over the midwest. On several nights we attempted to provide ground-based images of storms which were being observed with airborne sensors.

Also initial testing of a high speed infrared optical imager were conducted by the Lawrence Livermore National Laboratory. A narrow band photometer system designed to detect the presence of ionization with the sprite volume was initially tested by Mission Research Corporation.

The 1995 program was conducted on a much larger scale. Figure 2-10 summarizes the system that was deployed either at Yucca Ridge or in conjunction with observations there. The ASTeR configuration during 1995 was essentially the same as described above. A much larger viewing platform (Figure 2-11) was constructed. Data cables were routed into the tower which served as command and control center for the experiment. Many of the systems could be monitored concurrently in real-time.

Among the systems deployed in 1995 were a spectrometer and companion LLTV system from Lockheed Martin. See Mende et al. (1995) for details (Appendix XXX). This system is shown in its deployed configuration in Figure 2-12.

Key measurements were obtained by the Tohoku University team (shown in Figure 2-17) using a fast response pointing photometer array. The system is described detailed in Fukunishi et al. (1996) provided in Appendix XXX. This system uses four photometers with 1 x 9.5° field of view, using both broad band and red filters. By pointing at two elevations, the original concept was to attempt to determine the direction of propagation of the sprites (see Figure 2-14). While not achieving this goal, the system did result in the discovery of what are now called elves.

The Space Dynamics Laboratory of Utah State University provided a mobile van with several imaging systems (Figure 2-15), including a multi-spectral all-sky imager and several ISIT low light television systems. The former were successfully used to detect striations in the airglow layer associated with thunderstorm-generated upwelling gravity waves. The LLTV systems, though hampered by severe persistence in the imagery, given their greater sensitivity than the XYBION units, were used to determine if there may be luminous features in the sprites and elves not yet revealed by the current project LLTVs.

The liquid helium cooled Infrared Optical Camera System (IROCS) developed by Lawrence Livermore National Laboratory is shown in Figure 2-16. IROCS is a remote sensing platform designed to take both visible and IR images integration times as short as 0,5 ms. During 1995 it was tested in the water vapor window using narrow band (0.5 µm) samplers between 10 and 12 µm. The evidence suggests that significant signals were obtained in conjunction with sprites in this portion of the spectrum. Data are still undergoing analysis at this time and results are pending.

In cooperation with the MIT group, highly sensitive magnetometer coils and associated electronics and software were installed both at YRFS (Figure 2-17) and the Kennedy Space Center. Using data acquisition and display software developed by Bob Boldi and others from MIT and Lincoln Lab it is possible to use these orthogonal coils to monitor the ELF (3-120 Hz) Schumann resonance background as well as the transients known as Q-bursts (Williams, 1993). As described below and in the appendices (Williams et al., 1996), the ELF data can be used to detect and locate the large flashes involved with sprites using either single or multi-station techniques. One experiment that could not be completed during 1995 was to sample ELF transients form YRFS, KSC and the MIT site and Rhode Island, thus providing a three-station magnetic direction network for diagnosing sprite conducive conditions.

Remote ELF/VLF measurements were also made on selected nights by Les Hale and student Lee Marshall. The data were usually recorded at a rural, radio quiet location in central Pennsylvania.

The STAR Lab of Stanford University played a major role in the SPRITES'95 program. They installed a VLF magnetic loop antenna array for continuous monitoring US Navy transmissions (Figure 2-18). The audio output from the VLF system was also recorded along with the LLTV video. A mobile van was equipped with a portable vertically deployed 1.7 m2 square loop antenna to monitor the magnetic field component of the NAA and NSS transmitters in Maine and Maryland (Figure 2-19). The techniques used are described in detail in Inan et al. (1996, 1995).

The University of Otago, Dunedin, New Zealand has established one of its OmniPAL VLF receivers at YRFS along with others along the Front Range. By monitoring changes in the US Navy's VLF transmissions, amplitude and phase perturbations can be used to infer the characteristics of plasma associated with TLE and, in theory, even locate them automatically. Figure 2-20 shows the simple whip antenna used by the OmniPAL system. These data are recorded automatically on a dedicated PC-based data logging system. See Dowden et al. (1995) for further details (Appendix XXX).

A bi-static propagation experiment was conducted by GeoSpace, Inc. Using the transmissions from the WWV system (located 10 km east of YRFS) at 2.5, 5, 10, 15 MHz, signals were monitored at a receiving site in central Illinois. Also transmissions at 24 MHz were made from nearby LaSalle, CO and monitored at the same site. These data are still under study.

Active probing of sprites by microwaves was attempted in late July, 1995 by SRI International. A mobile radar, transmitting at 28 MHz was established and tested for a several day period (Fugues 2-21 and 2-22). During the test period, weather conditions were not favorable. Some data were acquired and are still under analysis by SRI.

Less formal coordination with other groups also occurred, such as attempting to image sprites during a passage of the Optical Transient Detector satellite (OTD) system in the area. Data were provided to Los Alamos National Laboratory in support of their ongoing investigation of transionospheric pulse pairs (TIPPS) (Holden, 1994) which may be linked to the sprite generating mechanisms.

2.3 Data Acquisition

2.3.1 Experimental Design

SPRITES'94 and '95 were scheduled to coincide with the climatological maxima of nocturnal thunderstorms over the High Plains, late June through August. The month of July is usually very productive as its maximizes the probability of electrical active MCS to the east while clear skies along the Front Range permit a line of sight over considerable distances. Early in the convective season, upslope clouds often obscure the deep convection to the east. As the summer wears on, clouds from the southwestern monsoon tend to infiltrate Colorado, also reducing viewing opportunities.

Once the equipment had been installed and checked out for both seasons, a notification system was established. All days were considered potential "Go days." Weather conditions were monitored on a continuous basis. A voice mail system was used to supplement direct conversation especially for those investigators not on site. By 4 pm, convective storm development was generally well enough established that a preliminary Go/No Go decision was made. However, final cancellation was not made until well after dark when it was clear sprites would/would not occur and/or be visible from YRFS. When conditions were favorable, all systems in ready status would be activated by 15 minutes after local sunset (typically round 0300 UTC).

The LLTV systems would be trained on candidate storms (or in some case intense local storms that were not expected to generate TLEs). With the appearance of the first TLE, notification would be sent to those remote teams (STAR Lab, GeoSpace, GI/UA, MIT, etc.) to begin making coordinated measurements.

Command and control was conducted from the tower in which most display systems were concentrated. Figure 2-23 shows part of the control system which includes displays for WSI/NLDN lightning data, the digital data acquisition system, the photometer controllers and a video monitor for weather information. Not shown are the displays for the LLTVs, the ELF waveforms, the OmniPAL VLF analyzer screen, the University of Tohoku real-time display, the S-VHS recording decks, audio mixers, VLF audio speakers, and the DTN weather radar display. The operation director could monitor the status of most systems, including the weather, and be in real-time communication with other participants either on-site (via intercoms) or remotely via phone.

Data were collected both automatically (video, audio, PC) and by using manual log forms. Figures 2-24 through 2-28 are examples of the sheets that were routinely filled out to record the status of equipment, active personnel, supplemental data acquisition, video camera characteristics and tape recording. A daily summary log n narrative form was also completed and included, among other things, the forecast made at the beginning of operations as to whether a given storm under surveillance would be expected to produce sprites. Notes and running commentary from ASTeR staff equipped with wireless mikes were also recorded on the audio channels.

The SPRITES'94 and 95 campaigns extended over a period of 126 nights combined. During 1994, 27 nights of monitoring produced the imaging of 1 or more sprites. In 1995, there were 25 nights with sprites (Figures 2-28 and 2-29). In this sample, 41% of nights had the proper combination of storm conditions and viewing angles to allow sprite imaging from YRFS. It is typical for Go and NoGo conditions to clump together in several day periods. The longest string of successive sprite detection nights was eight (20-27 July 1995). One week without sprite viewing also occurred.

Figure 2-30 is a summary of the operations for the SPRITES'95 campaign. It includes the dates, whether operations were conducted, the start and end time of video monitoring, whether storms were forecast to develop sprites (Y) or not (N), the number of sprites recorded (this is still preliminary for some dates) and the status of various experiments and systems.

2.3.2 Data Obtained

The database assembled directly by ASTeR is in part outlined in Appendix B. Between 1993 and 1995, well over 200 video tapes (2 hours, S-VHS) were taken of potential or actual sprite storms. For 1995, the start and stop times of the 135 tapes were logged. Over 500 digitized records of the photometer, Inspire and VLF signals were taken using Labview. The total size of these files approaches one gigabyte. During 1994 and 1995, between 20 and 40 slides of regional radar mosaics were obtained from the DTN weather display. Digital files of WSI radar, lightning and satellite data were obtained at the rate of about between 15 and 30 images per operational night. The complete NLDN national lightning base for 14 summer months over 1991, 1993, 1994 and 1995 are on file, and comprise almost 80 million flashes. Plots of only positive flashes in the central U.S. during sprite occurrence periods for the main study days of 1995 are also included in Appendix B, along with selected radar reflectivity mosaics.

Summary video and audio records for three selected case study days (23 June, 15 July and 16 July 1995) have been compiled and are included with the video tape appendix to this report. A similar video tape summary of LLTV observations was prepared by Lockheed Martin for those days on which concomitant spectrographic measurements were made (Appendix B).

Detailed analyses of the transient luminous events and their associated lightning flashes were prepared for selected events. Appendix A shows examples for 23 June, 15 and 16 July 1996. An explanation of the data format is included.

2.4 Data Analysis Techniques

2.4.1 Single and Multiple image Photogrammetry

One of the more basic analysis tools for the information contained in the LLTV videos is single and double image photogrammetry. The triangulation analysis of pairs of sprite images conducted by Perry Malcolm (USAFA) and Gene Wescott (GI/UA) will be discussed at greater length below.

Single image analysis techniques used here are those discussed in Holle (1982). Knowing the focal length of the lens and the elevation of the camera, it is possible to compute the elevation and azimuth of any point in the image. A suite of overlays for all focal lengths and elevations employed during SPRITES'95 was prepared (samples shown in Figure 2-31). These were then scaled to the video screens and transparencies prepared. It is estimated that the accuracy of the angles obtained are typically ±0.5 degrees. Since we can assume (see below) that the range of the sprite can be estimated using the range to the parent +CG event, it becomes a simple matter to obtain the dimensions of the sprite (at least in side view), including the top and bottom of the luminous structure (Figure 2-32 is an example for the 6 August 1994 case study). No account has been taken for atmospheric refraction which is not believed to be significant in this context for elevations above 2 degrees.

2.4.2 Lightning data processing

A key data set for investigating sprites, elves and blue jets is the ground flash data taken by the National Lightning Detection Network (Cummins et al., 1992, 1996). Data obtained from archive come on 8 mm Exabyte tapes. These have subsequently been converted to CD-ROM for ease of processing. Approximately 80 million flashes over 14 summer months are now on file. Included are the date, time (nearest millisecond), polarity and signal strength (kiloamps) of the first stroke in the flash, stroke multiplicity, and latitude and longitude.

The first process was to convert the flash locations into Azimuth/Range coordinates from YRFS and to convert the signal strength to peak currents. The azimuth and range were computed using spherical earth trigonometry. In addition, the distance east-west and north-south from YRFS was also computed. There has been some uncertainty as to the value of the multiplier for this last step, ranging from 0.20 to 0.185 (the former being used in most case in this report). The accuracy of the peak current estimates for strokes greater than 60 kAmp has been open to some question, but in the absence of indications to the contrary, the reported values are taken as accurate even for large amplitude-events. An example of the reformatted NLDN data is shown in Figure 2-33.

Other sorting routines have been developed. One question to be addressed is whether CG events do and do not cause TLEs within the field of view of the LLTV. Only those flashes, of a given polarity and above a given peak current can be sorted using the field of view of the video system and specified range bins from he YRFS site. An example for strokes of either polarity greater than 75 kAmp is shown for selected hours on 23 June 1995 (Figure 2-34).

2.4.3 Integration of disparate data sets

Of considerable interest to ASTeR is defining the relationship between meteorological conditions and the resultant sprite or elve. Software has been developed which allows taking archived digital national mosaic reflectivity and interlacing it with NLDN data. Figure 2-35 shows an example from 6 August 1995, in which the LLTV field of view is indicated over the radar reflectivity. The approximate location of the sprite is given by the hatch marks. The lateral extent of the luminous area is obtained from the LLTV record. The range to the center of the sprite was taken as was that of the parent +C event (+), and the depth is estimated as ±20 km. In this example the sprite appears above the large stratiform precipitation region and some distance from the high reflectivity core. This appears to be quite typical of most sprite observations.

During 1995, increasing numbers of NEXRAD (WSR-99D) radar systems came on line in the High Plains. This provided the opportunity to analyse LLTV, NLDN and NEXRAD data. ASTeR ordered a number of NEXRAD data sets (Level II) tapes from NCDC. There was, however, a considerable delay in their delivery, too late to be used in this report. It should be noted, however, that we are working with the University of Oklahoma in evaluating their new program to convert Level II tapes to CD-ROM format, which in turn can be processed and displayed using a NEXRAD PC-based software system (DoRaDa). When applied, we will be able to relate sprite events to key storm parameters such as the underlying peak reflectivity, radar echo tops, etc. A possible blending of DoRaDa with savi3D interactive 3-D software would further allow preparation of 3-D perspective views of sprites and their parent lightning discharges in the context of the radar reflectivity patterns.

2.4.4 Analysis of digital RF and optical samples

A variety of analysis tools are available to apply to both the LLTV imagery and the digitally sampled photometer and RF signals. Image analysis software, such as "V for Windows" and various enhancement packages (Photoshop) can be applied to the LLTV scenes (after single field video capture). A dedicated PC was configured for real-time sampling of photometer and selected RF signals. A listing of the Labview samples (typically 1000 ms in duration) is included in Appendix A.

On 6 August 1995, samples were taken using both the Inspire VLF receiver (nominally 1-10 kHz) and the newly installed ELF system (3-120 Hz nominal response). This night allowed for excellent viewing of sprites some 500-700 km to the east. Figure 2-36 shows two sprite views, at 0606 and 0645 UTC. Figure 2-37 presents the output from the Inspire and ELF systems. There were actually two sprites about 150 ms apart at this time. The first had a very minimal VLF response and a modest ELF pulse (Note: the ELF trace is time shifted about 20 ms later). The second event (shown in the picture) had both a very strong VLF and ELF signature. It was associated with a +CG of 46 kA peak current, and was located at 572 km to the east-southeast of YRFS. A time-frequency domain display of the Inspire output (Figure 2-38) shows a double peak for this second sprite. It had its signal maximum at 5 kHz along with several smaller maxima around 1000 Hz and 300 Hz. Figure 2-39 shows an Inspire and ELF trace that includes three CG events. The first (A) was from a 19 kA +CG event at 648 km. It produced a modest ELF response, but no sprite was visible. The second (B) was a +CG with a 77 kA peak current at 595 km range. It had a large VLF and ELF response and was associated with the 0645 UTC sprite event. The third (C) was a negative CG with a peak current of 21 kA at 701 km range. It had a modest VLF sferic but no ELF response was apparent. The ELF data represent some of the first known samples of transients within 2000 km of a sprite. This is too close for the familiar wave form use in global transient monitoring to be seen. It will require further investigation to determine the information content in the close range ELF signal. For the second sprite, the time-frequency plot (Figure 2-40) shows the most energy in the Inspire concentrated at very low frequencies, on the order of 300 Hz or less. Similar results have been reported by Hale (personal communication) during SPRITES'95.

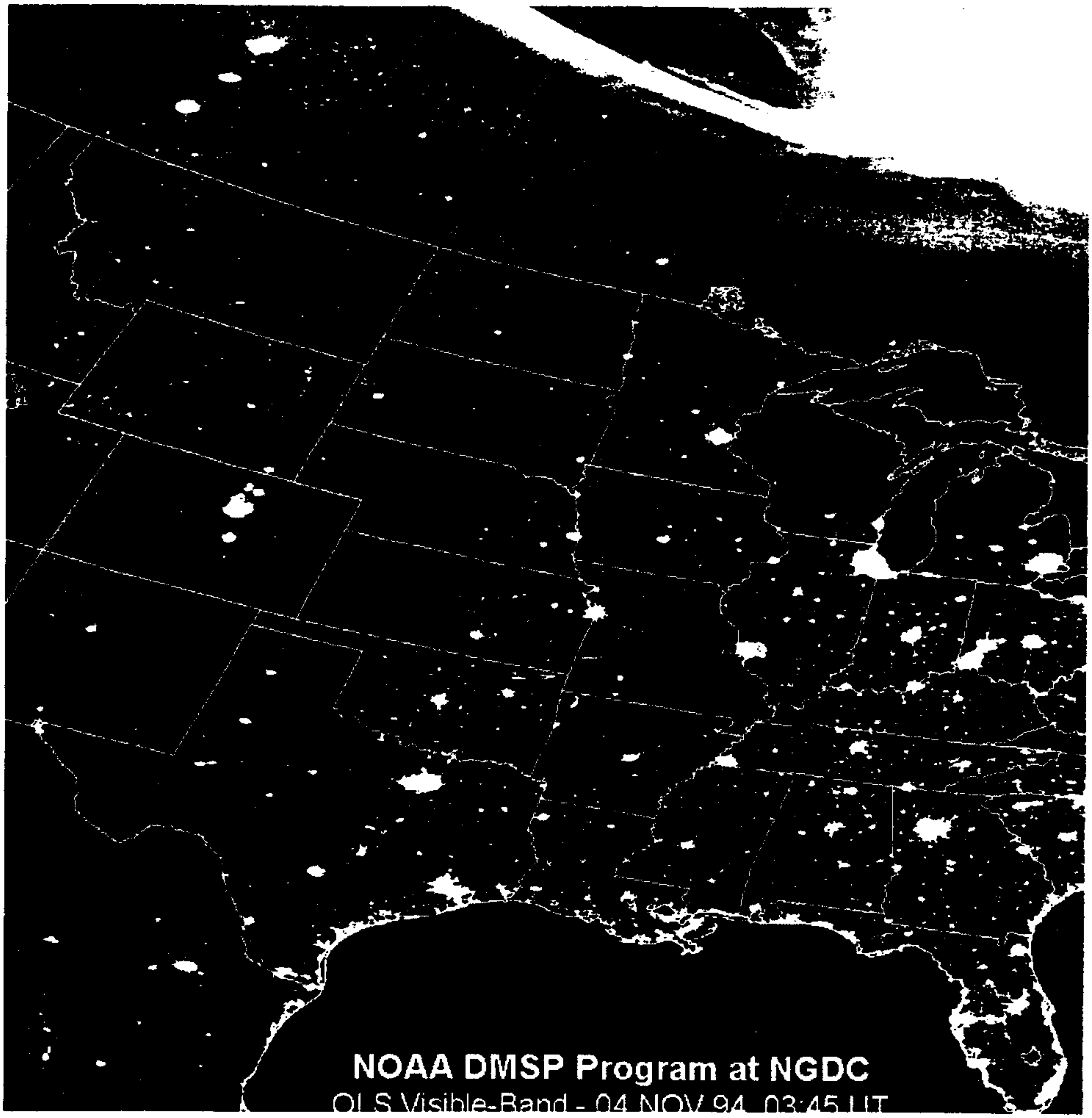


Figure 2-1. DMSP showing urban illumination across the central US. The Yucca Ridge Field Station is northeast of the northernmost light cluster along the Colorado Front Range.

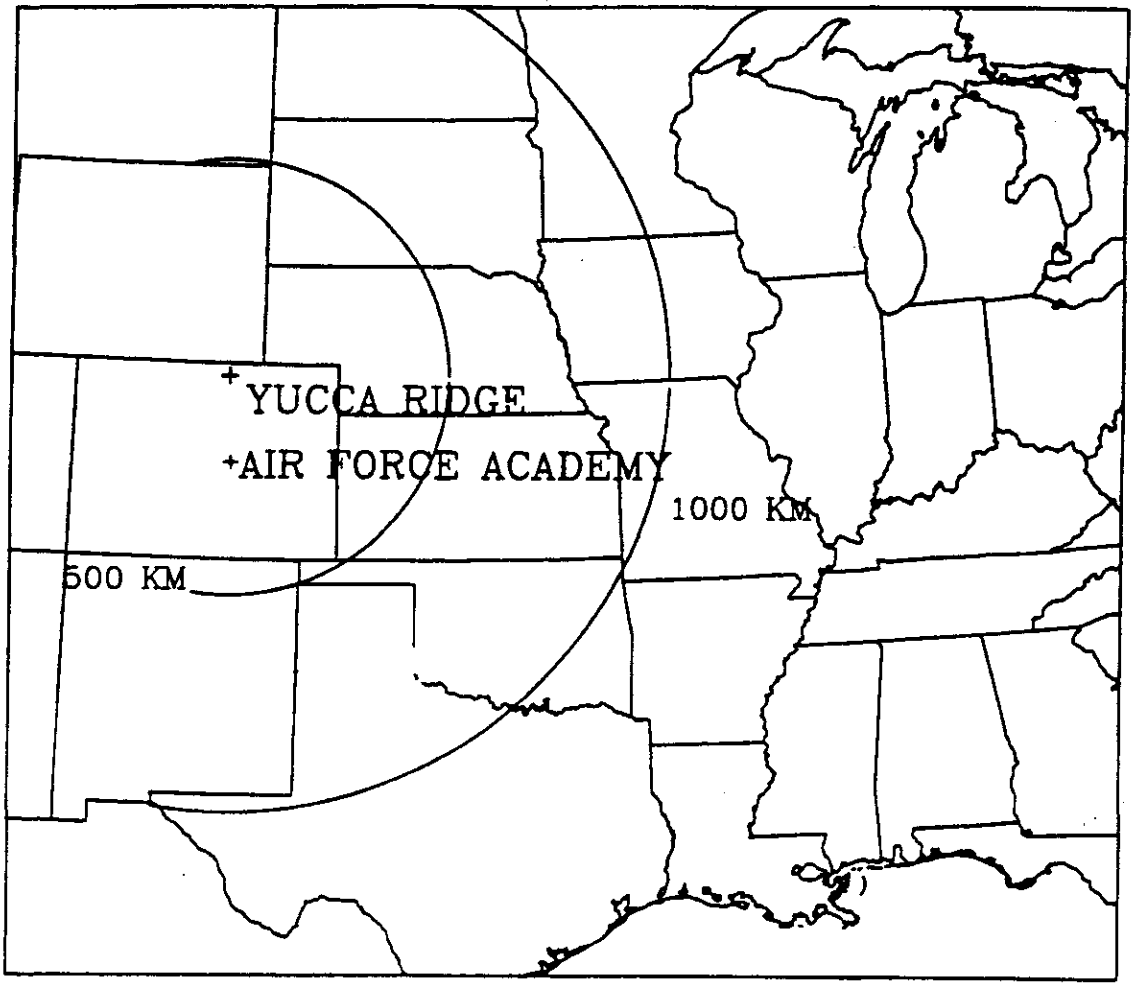


Figure 2-2. Anticipated maximum range for optical detection of sprites using LLTV system from the two project sites along the Front Range.

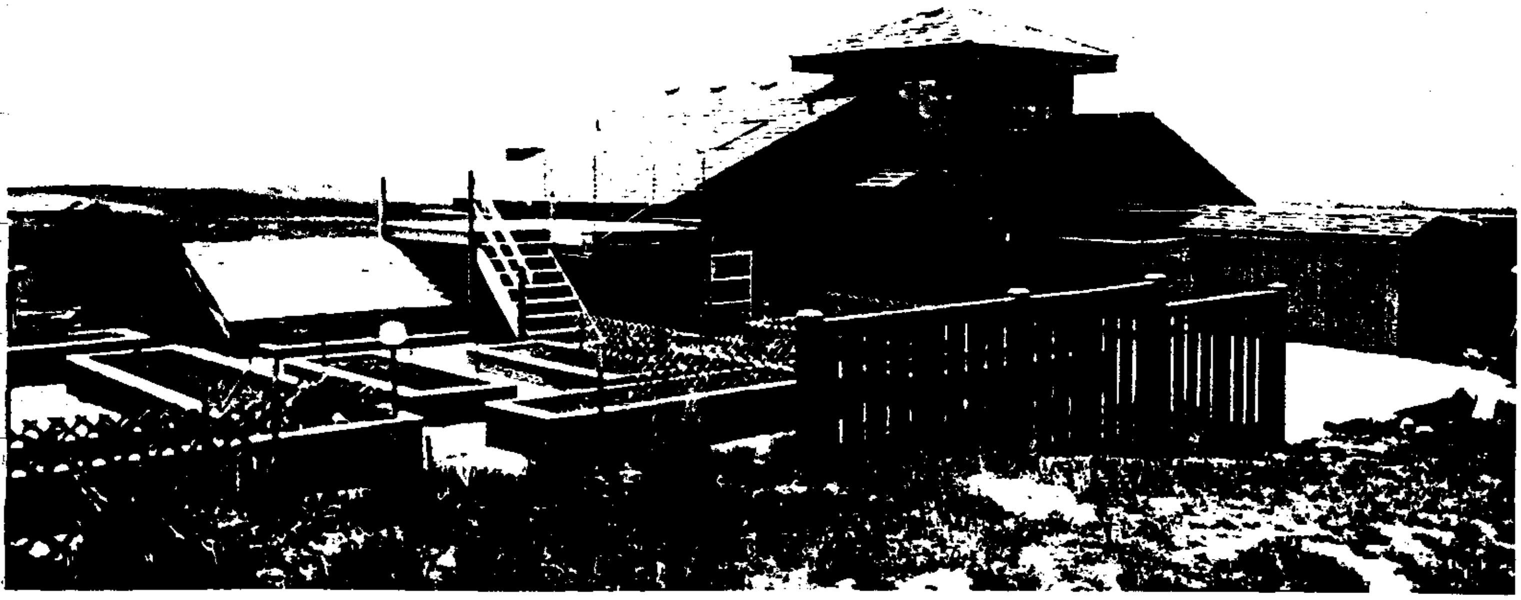


Figure 2-3. The configuration of the optical viewing platform for SPRITES'95. Most signals were routed inside the two level tower for acquisition, display and archival.

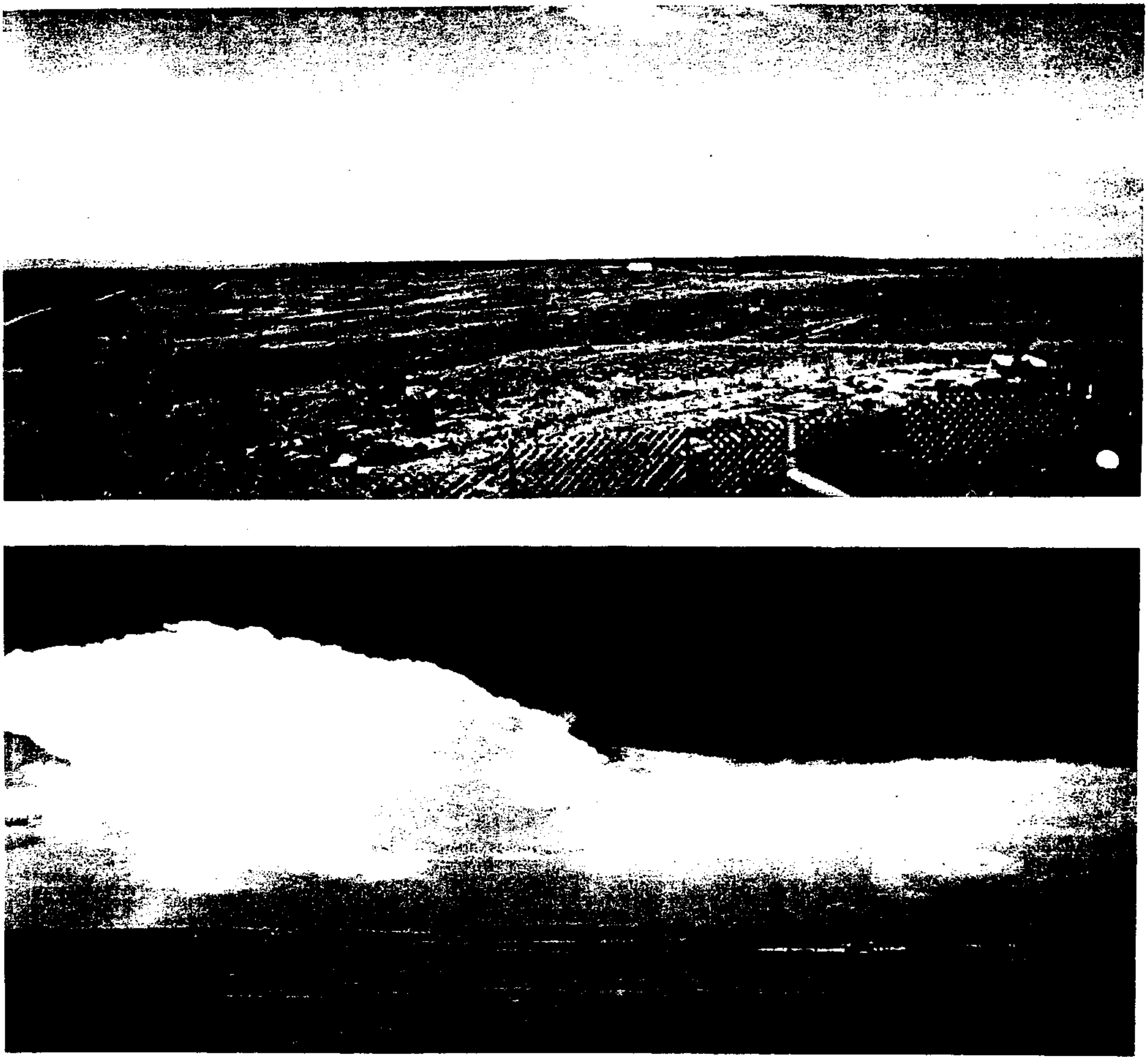


Figure 2-4. Typical views over High Plains from Yucca Ridge. On many afternoons, large mesoscale convective systems could be seen developing just east of YRFS, ready to begin the nocturnal journey eastward across the plains.

Table 2-1.

1994 FIELD OBSERVATION PROGRAM
YUCCA RIDGE FIELD STATION, FT. COLLINS, CO

ASTER, Inc
Walt Lyons/Ian Baker/Tom Nelson/Liv Lyons/Bob Nemzek
Dual Xybion Low-Light Imaging Systems
Multi-Channel Data Acquisition and Logging System
GPS Time Base for Coordinated Measurements
Data Analysis and Display System
Radar reflectivity composite database
National Lightning Detection Network data base
Digital IR GOES satellite imagery database

UNIVERSITY OF MINNESOTA
Jack Winckler
Skyflash Pointable Photometer
VLF sferics receiver (10-100 kHz)

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Earle Williams/Dennis Boccippio
MIT C-Band Radar (Albuquerque)
MIT Schumann Resonance Receiver (Rhode Island) (3-30 Hz)

US AIR FORCE ACADEMY
Major Perry Malcolm
Inspire Whistler Measurements (1-10 kHz)
Third Low-Light Imager

LAWRENCE LIVERMORE LAB
John Molitoris, Colin Price
Fast Response Imager - IROCS (Infrared Optical Camera System)

MISSION RESEARCH CORPORATION
Russ Armstrong/Jeff Shorter
Optical Multispectral Analyzer

UNIV. OF ALASKA/GEOPHYSICAL RESEARCH INSTITUTE
Davis Sentman, Gene Wescott
Two instrument reconnaissance jets with color, low-light imagers
ELF/VLF receivers and recorders

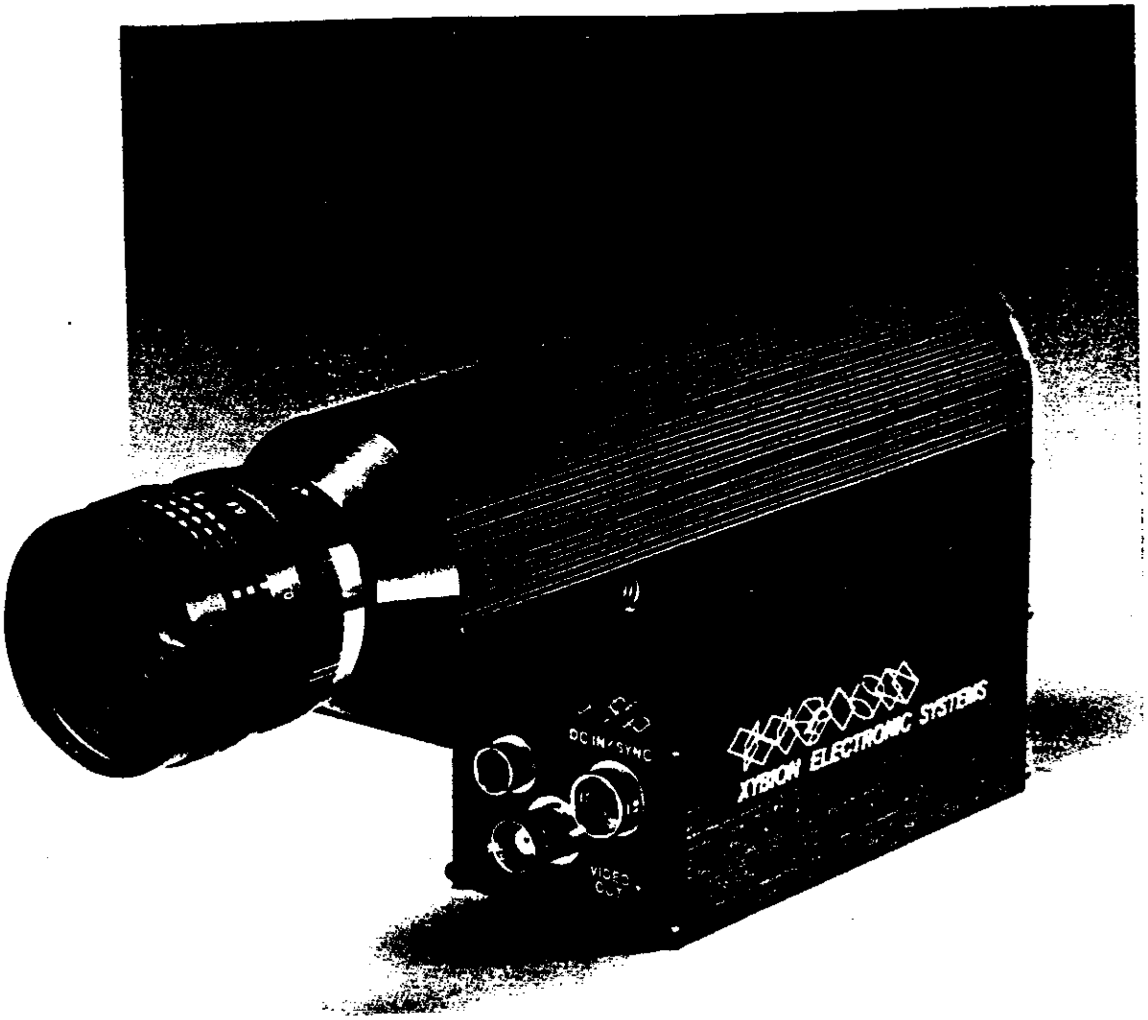


Figure 2-5. The XYBION Model ISS-255 low light CCD camera unit.

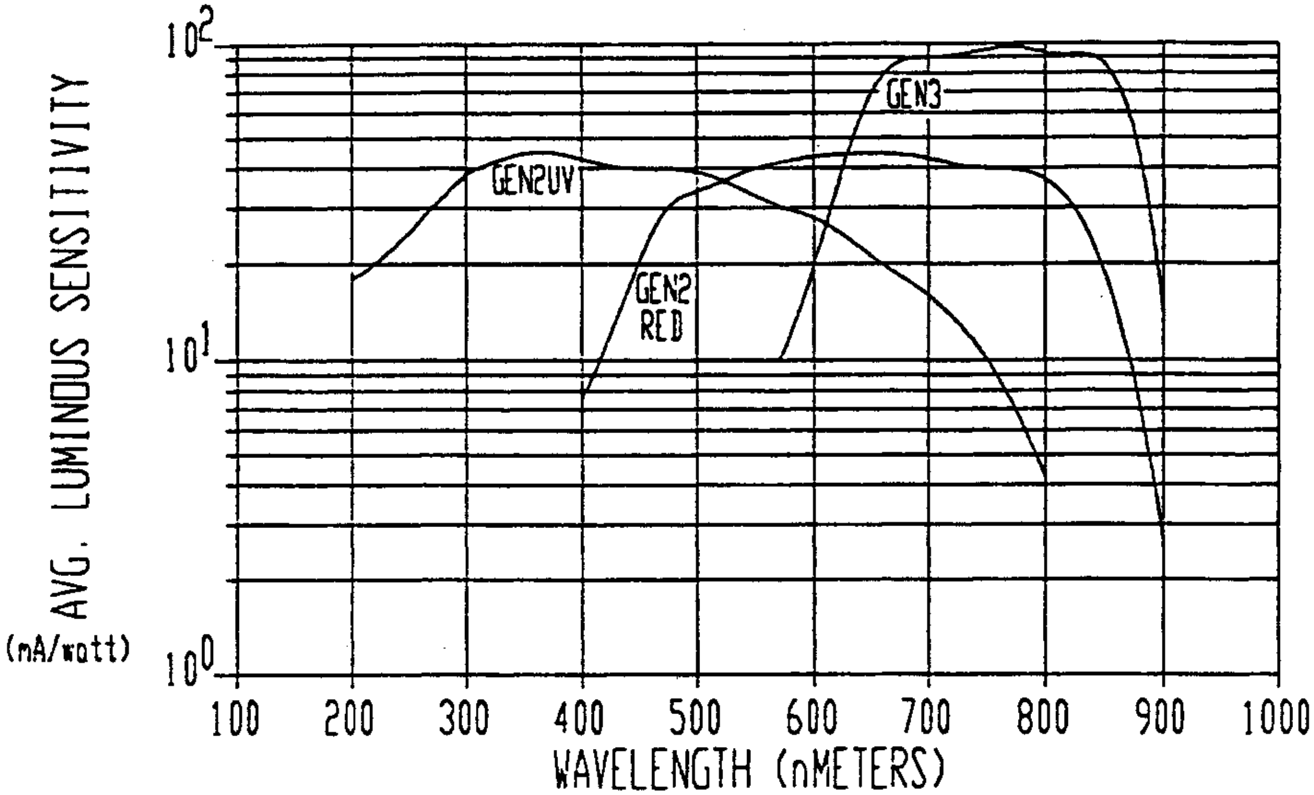
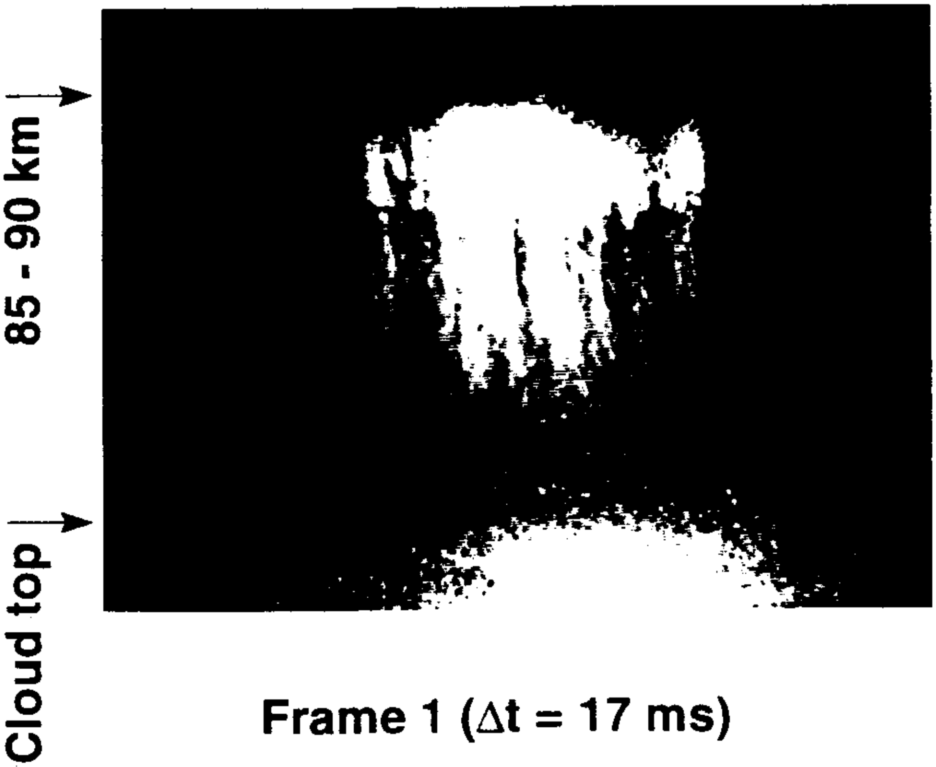


Figure 2-6. Spectral response of several available photocathodes, including the red-sensitive GEN 2 Red used for this study.



Frame 1 (Δt = 17 ms)

Frame 2 (Δt = 17 ms)

Figure 2-7. Two successive 16.7 ms video fields, which together would comprise a single 33 ms frame of video. The XYBION systems are configured to produce two independent fields per frame.

Figure 2-8. A very large and bright sprite, imaged from YRFS at 0604.01.543 UTC 16 July 1995. The video fields before and immediately after this showed absolutely no trace of the sprite. This demonstrates that continuation of sprite features from field to field reflects true luminosity rather than an artifact of the video system through persistence.

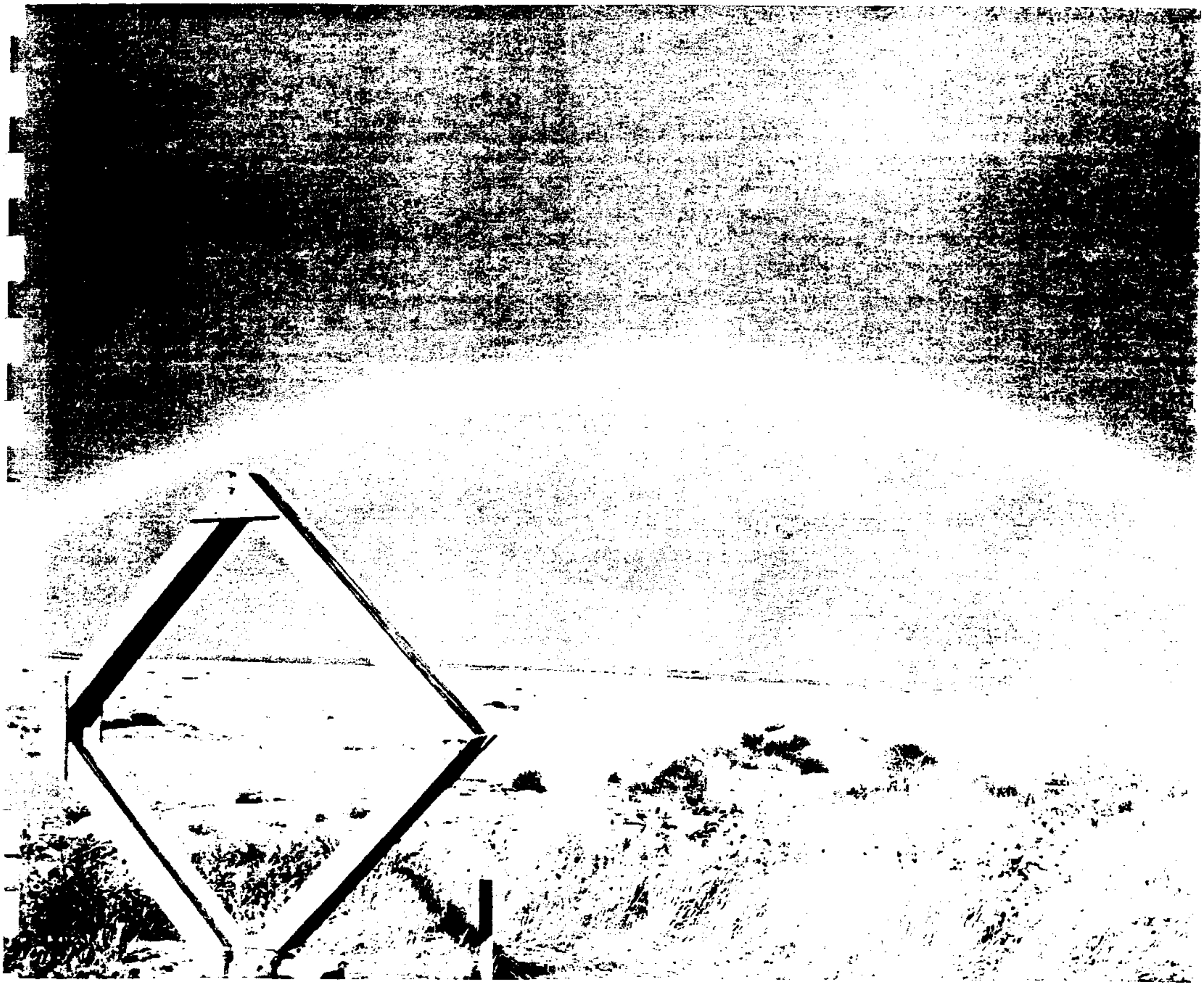


Figure 2-9. A typical late afternoon scene, looking east from YRFS as convective storms moving off the Front Range continue to grow to a nocturnal maximum over the High Plains. In the foreground is the University of Minnesota magnetic loop VLF receiver.

Figure 2-10. Participants in the SPRITES'95 Campaign.

ASTeR, Inc., Fort Collins, Colorado.
Walter Lyons, Project Director; Tom Nelson
dual Xybion ISS-255 low light imagers • ELF and VLF measurements • photometer • meteorological data

Tohoku University, Sendai, Japan
Hiroshi Fukunishi, Yukihiro Takahashi, Minoru Kubota
multiple (4) high speed 1°x10° FOV photometers

University of Otago, Dunedin, New Zealand *Richard Dowden* - OMNI-PAL VLF interferometer (3 sites)

STAR Laboratory, Stanford University
Umran Inan, Steve Reising, Bill Trabucco, Alex Slingeland
narrowband VLF from mobile van • VLF narrowband and broadband (0-30 kHz) VLF at YR • VLF observations in conjugate region (Palmer station)

GeoSpace Research, Inc.
Frank Djuth, Matt Cox, Ken Williams - bi-static propagation (WWV at 2.5, 5, 10, 15 and 20 mHz and 28 mHz transmissions)

Utah State University, Space Dynamics Lab
Michael Taylor, Peter Mace
all sky airglow camera • highly sensitive low-light vidicon and SIT cameras (filtered)

Lawrence Livermore National Laboratory
John Molitoris, Colin Price
IROCS - infrared optical camera system • fast optical imager • large format optical imager

Massachusetts Institute of Technology
Earle Williams, Charles Wong, Bob Boldi
Schumann Resonance/Q-bursts at Rhode Island and YR sites

NOAA, National Severe Storms Laboratory
David Rust, Thomas Marshall
lightning video and balloon-borne electric field mill

Pennsylvania State University
Les Hale, Lee Marshall
ELF and VLF measurements

Los Alamos National Laboratory
Robert Franz, Dave Smith
measurements of TIPPS and SIPPS

Mission Research Corporation, Nashua, NH.
Russ Armstrong, Jeff Shorter
CCD cameras system and photometer

Lockheed Space and Missile
Steve Mende, Rick Rairden
imaging spectrometer and low-light video

SRI International
Roland Tsunoda, John Buonocore
tunable radar system (2-30 mHz)

NASA Kennedy Space Center & MSFC
Carl Lennon, Launa Maier, Otha Vaughan, Jr.
LDAR • ELF/Q-burst measurements • OTD

Figure 2-11. Close up of the platform built to house optical sensors used during SPRITES'95. From the platform there was an unobstructed view from north-northwest clockwise through south-southwest.

Figure 2-12. The Lockheed Martin spectrograph and LLTV systems deployed (Mende et al, 1995;Rairden and Mende, 1995). The True Time GPS receiver can also be noted lashed to the post.

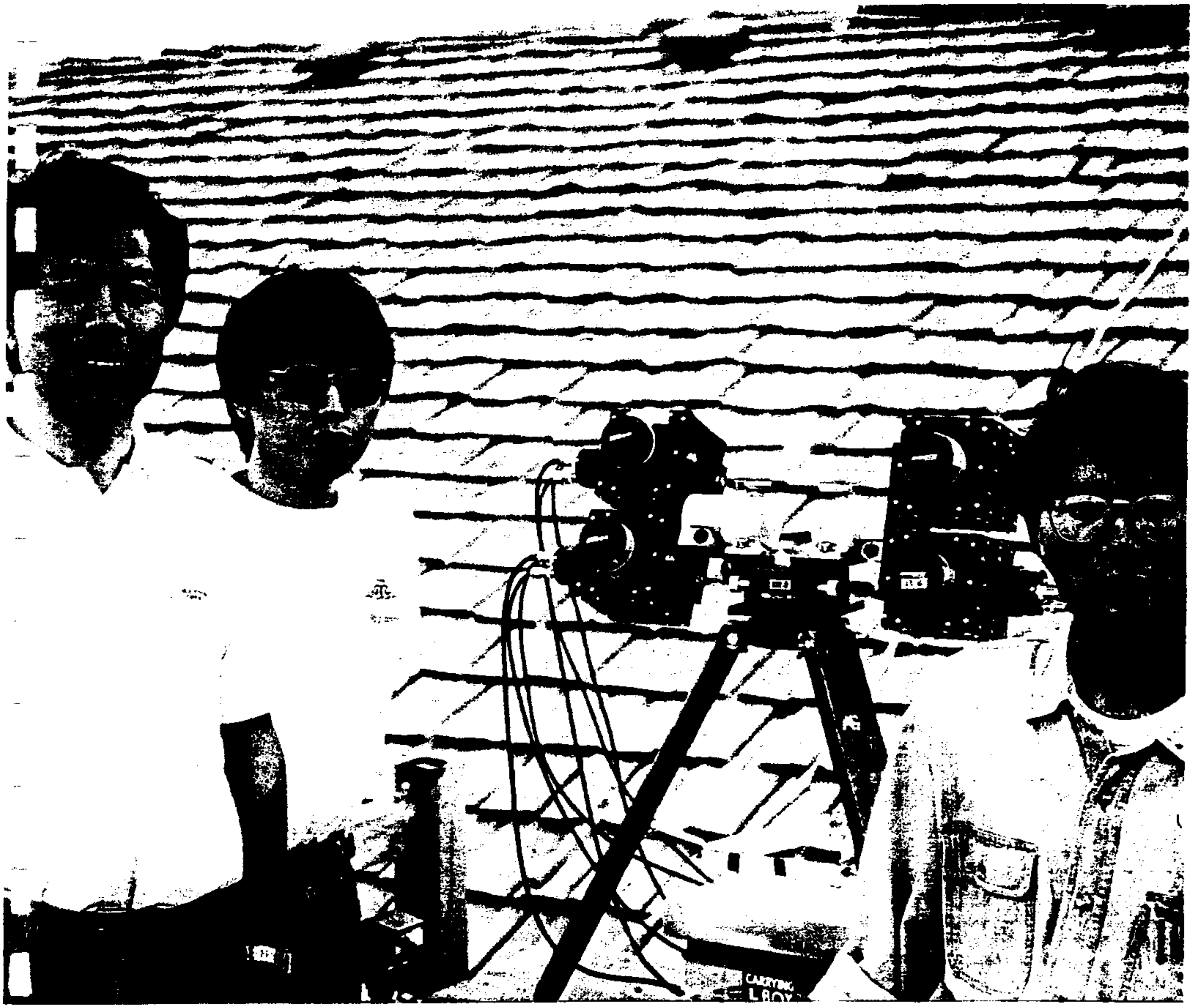


Figure 2-13. The pointing photometer system and its developers from Tohoku University, Sendai, Japan, H. Fukunishi, M. Kubota, and Y. Takahashi (right to left).

Department of Astrophysics and Geophysics
Tohoku University
Sendai, Miyagi, 980-77 Japan

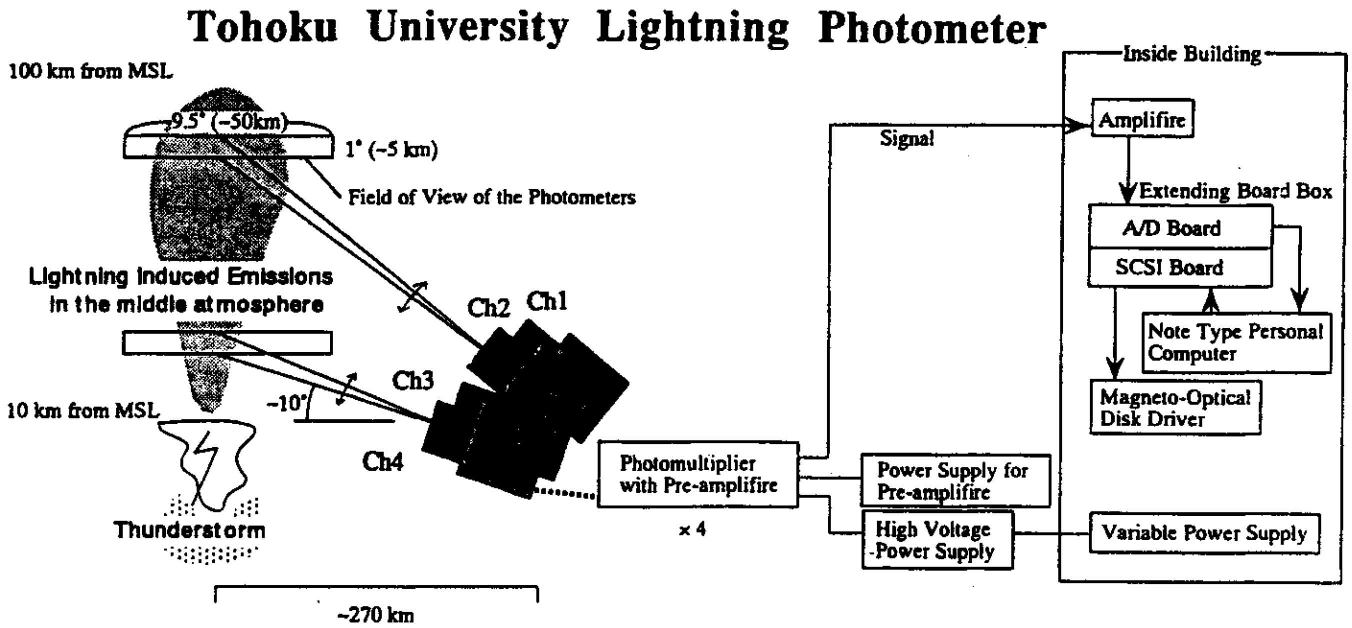


Figure 2-14. Schematic of the Tohoku University pointing photometer system (Fukunishi et al., 1996).

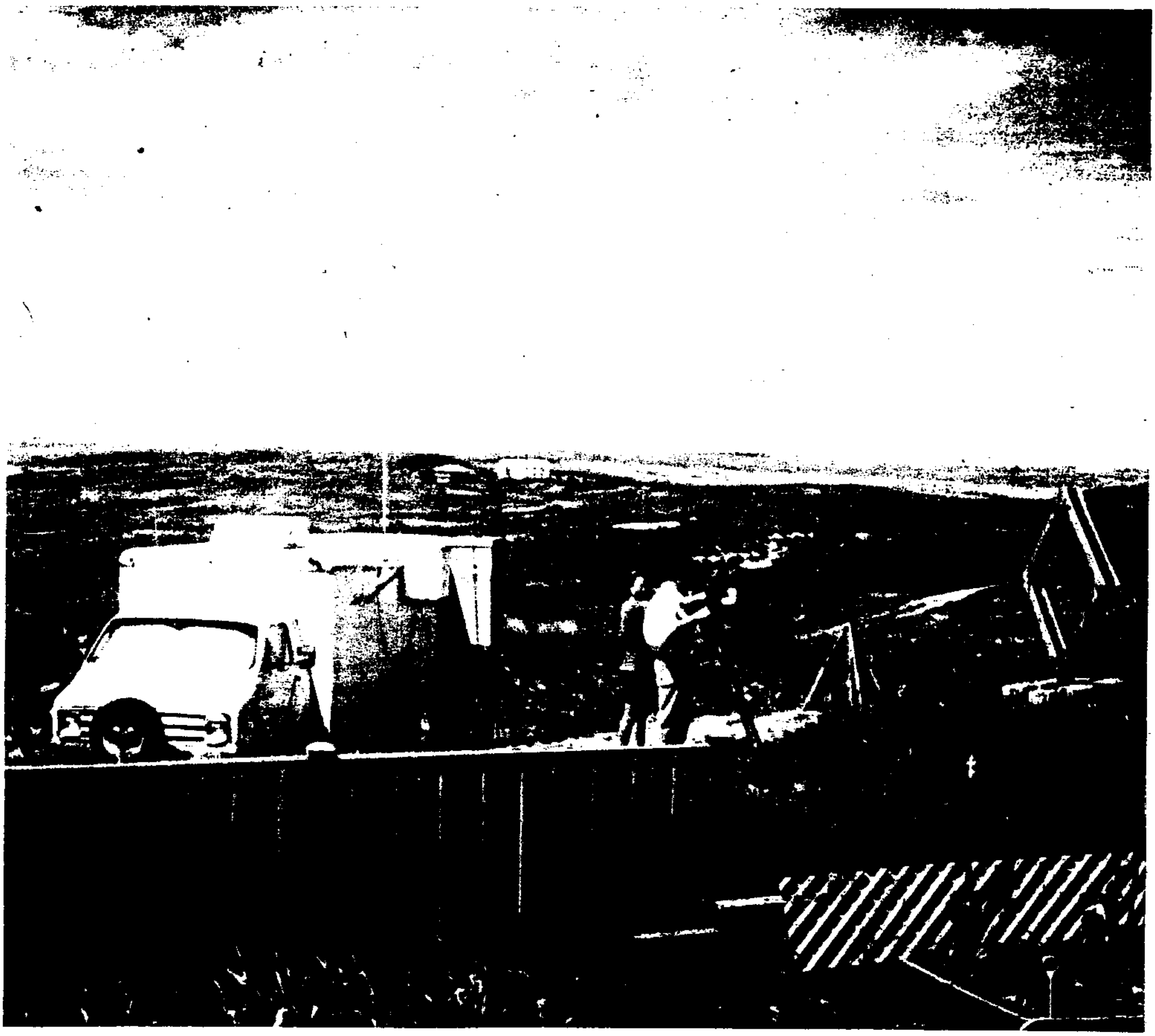


Figure 2-15. The mobile van of the Space Dynamics Laboratory, Utah State University.

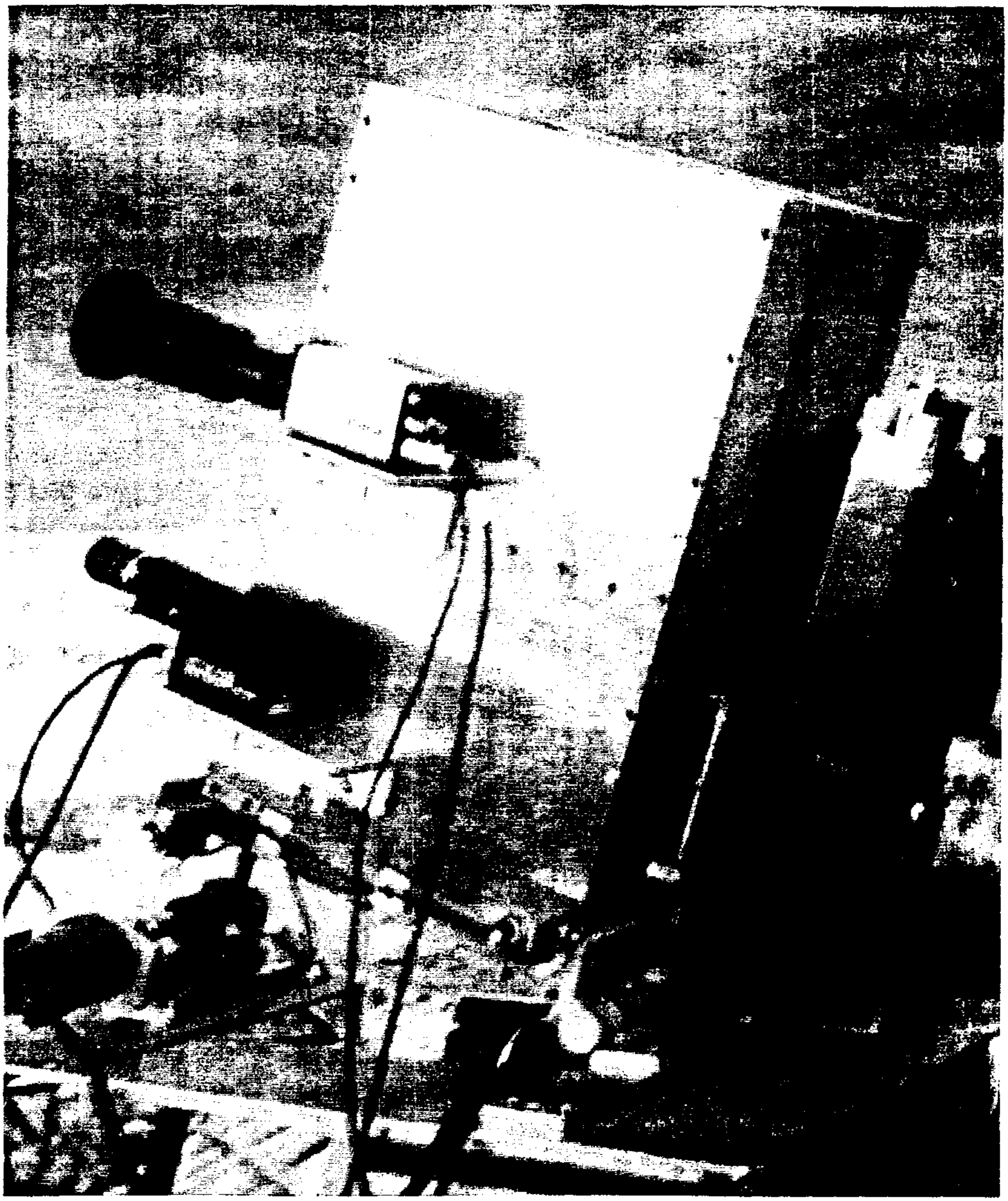


Figure 2-16. The Infrared Optical Cameras Systems (IROCS) developed and tested by Lawrence Livermore National Laboratory.

Figure 2-17. The magnetometer coils used for ELF measurements before their installation as E-W and N-S orthogonal receivers. Equipment supplied courtesy of Earle Williams (MIT).

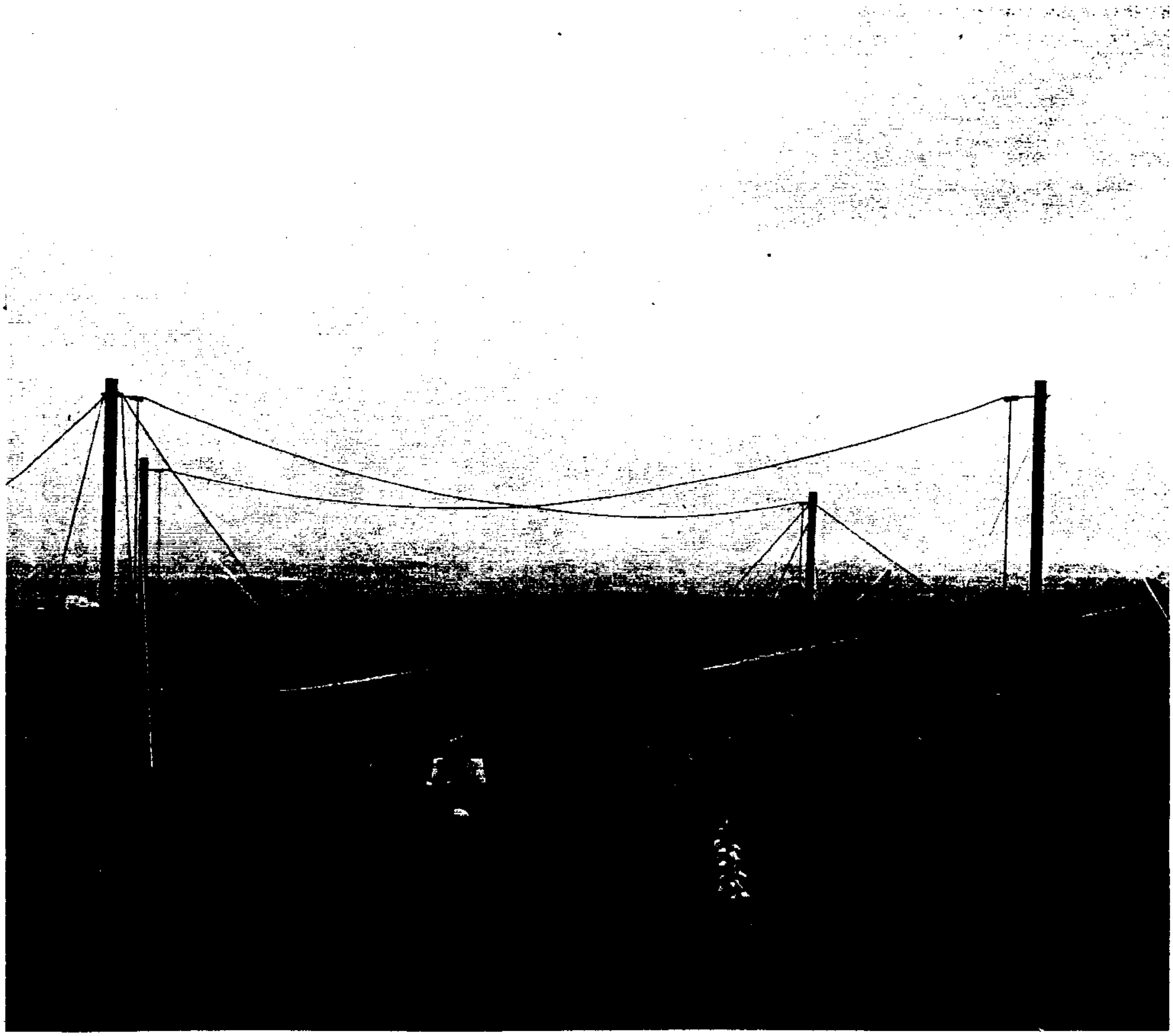
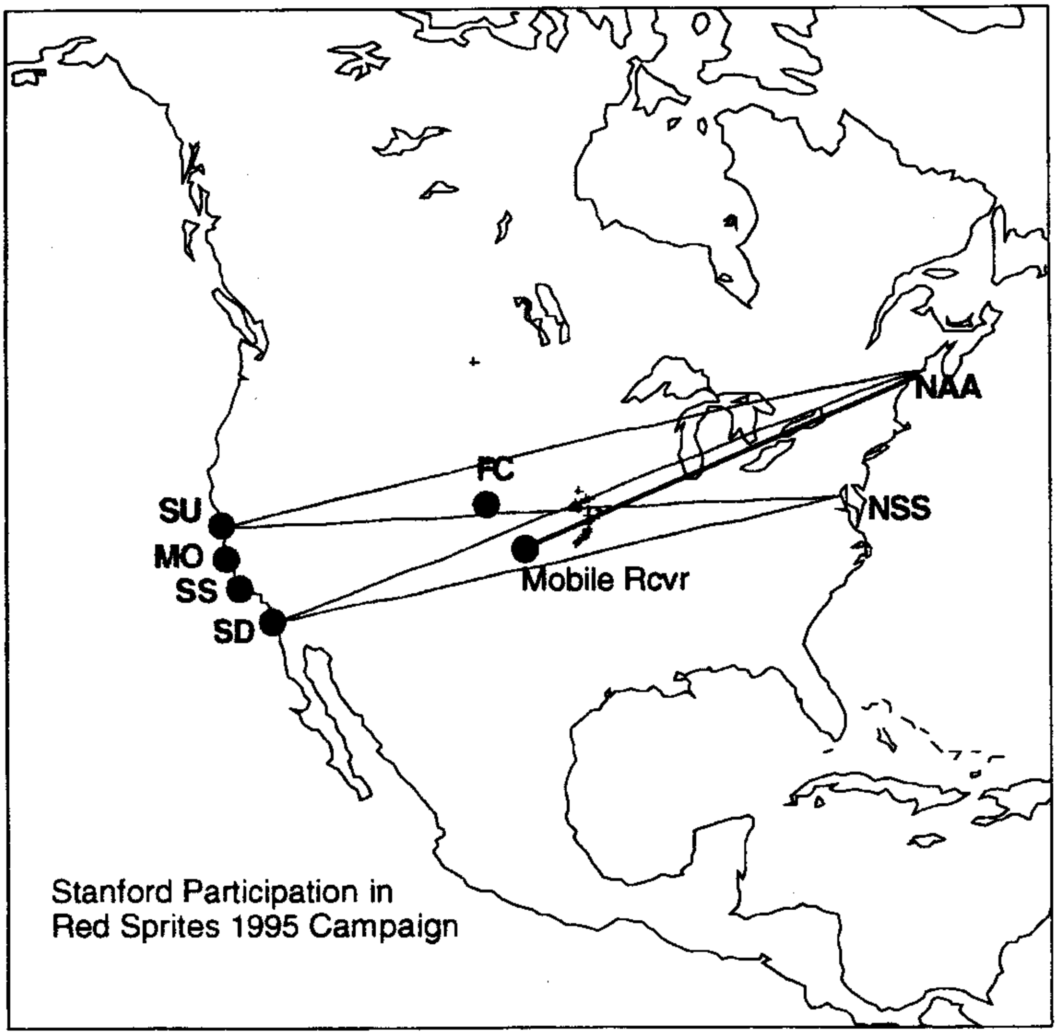


Figure 2-18. The Stanford University STAR Lab broad band magnetic loop VLF receiver.



Mobile receiver consists of a one-half rack of equipment carried around in a VAN. Once the storm activity is identified (using lightning data) the receiver is deployed at a location so as to optimize the alignment of the VLF path with the active storm center. Typically, operation at a nearby gas station or hotel/motel envisioned, as we only need to be able to plug into a power outlet.

The fixed receiver to be deployed at Fort Collins (FC), Colorado will allow higher measurements of the VLF Sprites, since the signals scattered from the ionospheric disturbances would not have travelled over long distances.

The measurements at the stations across California are already ongoing and will be operated throughout the summer nights.

Figure 2-19. The STAR Lab VLF mobile van sampling strategy, placing the VLF receiver with ±50 km of the line of site between a Navy VLF transmitter and a sprite-generating storm.

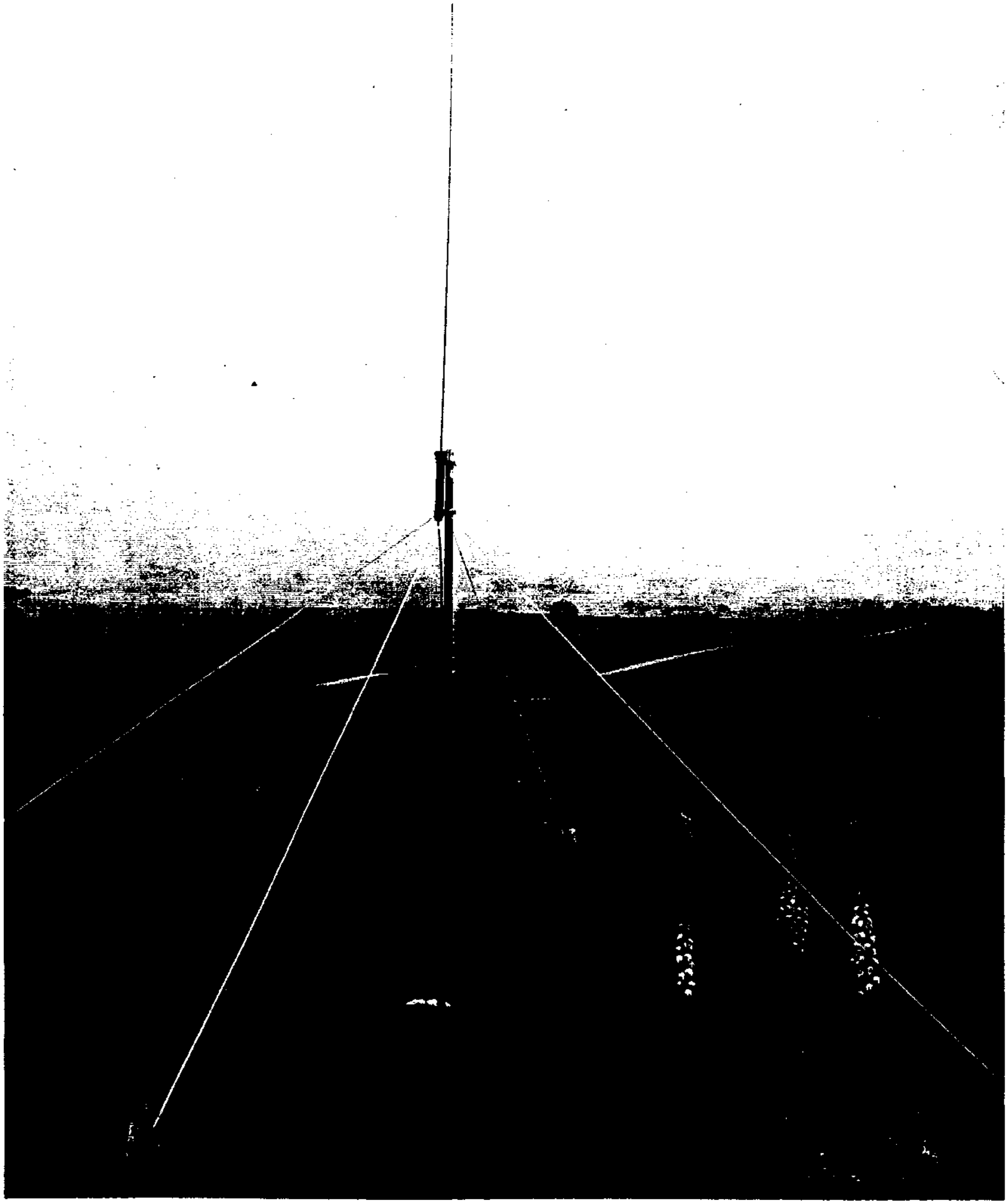


Figure 2-20. The OmniPAL VLF receiver installed at Yucca Ridge (and at other sites along the Front Range) by the University of Otago (Dowden et al., 1995).

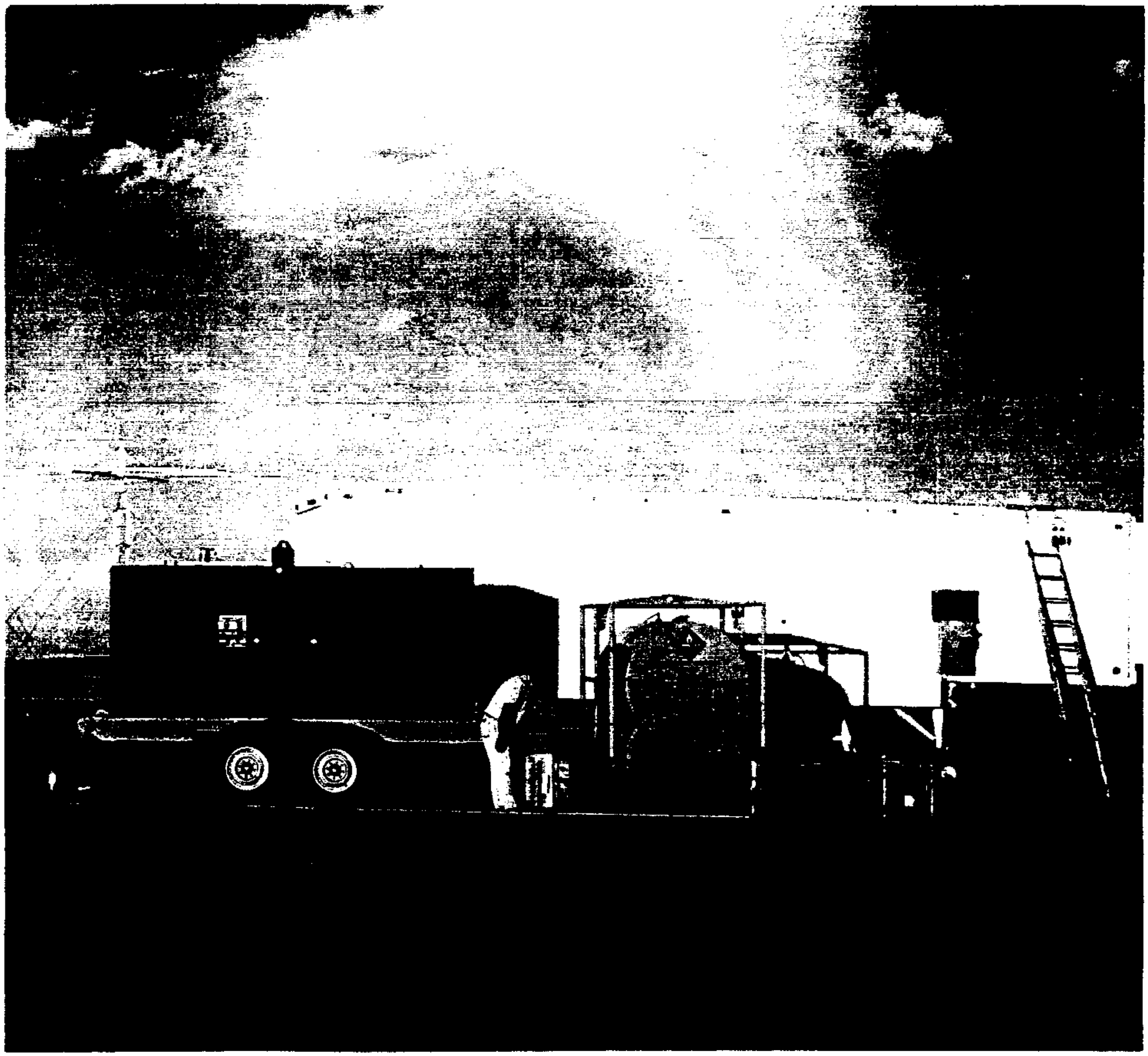


Figure 2-21. The trailer housing the electronics for the SRI mobile radar system.

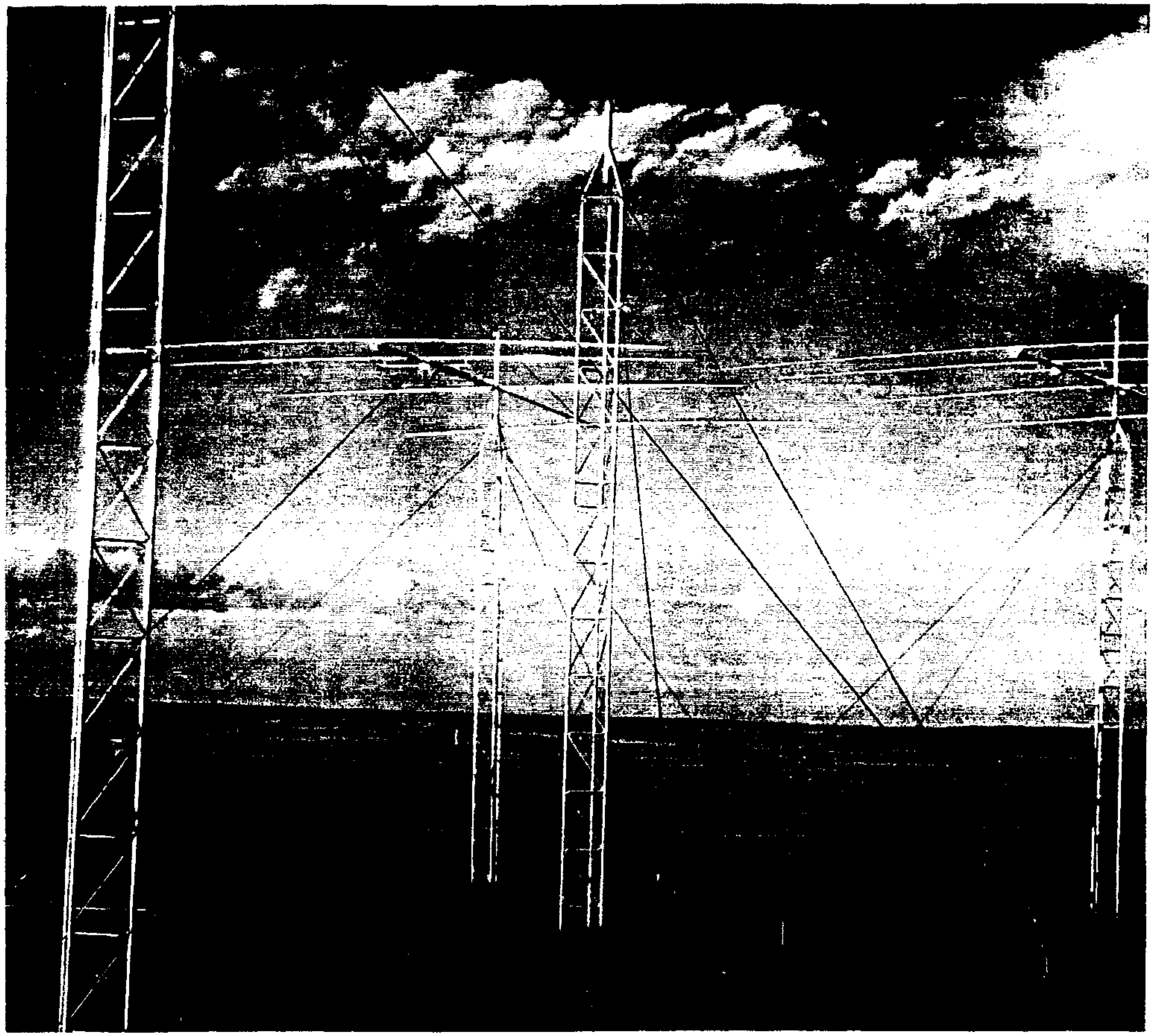
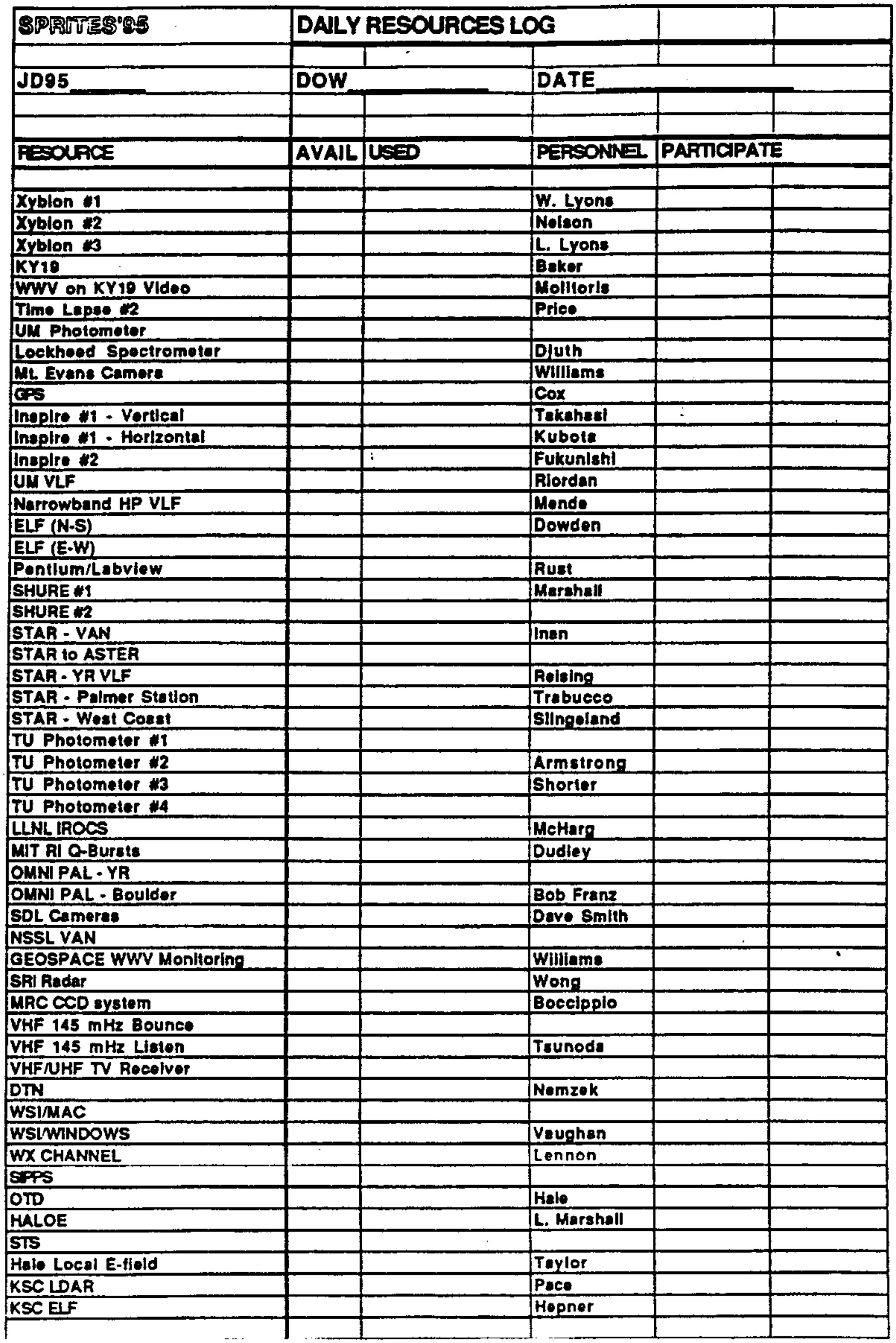


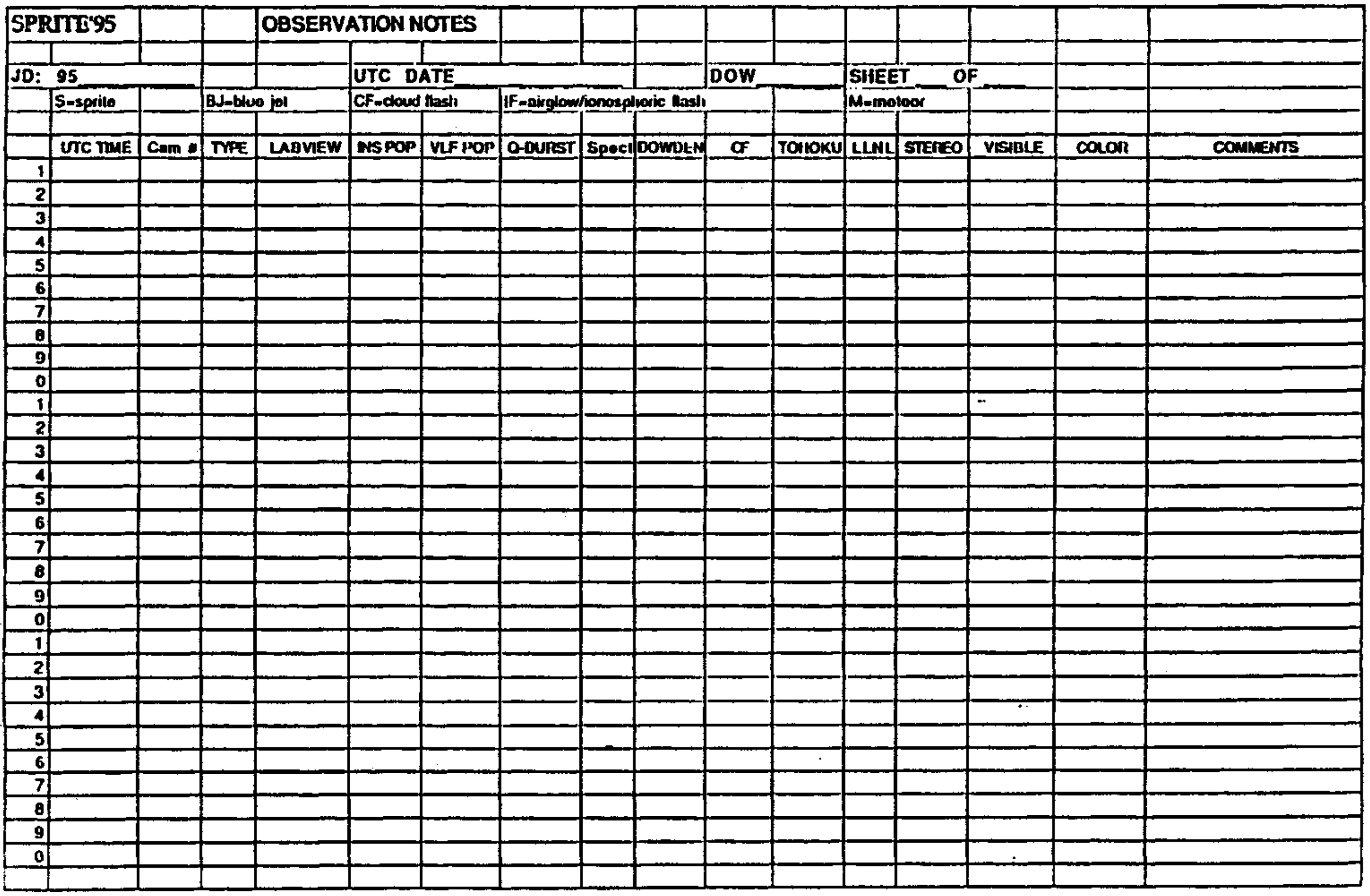
Figure 2-22. The SRI mobile radar antenna array installed at Yucca Ridge.

Figure 2-23. A portion of the command and control system established in the research tower at YRFS. Shown are the controls for the University of Minnesota photometer, the WSI data acquisition system, the Labview data acquisition and display unit and an LLTV monitor.



SPRITES'95	DAILY RESOURCES LOG				
JD95____	DOW____		DATE____		
RESOURCE	AVAIL	USED	PERSONNEL	PARTICIPATE	
Xyblon #1			W. Lyons		
Xyblon #2			Nelson		
Xyblon #3			L. Lyons		
KY19			Baker		
WWV on KY19 Video			Molitoris		
Time Lapse #2			Price		
UM Photometer					
Lockheed Spectrometer			Djuth		
Mt. Evans Camera			Williams		
GPS			Cox		
Inspire #1 - Vertical			Takahasi		
Inspire #1 - Horizontal			Kubota		
Inspire #2			Fukunishi		
UM VLF			Riordan		
Narrowband HP VLF			Mende		
ELF (N-S)			Dowden		
ELF (E-W)					
Pentium/Labview			Rust		
SHURE #1			Marshall		
SHURE #2					
STAR - VAN			Inan		
STAR to ASTER					
STAR - YR VLF			Reising		
STAR - Palmer Station			Trabucco		
STAR - West Coast			Slingeland		
TU Photometer #1					
TU Photometer #2			Armstrong		
TU Photometer #3			Shorter		
TU Photometer #4					
LLNL IROCS			McHarg		
MIT RI Q-Bursts			Dudley		
OMNI PAL - YR					
OMNI PAL - Boulder			Bob Franz		
SDL Cameras			Dave Smith		
NSSL VAN					
GEOSPACE WWV Monitoring			Williams		
SRI Radar			Wong		
MRC CCD system			Boccippio		
VHF 145 mHz Bounce					
VHF 145 mHz Listen			Tsunoda		
VHF/UHF TV Receiver					
DTN			Nemzek		
WSI/MAC					
WSI/WINDOWS			Vaughan		
WX CHANNEL			Lennon		
SPPS					
OTD			Hale		
HALOE			L. Marshall		
STS					
Hale Local E-field			Taylor		
KSC LDAR			Pace		
KSC ELF			Hepner		

Figure 2-24. The daily resources log kept during SPRITES'95.

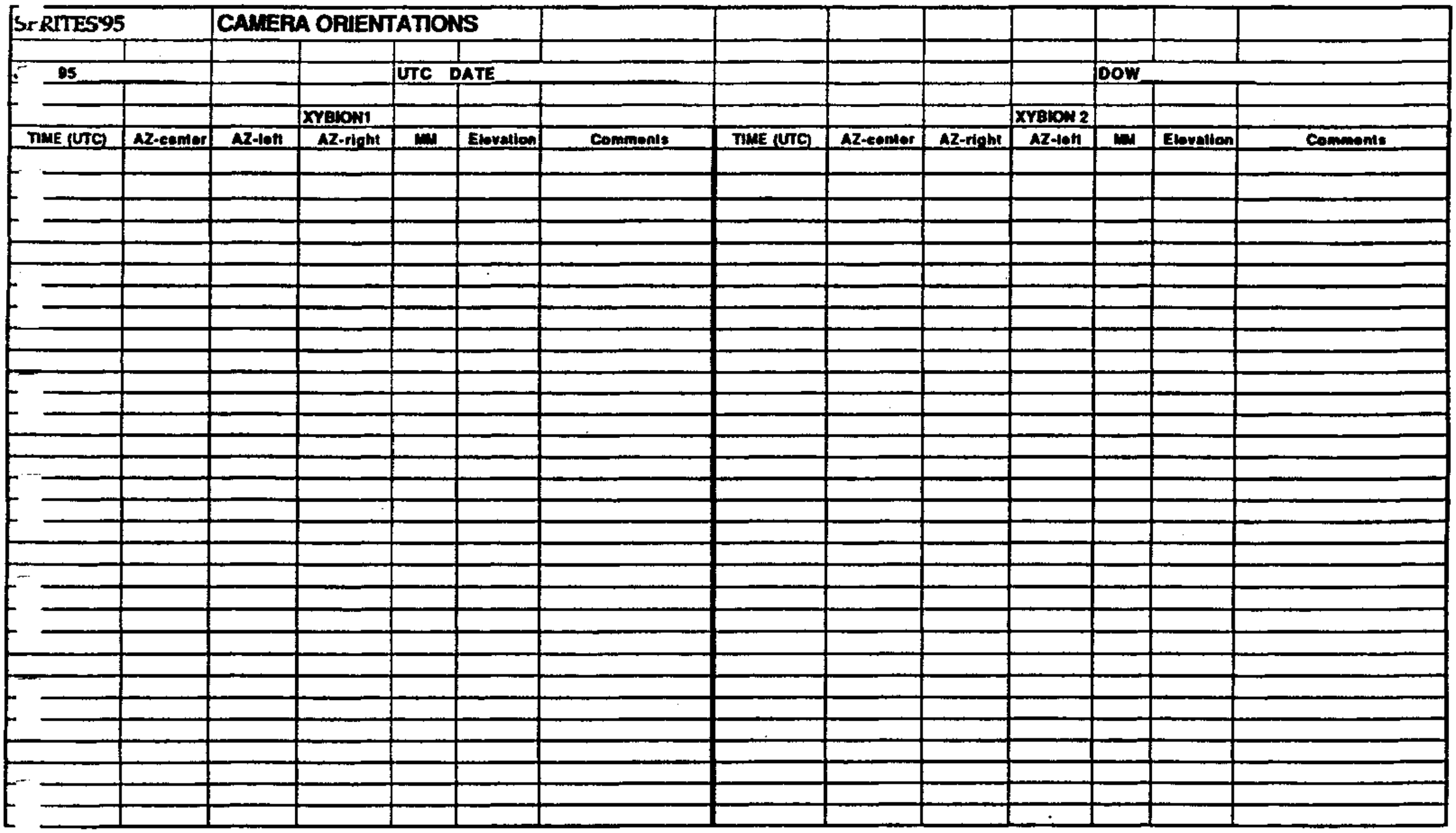


SPRITE'95				OBSERVATION NOTES												
JD: 95____					UTC DATE____				DOW____		SHEET ___ OF ___					
	S=sprite		BJ=blue jet		CF=cloud flash		IF=airglow/ionospheric flash				M=meteor					
	UTC TIME	Cam #	TYPE	LABVIEW	INS POP	VLF POP	Q-BURST	Spect	DOWDEN	CF	TOHOKU	LLNL	STEREO	VISIBLE	COLOR	COMMENTS
1																
2																
3																
4																
5																
6																
7																
8																
9																
0																
1																
2																
3																
4																
5																
6																
7																
8																
9																
0																
1																
2																
3																
4																
5																
6																
7																
8																
9																
0																

Figure 2-25. A form of real-time notation of TLE occurrences.

SPRITES'95		**DATA ACQUISTION LOG**									
JD______		DOW______			UTC DATE______						
WSI	PC	MAC									
Hour starting	2z	3z	4z	5z	6z	7z	8z	9z	10z	11z	Sum
STRIKES											
LITRAD											
LITSAT											
REGRAD											
GOES											
USRAD HIRES											
SUMSTR											
Misc WSI											
DTN	2z	3z	4z	5z	6z	7z	8z	9z	10z	11z	
	9Pcdt	10Pcdt	11Pcdt	12cdt	1Acdt	2Acdt	3Acdt	4Acdt	5Acdt	6Acdt	
National Radar											
Satellite											
Radar#1 -00											
-15											
-30											
-45											
Radar#2 -00											
-15											
-30											
-45											
Surface		Svr Wx									
Jet											
Temps											
WxChannel											
MSU					HALOE						
OTD					STS						
CHECK LIST											
Dog Fence				STAR Tapes			Dowden				
LR Lamp				Film Warm			Start VM				
Porch Lights				Front lights			End VM				
Dimmers				Pump							
TAPES	On	Off	Lens	Filter	Summary						
1a of											
1b of											
1c of											
2a of											
2b of											
2c of											
3a of											
3b of											
4c of											
4b of											
4c of											
KY											
LITLIST	LITLIST xxxxZ-yyyyZ -LAT=40.4 -LON=-105 -POS -RANG=kmkm										

Figure 2-26. SPRITES'95 Data Acquisition Log.



SPRITES'95		CAMERA ORIENTATIONS											
95				UTC	DATE						DOW		
			XYBION1							XYBION 2			
TIME (UTC)	AZ-center	AZ-left	AZ-right	MM	Elevation	Comments	TIME (UTC)	AZ-center	AZ-right	AZ-left	MM	Elevation	Comments

Figure 2-27. Camera Orientation Log used during SPRITES'95.

30 June
1 July
4 July
7 July
8 July
9 July
11 July
12 July
13 July
16 July
17 July
18 July
21 July
25 July
26 July
28 July
30 July
6 August
8 August
12 August
14 August
17 August
19 August
23 August
30 August
4 September
7 September

Figure 2-28. Dates with imaged sprites during SPRITES'94.

1995 COLORADO SPRITE CAMPAIGN

DATES (UTC) WITH IMAGED SPRITES/ELVES

§ § § § §

19 June
20 June
21 June
23 June
25 June
27 June
04July
07July
08July
12July
13July
15July
16July
20July
21July
22July
23July
24July
25July
26July
27July
31July
03August
04August
06August

Figure 2-29. Dates with imaged sprites during SPRITES'95.

RITES '95

DAILY SUMMARY CHART - Systems AVAILABLE (not necessarily collecting data)
YUCCA RIDGE FIELD STATION

All Times are UTC

				TAPE																												
D	DOW	UTC Date	GPS	START	END	PROC?	#Sprites	Imager	ELF/VLF	UltPho	HPWA	LabView	Stereo	KY19	Q Burst	VHF S	VHF R	Radar	Dpath	IBOCS	4PHO	CCD	SU Van	NSSL	STAR	NW Z	WSI	DTN	SDL	Lock	Vite	PBU
2	Sa/Su	11-Jun-95	N																													
163	Su/M	12-Jun-95	N																													
164	M/T	13-Jun-95	Y	0350	0560	N	0	Y	N	Y	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	Y	N	Y	Y	N	N	N	N
165	T/W	14-Jun-95	Y	0409	0609	N	0	N	N	N	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	Y	setup	Y	Y	N	N	N	N
5	W/Th	15-Jun-95	Y	0400	0530	N	0	Y	N	N	N	N	N	Y	N	N	N	N	N	N	Y		N	N	Y	setup	Y	Y	N	N	N	N
7	Th/F	16-Jun-95	N																													
3	F/Sa	17-Jun-95	N																													
3	Sa/Su	18-Jun-95	N																													
170	Su/M	19-Jun-95	Y	0356	0737	N/Y	0/9	Y	Y	Y	N	N	Y	Y	N	N	N	N	Y	N	Y	N	Y	N	Y	Y	Y	Y	N	N	N	N
171	M/T	20-Jun-95	Y	0337	0815	Y	4	Y	Y	Y	N	N	?	Y	N	N	N	N	Y	N	Y	N	N	N	Y	Y	Y	Y	N	N	N	N
172	T/W	21-Jun-95	Y	0402	1025	Y	17	Y	Y	Y	Y	Test	?	Y	N	N	N	N	tstm	N	Y	N	Y	N	Y	Y	Y	Y	N	N	N	N
	W/Th	22-Jun-95	N	0639	0655																											
	Th/F	23-Jun-95	Y	0607	1010	Y	23	Y	Y	Y	Y	Y	?	N	N	N	N	N	Y	N	Y!	N	Y	Y	Y	Y	Y	Y	N	N	N	N
5	F/Sa	24-Jun-95	N																													
176	Sa/Su	25-Jun-95	Y	0515	0720	Y	2	Y	Y	N	Y	N	N	N	N	N	N	N	Y	N	Y	N	N	N	Y	Y	Y	Y	N	N	N	N
177	Su/M	26-Jun-95	N																													
178	M/T	27-Jun-95	Y	0356	0630	Y	40	Y	Y	Y	Y	Y	N	N	N	N	N	N	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	N	N	Y
	T/W	28-Jun-95	N																													
	W/Th	29-Jun-95	N																													
	Th/F	30-Jun-95	N																													
182	F/Sa	01-Jul-95	N																													
183	Sa/Su	02-Jul-95	N																													
184	Su/M	03-Jul-95	Y	0418	0618	N	0	Y	Y	Y	Y	Y	?	N	N	N	N	N	Y?	N	Y	N	N	N	Y	Y	Y	Y	N	N	N	N
	M/T	04-Jul-95	Y	0435	0635	Y	51	Y	Y	Y	Y?	Y	?	N	N	N	N	N	Y	N	Y	N	Y-	N	Y	Y	Y	Y	N	N	N	N
	T/W	05-Jul-95	N																													
	W/Th	06-Jul-95	N																													
188	Th/F	07-Jul-95	Y	0336	0600	Y	14	Y	Y/N	Y	Y	Y	N	N	N	N	N	N	Y?	N	Y	N	N	N	Y	Y	Y	Y	Y	N	N	N
189	F/Sa	08-Jul-95	Y	0326	0636	N/Y	0/50	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	N	Y	N	Y	N	Y	Y	Y	Y	Y	N	N	Y
190	Sa/Su	09-Jul-95	Y	0330	0530	N	0	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
	Su/M	10-Jul-95	N																													
	M/T	11-Jul-95	Y	0330	0730	N	0	Y	Y	Y	Y	Y	Y?	Y	N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y/N	Y
	T/W	12-Jul-95	Y	0428	0745	Y	1	Y	Y	Y	Y	Y	?	Y	N	N	N	N	Y	N	Y	Y	N	N	Y	Y	Y	Y	N	Y	N	Y
	W/Th	13-Jul-95	Y	0344	0755	Y	13	Y	Y	Y	Y	Y	?	Y	Y/N	N	N	N	N	N	Y	Y	N	N	Y	Y	Y	Y	N	Y	N	Y
195	Th/F	14-Jul-95	N																													
196	F/Sa	15-Jul-95	Y	0515	0815	Y	38	Y	Y	Y	Y	Y	N	N	N	N	N	N	Y	N	N	Y	N	N	Y	Y	Y	Y	N	Y	Y	N
	Sa/Su	16-Jul-95	Y	0314	0716	N/Y	0/24	Y	Y	Y	Y	Y	N	Y	Y	N	N	N	N?	N	N	Y	N	N	Y	Y	Y	Y	N	Y	Y	N
	Su/M	17-Jul-95	N																													
	M/T	18-Jul-95	N	0352	0632	N	0	Y	Y	Y	N	Y	N	Y	Y	N	N	N	?	N	N	Y	N	N	Y	Y	Y	Y	N	Y	Y	?
	T/W	19-Jul-95	Y	0322	0706	N	0	Y	Y	Y	N	Y	N	Y	Y	N	N	N	?	N	N	Y	N	N	Y	Y	Y	Y	N	Y	Y	?
201	W/Th	20-Jul-95	Y	0320	0917	Y	46	Y	Y	Y	Y	Y	N	Y	Y	N	N	N	Y?	N	N	Y	N	N	Y	Y	Y	Y	N	Y	Y	?
202	Th/F	21-Jul-95	Y	0322	0700	Y/N	5/0	Y	Y	Y	Y?	Y	N	Y	Y	N	N	N	N	N	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	N
203	F/Sa	22-Jul-95	Y	0304	0700	Y	6	Y	Y	Y	Y?	Y	N	Y	Y	N	N	N	Y	N	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	N
2	Sa/Su	23-Jul-95	Y	0415	0630	Y/Y	03/04	Y	Y	Y	?	Y	N	Y	Y	N	N	Setup	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	N
2	Su/M	24-Jul-95	Y	0309	1035	Y	225	Y	Y	Y	Y	Y	N	Y	Y	N	N	Setup	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y
2	M/T	25-Jul-95	Y	0309	0730	Y/Y	29	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	?
207	T/W	26-Jul-95	Y	0304	0707	Y	53	Y	Y	Y	Y	Y	N	Y	Y	N	Y	Y	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	?
208	W/Th	27-Jul-95	Y	0340	1035	Y	91	Y	Y	Y	Y	Y	N	N	Y	N	Y	Y	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	?
209	Th/F	28-Jul-95	N																													
2	F/Sa	29-Jul-95	N																													
2	Sa/Su	30-Jul-95	N																													
2	Su/M	31-Jul-95	Y	0442	0600	Y	29	Y	Y	Y	Y	Y	N	Y	Y	N	Y	N	?	Setup	N	N	N	N	Y	Y	Y	Y	N	N	Y	N?
213	M/T	01-Aug-95	Y	0310	0510	N	0 haze	Y	Y	Y	Y	Y	N	Y	Y	N	Y	N	?	Y	N	Y	N	N	Y	Y	Y	Y	N	N	Y	Y
214	T/W	02-Aug-95	N																													
215	W/Th	03-Aug-95	Y	0305	0605	Y	62	Y	Y	Y	Y	Y	N	Y	Y	N	Y	N	?	Y	N	N	N	N	Y	Y	Y	Y	N	N	Y?	Y
2	Th/F	04-Aug-95	Y	0307	0835	Y	51	Y	Y	Y	Y	Y	N	Y	Y	N	Y	N	?	Y	N	N	N	N	Y?	Y	Y	Y	N	N	Y?	Y
2	F/Sa	05-Aug-95	N																													
2	Sa/Su	06-Aug-95	Y	0305	0714	Y	50	Y	Y	Y	Y	Y	N	Y	Y	N	Y	N	?	N	N	N	N	N	Y	Y	Y	Y	N	N	?	N

Figure 2-30. SPRITES'95 System Deployment Summary.

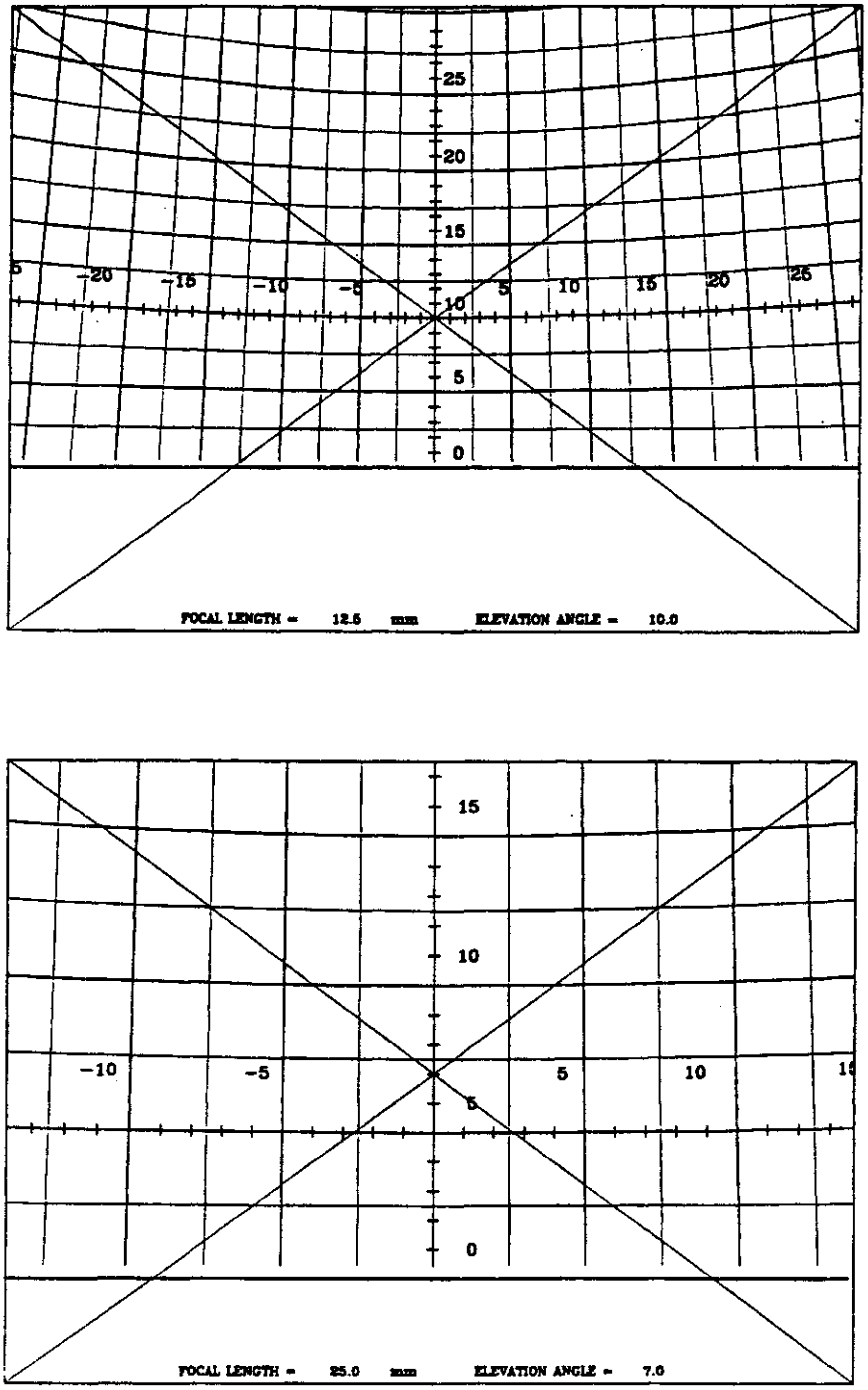


Figure 2-31. Examples of single image photogrammetric grids used for analysis of azimuth and elevations of events image by the LLTV systems.

TABLE OF SPRITE CHARACTERISTICS DATE: 05-6 AUGUST 1994 (JULIAN DAY 218)

#	START TIME	L.H. AZ	R.H.AZ	TOP EL	BOT EL	TP HGT(KM)	BT HGT(KM)	RANGE +CG	AZ +CG	MULT	~~STRNGTH~~
1 *	04:40:43.005	-22.5	-17.0	15.0	12.0	64.830	53.710	243.432	44.442	11	14.9
2	04:45:44.040	-15.0	- 7.5	13.0	8.0	78.616	52.723	325.164	45.361	11	36.1
3 *&	04:50:42.105	-12.0	- 8.0	13.0	6.0	62.277	32.518	-262.267	-80.000	1-71	?
4 *	04:56:06.096	-16.0	- 3.0	15.0	7.5	83.038	46.816	306.973	48.512	21	95.1
5	04:58:31.174	-12.0	- 1.0	15.0	7.5	78.754	44.237	292.185	52.764	1	45.3
6	05:28:13.024	-15.0	- 4.0	15.0	8.0	70.092	41.248	261.984	61.055	1	57.8
7	05:35:38.736	-12.5	- 9.0	13.0	8.0	80.381	53.969	331.835	61.410	21	62.3
8	05:42:59.644	-16.0	- 7.5	14.0	9.0	63.877	43.910	253.413	65.270	21	44.4
9	05:47:50.702	-16.0	- 6.0	13.0	9.0	76.173	56.185	315.887	53.747	1	64.2
10	06:00:25.321	-14.0	+ 1.0	15.0	8.0	81.070	48.117	300.194	63.887	1	32.5
11	06:05:56.788	-15.0	- 3.0	15.0	7.5	79.862	44.903	296.021	58.497	1	86.5
12	06:10:26.425	+ 1.5	+ 2.0	11.0	8.0	64.394	48.721	307.494	75.240	11	48.6
13	06:10:26.592	- 9.0	+ 1.5	14.0	5.0	78.629	33.973	307.494	75.240	11	48.6
14	06:14:33.105	- 6.0	- 2.0	13.0	8.0	74.027	49.493	307.705	58.713	2	77.2
15	06:14:33.572	-10.5	-10.0	13.0	10.0	74.027	59.530	307.705	58.713	2	77.2
16	06:18:04.083	- 3.0	+ 2.0	12.5	8.0	72.032	49.760	309.156	74.959	21	33.9
17	06:18:04.750	- 8.0	- 7.0	13.5	11.0	75.003	63.270	302.625	61.175	2	51.5
18	06:24:36.875	- 4.5	+ 9.0	13.0	6.5	72.690	40.992	302.590	75.169	11	42.5
19	06:35:02.468	- 2.0	+ 7.0	12.5	6.0	77.882	42.925	332.009	70.507	11	109.8
20	06:45:20.085	- 8.0	- 2.0	12.5	4.0	76.153	30.830	325.285	74.952	21	106.1
21	06:57:38.390	- 4.0	+ 6.0	13.0	3.0	79.861	25.714	329.872	76.281	11	152.4
22	07:00:07.639	+ 5.0	+15.0	12.5	7.5	79.491	52.375	338.247	88.739	1	89.4
23	07:00:25.724	-11.0	- 6.0	9.0	7.5	78.437	68.072	422.481	71.537	11	68.3
24	07:03:49.762	- 8.0	- 4.0	12.5	9.0	71.596	54.492	307.440	72.064	11	55.3
25	07:07:44.096	- 8.0	0.0	12.5	7.0	70.993	43.940	305.068	72.402	11	42.9
26	07:09:15.220	+ 7.0	+17.0	13.0	9.0	81.234	60.064	335.053	88.898	1	129.1
27	07:09:57.896	- 3.0	+ 5.0	12.0	9.5	72.791	60.009	321.895	78.813	11	40.3
28	07:11:42.568	+ 7.0	+18.0	12.5	9.0	79.543	60.757	338.451	89.373	21	150.3
29	07:21:38.830	+ 1.0	+ 9.5	12.5	7.0	79.229	49.388	337.233	84.270	21	140.8
30	07:25:24.823	- 3.5	+ 8.0	12.0	4.0	78.809	33.339	345.941	80.048	11	153.4
31	07:30:21.152	+ 3.0	+13.0	11.0	5.0	75.217	40.322	353.642	88.470	11	72.1
32	07:34:29.701	+ 3.0	+15.0	11.0	8.0	76.560	59.164	359.280	88.884	41	52.4
33	07:42:10.028	+ 2.5	+13.0	11.5	3.5	81.360	32.856	367.294	86.705	11	128.0
34	07:44:47.852	+ 9.0	+15.0	11.0	4.0	77.405	35.439	362.818	90.772	11	57.7
35	07:48:42.520	+ 5.0	+10.0	13.0	4.0	92.977	37.469	378.816	87.142	2	137.2
36	07:57:24.308	- 2.0	+ 5.0	11.0	3.0	80.076	30.432	373.956	85.688	2	195.9

* - no strike recorded within 0.5 seconds of sprite
& - no positive strike recorded in association with sprite

Figure 2-32. Example of the calculation of the top and base of sprites as seen during the 6 August 1994 case, using the parent +CG location from the NLDN as the range determinant.