CHAPTER I.
THE INVESTIGATION OF TRANSIENT ELECTROMAGNETIC EVENTS (TREMEs) ASSOCIATED WITH MESOSCALE CONVECTIVE SYSTEMS (MCSs) AND THEIR RELATIONSHIP TO TREATY MONITORING PROGRAMS
OVERVIEW

I.1. Introduction**:** The mission of the U.S. Department of Energy's Treaty Monitoring Program is enhanced by an improved understanding of certain classes of atmospheric phenomena that interfere with the detection and identification of nuclear detonations (NUDETS). The purpose of this research project was to advance fundamental knowledge of such atmospheric phenomena and to more fully characterize their electrodynamic emissions in order to detect their presence, determine their effects, and mitigate their impact on sensor performance and data analysis and discrimination systems. This report gives the details of our research findings.

I.2. Background**:** Both lightening and nuclear airbursts are well-established sources of optical and radio frequency (RF) emission observed by satellites and ground stations. Attempts to detect nuclear airbursts using optical and/or RF techniques frequently encounter lightening and related phenomena as "background clutter." While a number of data processing techniques for automatically extracting more accurate information from a sensor's raw signal have been developed over the last decade, these do not, as yet, unambiguously identify the source as nuclear or non-nuclear. Other related atmospheric phenomena which may trigger a sensor system include: meteors entering the atmosphere at high velocity (bolides), laser tests (lazaps), solar glints, and solar compensations. Recently, a new class of atmospheric phenomena which are manifestations of unique electromagnetic activity exhibiting optical and RF signatures, have been identified in the middle atmosphere above thunderstorms. These phenomena, called "sprites," "elves," and "jets", collectively referred to as Transient Electromagnetic Events (TREMEs), have the potential for introducing uncharacterized backgrounds and clutter that can also interfere with NUDET detection and identification.

Events recorded by the Compton Gamma-Ray Observatory confirm the occurrence of highly energetic events on the order of 1 MeV in the middle atmosphere above thunderstorms. Assessments of the effects of these very high energy phenomena are complicated, however, by the uncertainty of their direct association with the various physical processes occurring in storm systems**.** Such physical processes include the formation of large Mesoscale Convective Systems (MCSs) which often give rise to a high percentage of positive lightning strikes exhibiting evidence of continuing current, spatial charge re-distribution resulting in extensive "spider lightning" (dendritic lightning structure in the stratiform region), and which often contain significant hail formation. Certain types of lightning exhibit high-amplitude optical and RF waveforms. The presence of cloud cover can attenuate these effects. Despite the complexity, data on TREME phenomena and the various theories purporting to explain the data, suggest highly energetic processes that can yield electromagnetic signatures of interest to processing and interpreting satellite data. They may also form a basis for developing and validating models for nuclear weapons effects.

The occurrence of physical processes associated with TREMEs has been detected in geographic regions of interest for the purposes of treaty monitoring. While current data is severely geographically biased due to the preponderance of observations in the high plains of the U.S., there is sufficient data to suggest that TREMEs occur commonly in many, diverse geographic locales, including those of interest from the standpoint of politico-military missions.

I.3. Objectives of this effort: The purpose of this research project was to advance fundamental knowledge of atmospheric phenomena associated with thunderstorms that can interfere with NUDET detection and identification and to more fully characterize the electrodynamic emissions associated with these phenomena. The primary objectives of the research were to:

- Analyze existing satellite, ground-truth, and other data sources or interest.
- Collaborate with other researchers in the community to measure electromagnetic emissions in the upper atmosphere and collect additional data of specific interest.
- Derive models to aid in data analysis which will lead to higher fidelity processing algorithms for system effects mitigation.

To meet these requirements, Mission Research Corporation, and its collaborators, FMA Research and Massachusetts Institute of Technology collected and analyzed data on selected atmospheric phenomena and used the results to develop model-based analysis that aid in segregating the sources of the various electromagnetic atmospheric events. Starting with the substantial body of existing data, we performed detailed analyses on the observable characteristics of TREMEs themselves, their parent lightning discharges, and the types of storms capable of producing TREMEs in order to discriminate among their signals and other signal sources.

Data on events were analyzed for specific distinguishing characteristics in both the optical and RF regions. The relative intensities of the optical and RF signatures of TREMEs were determined. Statistics on the spatial clustering of TREMEs and their temporal patterns were developed to determine the most likely time and location of a subsequent event following the detection of an initial event. The relationship between TREMEs and Cloud-to-Ground (CG) discharges was investigated and more fully characterized. Meteorological conditions were investigated to determine criteria for lightning and TREMEs phenomena. Storm size criteria were evaluated to determine whether this characteristic represents a robust metric that allows discrimination of storms which do and do not generate TREMEs. The visibility of Cloud-to-ground events were examined at various depths to characterize the relationship between Cloud-to-Ground luminosity and optical path length through convective clouds.

Extremely low frequency (ELF) characteristics of the Q-burst events associated with TREMEs were related to the brightness of the TREMEs to determine and verify the functional dependence of optical density on total charge transfer by the electromagnetic event and to provide a quantitative link between the space-based observations and the electromagnetic source properties. Maps of events were constructed to indicate regions of preferred activity. Finally, satellite-based observations were correlated with the ground-based optical and RF signatures to aid in the discrimination and classification of optical sources.

We examined and included, where relevant, the optical and RF data sets obtained in measurements sponsored by DOE, the Air Force Research Laboratory (then AF Phillips Laboratory), Office of Naval Research and the National Science Foundation during the SPRITES

’95, ‘96 and ‘97 data-gathering campaigns. Optical and image data generated under the sponsorship of NASA in 1996 for shuttle launch and recovery safety were also included in the analysis.

Concurrent with this review of existing data, we participated in planned measurement campaigns to leverage other programs and to collect additional data of specific interest. These campaigns included the coordinated, multi-Agency SPRITES ‘98 and SPRITES ’99 campaigns. We leveraged NASA’s airborne observations of TREMEs as well as Optical Transient Detector (OTD) and Tropical Rainfall Measurement Mission / Lightning Imaging System (TRMM/LIS) satellite measurements. We also leveraged DOE efforts to make coordinated measurements with the FORTE satellite, the M46 satellite and other DOD assets as available. Data from the Mesoscale Electrification and Polarized Radar study (MEaPRs) being conducted by the National Severe Storms Laboratory and the University of Oklahoma were included. We also leveraged ongoing efforts by the Navy addressing research on very low frequencies (VLF) and by NASA and the National Science Foundation addressing launch safety and general atmospheric research.

We coordinated ground optical and extremely low frequency measurements of TREMEs with high plains stratospheric balloon flights conducted by the University of Houston under NASA sponsorship. The ad-hoc, extremely low frequency network (Hungary, Israel, Germany) led by the Massachusetts Institute of Technology permited initial investigations of global scale transient detection and location. A limited number of Q-bursts data sets were linked to storm systems in various parts of the world. We also cooperated with several groups operating space-borne sensors, including Los Alamos National Laboratory, Sandia Laboratories and the NASA Marshall Group. We also continued to cooperate in additional measurements of phenomena associated with TLEs performed by University of Alaska, Stanford University (STAR Lab), and the University of Otago in New Zealand.

The scope of this effort was comprised of two major tasks and their associated subtasks:

4.1 Targeted Analysis of Existing Data

- Define optical and RF characteristic signal patterns of interest
- Correlate recorded data with satellite observations
- Define additional data needed to develop and verify analytical models which will lead to enhanced discrimination algorithms
- Integrate ancillary data as available
- Apply physical models of optical scattering in clouds to determine attenuation effects
- Derive electron density and “temperature” time histories associated with sprites

4.2 Participation in planned measurements campaigns

- Use currently available instruments to fill gaps in the data sets
- Relate observations from NASA sponsored balloon-borne electromagnetic field and aircraft observations
- Exploit multi-station Q-burst network for event location and timing
- Coordinate with current DOE and Air Force Technical Applications Center measurements programs, including the LANL ground-based photometry and imagery and balloon-borne x-ray detectors, M46, FORTE and other satellite data sets

The specific topics addressed in this final report include:

1. Details of the storm formation (dynamics that give specific clues to sprite formation);

2. Character of the parent stroke to determine the particulars of flash duration, the role of continuing current, the correlation of optical energy and occurrence of TREMEs;

3. Determination of the formation and duration of the "spider" lightning relative to the formation of sprites (is it the electrode attached through the parent Cloud-to-Ground event and does it spread in a way that is directly proportional to the current in the parent Cloud-to-Ground event);

4. Characterization of multi-color waveforms to confirm that multi-color signatures can be used to discriminate lightning, sprites and other electrodynamic activity from possible man-made sources;

5. Characterization of extremely low frequency signatures and determination of whether the magnitude of the vertical charge moment is an important characteristic;

6. Confirmation of the nature of Schumann resonance waveforms as a predictor of location, time, and intensity of electrodynamic activity above thunderstorms;

7. Determination of the electron density and temperature as a function of time as they relate to natural relaxation times versus NUDETS relaxation times; and,

8. Correlation of the parent stroke waveform, the spider lightning waveform and the waveform recorded from space (FORTE, M-46, etc.) to assess cloud obscuration and signal delay dynamics.

In addition, as a part of our on-going research, we discovered the importance of three related additional topics, which we have included in the report. These are:

9. Anomalous GPS satellite observations above the types of large thunderstorms observed during this investigation;

10. Calculations confirming that small near-surface NUDETs may give rise to observable TREMEs;

11. Investigation of a common source of infrasound and transient electromagentic events associated with large thunderstorms.

Because of the complexity of the interrelated topics, we have organized the report in topical chapters, each of which we have attempted to present as "stand-alone" for ease of interpretation and reference. This has led to some amount of duplication, which we assert is warranted for ease of reading the report.