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**Final Report**

for

**Middle Atmosphere Electrodynamics During a Thunderstorm**

**Grant No. NAG5-683**

to

**National Aeronautics and Space Administration**

by

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## I. Thunderstorm Program Summary

Rocket-based instrumentation investigations of middle atmospheric electrodynamics during thunderstorms were conducted in coordination with balloon-measurements at Wallops Island, Virginia. Middle atmosphere electrodynamics and energy coupling are of particular importance to associated electrical processes at lower and higher altitudes. Objectives of this research effort included: (1) investigation of thunderstorm effects on middle atmosphere electrical structure, including spatial and temporal dependence; (2) characterization of electric field transients and the associated energy deposited at various altitudes; (3) evaluation of the vertical Maxwell current density over a thunderstorm to study the coupling of energy to higher altitudes; and (4) investigation of the coupling of energy to the ionosphere and the current supplied to the "global circuit."

## II. Launch Program Activities

Two Penn State Thunderstorm payloads (PSTs) carrying electric field boom sensors, Gerdien condensers, and nose-tip probes for ion and electron measurements were designed, constructed, and qualified for launch. The nose-tip probe was designed to measure, during the rocket's ascent, charged particle current and associated small-scale density irregularities, which are used to characterize turbulence in the middle atmosphere. The charged particles essentially serve as tracers of small-scale motions.

Near the rocket's apogee, the payload, carrying the remaining instruments, was to be ejected on a stabilized parachute. The ideal parachute deployment altitude was about 90 km. This permitted the measurement of small-scale plasma density irregularities during the upleg portion of the flight almost to apogee. Deployment of the electric field booms at this altitude enables study of the energy coupling through a critical region of the middle atmosphere. Data from both the electric field booms and the Gerdien condenser was to continue being taken during the downleg portion of the flight to below 30 km so that comparisons with the balloon-borne sensors of R. Holzworth could be made.

The nose-tip probe is discarded with the nosecone at ejection. At this time the electric field booms deploy, and the Gerdien condenser is exposed. The electric field booms measure both the DC components and AC lightning-induced transients of the three-axis electric field. These electric field measurements improve our modeling of the coupling of energy between regions. This coupling of energy between

regions can also be observed by the AC outputs of the total Maxwell current sensor. The Gerdien condenser measures ion electrical properties, including polar conductivity, ion mobility, and number density. The detection and characterization of ion species by their mobility helps to determine the nature of any observed lightning-induced conductivity changes.

Supplementary instrumentation planned for the two PSTs included a down-looking optical flash detector and a high-gain AC magnetic-field channel coupled from the magnetometer.

### III. Tasks Accomplished During Year One

Most of the effort of the first year of this project was devoted to planning the payload configuration for flights 31.086 and 31.087. Because different performance goals were emphasized at different altitude regions, a compromise of performance characteristics for the whole flight was required. Many of these tradeoffs were discussed at the project initiation conference (PIC) that was held at Wallops Island, Virginia, on September 20, 1991. The following is a summary of some of the resulting design decisions.

During the upleg portion of the flight, the only exposed sensor would be a nose-tip electrode which passively connects to the center electrode of the instrument's Gerdien condenser. During this portion of the flight, the electrical configuration of the payload is arranged so that multiple data channels in the 16-channel telemetry system are devoted to each of several different sensitivities of this nose-tip data. The resulting supercommutation of these channels results in a high Nyquist sampling rate so that wide bandwidth, post-flight spectral analysis will be possible. The electrical bias voltage of the nose tip is held constant during the upleg portion of the flight. When the downleg portion of the flight commences with nosecone ejection near apogee, the internal sweep generator of the Gerdien condenser is activated, a condition that can be monitored with the "sweep monitor" housekeeping data channel.

Since electrical discharges within the active thunderstorm may occur during the upleg portion of the flight, we hoped to observe small perturbations in the local Earth's magnetic field caused by each strike. We included a high-gain AC magnetometer data channel that was active during both the upleg and downleg portions of the flight. This AC magnetometer data is derived from the housekeeping magnetometer and provides a high sensitivity along with a high-pass filter to reduce roll-rate modulation.

Near apogee, the nosecone is ejected. As part of the nosecone, the passive nose-tip probe pulls away from the payload at this time and is discarded. At this time four electric field booms that were constrained by the nosecone deploy. These rigid fiberglass booms are spring loaded at their point of attachment to the payload and snap into position at deployment. Two of the booms sweep forward (downward) while the remaining two sweep backwards towards the parachute (upward). Boom deployment activates one or more microswitches that in turn configure the sensor data channels and telemetry configuration for a downleg mode which is maintained the remainder of the flight. Closure of at least one of these microswitches also activates the sweep circuitry and configures the telemetry system for the downleg mode. During this portion of the flight, three separate instruments operate.

The three-dimensional electric fields that surround the payload are measured by the four electric field booms. Conditioning electronics on board form differential pairs of observations so that three orthogonal measurements of the electric field are made. The voltage measured by the exposed electrode at the end of each boom and the three differential combinations of these voltages are telemetered to ground during this portion of the flight.

The PCM telemetry rate was increased to 400 kbit/sec from the previously used 100 kbit/sec rate. This change increased the effective sample rate of many of the data channels so that the high-speed transients associated with thunderstorm activity could be observed. In addition, two high-speed (30 kHz bandwidth) FM VCO channels were combined with the PCM BiPhaseL digital data to form a composite modulation signal. An S-band, 2-watt, telemetry transmitter was used rather than the one-half watt unit that had been used most recently.

At the January 30th, 1992, Design Review Meeting several additional payload variations were discussed. The design length of the booms used for the electrical measurement was lengthened to reduce the perturbing effect of the payload central body. Most of the payload electronics, including the transmitter, telemetry encoder, data scalars, and magnetometer were moved to an hermetic canister to make possible post-flight water recovery and reuse of much of the electronics. Two additional housekeeping accelerometer data channels were added at the request of the Wallops engineers.

After the Design Review Meeting, fabrication of the payloads began at Penn State. This construction included the mechanical structure, the electronic circuit boards and sensors for the payloads. Vibration

and mechanical testing of the complete payloads was performed at Wallops Flight Facility. A new Penn State-developed, microprocessor-based telemetry system was separately tested to qualification levels.

#### IV. Tasks Accomplished During Year Two

Environment testing and integration of the two Penn State Nike-Orion payloads was completed on July 15, 1992. The mission readiness review meeting was held on July 16, and the launch window opened on the following Monday. Co-Investigator Robert Holzworth of University of Washington had his four balloon electronics packages and five balloons available at that time.

The weather patterns during the summer of 1992 were unusual in that they were located in an east-west direction. On many evenings this weather pattern caused too much cloudiness in the balloon impact areas to permit balloon launches, although three balloon launches did take place, on July 23, July 31, and August 11. The balloons must be launched about 1 to 1-1/2 hours before the first rocket launch to attain sufficient altitude for the intercomparison. On July 23 and July 31, the thunderstorm activity did not last, dying out completely as the frontal activity crossed the Chesapeake Bay. (Local convective activity also dies out rapidly after sunset.) On August 11, the storm activity did continue into our rocket target area, but unfortunately, the surveillance aircraft used to ascertain safe rocket launch conditions (absence of ships in the impact area) developed a directional navigation problem in its radar while in flight. The airplane was forced to land, fix the problem, and restart. By this time the rain was so intense that the airplane's radar could not penetrate to the sea surface to verify safe launch conditions. After a short operation in this mode, the aircraft could no longer stay on station due to the severity of the storm, so we were unable to launch the rockets that evening.

By August 14 Dr. Holzworth and the balloon support people from Palestine, Texas, had supported our program four weeks, although they had only planned to be present three weeks. Depletion of their travel funds and previous commitments forced their withdrawal from the program for the summer.

We continued to try to launch the Penn State payloads through the third week of September. When good launch weather conditions were predicted by the Wallops' morning weather forecast, the Penn State team then travelled from University Park to Wallops during the day for an evening launch, typically reaching Wallops Island at 4 p.m. On three occasions (Aug. 28, Sept. 10, and Sept. 22), we counted through the

evening when thunderstorms associated with a frontal passage were predicted. In each case the thunderstorm activity located west of the Chesapeake Bay died out after sunset before reaching the downrange area of the rocket range. Based upon the seasonal change in weather patterns, it seemed unlikely that the proper launch conditions would be obtained that year. In consultation with Dave Evans and Larry Early, we therefore decided to stand down for the season.

#### V. Tasks Accomplished for Years Three and Four

For the third year of this work, R. Holzworth built four additional balloon packages, and we re-qualified our two prime payloads. We also refurbished a previously recovered payload for use as a backup/fair-weather flight. Our launch window opened June 28th, 1993. The launch operations were similar to those used in the summer of 1992. Depending on the weather forecast, countdown procedures commenced in the early evening. If weather conditions remained encouraging, one of the balloon packages of R. Holzworth would be launched. The balloon launches could also be delayed through the evening until promising thunderstorm activity was observed. Based on encouraging weather predictions, Penn State personnel travelled to Wallops nearly every week throughout the summer in anticipation of a possible launch. The University of Washington and NSBF personnel remained at Wallops; however the weather patterns were once again very unusual. The position of the jet stream that brought the severe flooding to the Midwest brought drought to the Eastern Shore region. Through most of the summer very few of the storms that we tracked survived off-shore; none reached our target area. On August 17th we launched a Holzworth balloon, but again the storm died as it moved across the peninsula towards the ocean target area. After supporting the field program for nine weeks, Bob Holzworth and his balloon support team were forced to withdraw from the program on August 27. We continued to keep the Penn State rockets staged for a possible reduced-scope program through September and mid-October. Based upon a weather briefing held at Wallops each morning, a decision was made about a possible countdown for that evening. On October 8th we made our last journey from Penn State to Wallops in anticipation of possible appropriate conditions but again did not have the desired thunderstorms develop. Based on general weather forecast expectations for the coming months and in consultation with Wallops Island personnel, we closed the launch window for that year.

Both the University of Washington and Penn State then received some small supplementary funding for field support activities for a third summer of launch support, and we had three remaining balloon packages

from the University of Washington and three rocket packages available.

The payloads were re-qualified and a launch window again opened during the third week of May, 1994. Weather conditions were appropriate for countdowns during the first and third weeks of June. On June 21, Flight 31.087 was launched at 2220 EDT. Payload separation did not occur, so the nose cone did not deploy, and no electric field or Gerdien condenser measurements were obtained. A postflight failure analysis of the flight accelerations and roll rates indicate that the deployment gas generator did not operate at apogee as it should. Because the payload was not recovered from its deep water impact, absolute determination of the cause of the failure was not possible; however, the Anomaly/Failure Report Review Committee felt the most probable cause was hidden damage to the wiring from the deployment timer to the gas generator.

At this point, the previously refurbished spare payload was staged for launch, so that the program could continue with the intent of having two spacecraft in the air at the same time to provide verification of the three-dimensional mapping of lightning-produced transients. On the evening of July 15, a moderately active thunderstorm reached the appropriate down-range region, and 31.086 was launched. At  $t+0.8$  seconds after launch, the modulation (both PCM and VCO) of the telemetry transmitter was lost. Because ground tracking of the unmodulated signal was continuous, the failure could be attributed to a payload rather than a ground-station problem. The telemetry system in the refurbished payload had a different design (an older design that had a lower data rate). Therefore it was thought that the failure in 31.086 was not due to a "pathological" design problem present in both payloads, and such a failure would not likely be present in the refurbished payload (30.039). Because the storm activity had continued, 30.039 was launched at 2023 EDT. Ten seconds after launch the science data channels shifted to zero volts (band edge) and remained pinned for the remainder of the flight. The PCM encoder and magnetometer data continued to operate normally.

Post-flight failure analysis conducted by Wallops personnel with help from Penn State found that during the time of the launches, very high DC electric fields were located over the Wallops Island launch pad area. Through study of the electrical diagrams for the payloads, it was found that if the electric field sensors suffered overvoltage breakdown, they drew excessive current from the power supplies, which in turn caused a failure in the DC-DC converter of the payload. Because the two payloads had a different power distribution structure, the loss of the DC-DC converter produced a different type of loss in the

telemetry signal for each payload. While some protection for overvoltage breakdown of the sensors had been included in the payload design, it was apparently not sufficient for unusually large fields that the payloads encountered as they penetrated the cloud cover above the launch site at the time of the launch. Eyewitness accounts reported seeing horizontal lightning just below each rocket body as the rockets disappeared into the clouds.

## VI. Theoretical Modeling Activities

This project also involved study and modeling of the coupling of electrical energy from active thunderstorms to the global circuit. This work is an extension of the modeling efforts associated with previous thunderstorm campaigns. Earlier modeling efforts used a general purpose finite-element software package that required very long computer run time to obtain useful results. Penn State's Electrical and Computer Engineering department has several experts in the Finite Difference Time Domain (FDTD) method. Most of the modeling utilized the FDTD method, since a custom program optimized for the particular geometry and parametric equations could be developed. The FDTD method normally does not consider charge; however, Lee Marshall, the Master's Degree student who worked on the project, found an extension to the FDTD method that does this. He presented a paper based on this new technique, "Electrostatic Field Solutions Using FDTD," at the 1993 IEEE AP-S International Symposium and URSI Radio Science meeting. His M.S. thesis, "Rocket Payload Development for the Investigation Thunderstorm Region Electrodynamics," described the design and construction of the new payload design.

A second student, Zhaofeng Ma, completed his requirements for the Ph.D. degree under the sponsorship of this work. His thesis, "Finite Difference Time Domain Simulation of the Atmosphere's and Ionosphere's Electromagnetic Responses to the Lightning Discharge," used a three-dimensional model to calculate the transient electric field and Maxwell current that flows from the thunderstorm to the ionosphere during the lightning discharge process. The model contains an isotropic conductivity profile below 70 km and an anisotropic conductivity profile from 70 km to 150 km (different latitudes, day, and night were considered), a time-varying thunderstorm (source function), and a perfectly conducting ground surface. Both vertical and horizontal quasi-static transient electric fields in the ionosphere were calculated. The results show that the relaxation time of the electric field due to the lightning discharge, which is longer than  $\epsilon/\sigma$ , will decrease with an increase of the altitude of observation and will have little change with the horizontal distance from the lightning discharge. The Maxwell current from the thundercloud spreads out



to the ionosphere with a period of several milliseconds following the lightning discharge. This current flows along the directions both parallel and perpendicular to the geomagnetic field lines and mainly propagates horizontally above 70 km. Agreement between the simulation results and measurement data obtained during previous sounding rocket in situ measurements was found.

Two manuscripts based on this thesis (The Atmosphere's and Ionosphere's Electrodynamic Responses to the Lightning Discharge: 1. Transient Electric Field, The Atmosphere's and Ionosphere's Electrodynamic Responses to the Lightning Discharge: 2. Transient Maxwell Current) have been prepared for submission to Journal of Geophysical Research.

Papers presented:

Electrostatic Field Solutions Using FDTD, Kunz, K. S., and L. H. Marshall, 1993 IEEE AP-S International Symposium and URSI Radio Science meeting, Ann Arbor Michigan, June 29, 1993.

Finite Difference Time Domain Simulation of ELF Wavelets Initiated by Lightning, Ma, Zhaofeng, L. C. Hale, C. L. Croskey, Spring Annual Meeting, American Geophysical Union, 1994, Abstract in *EOS*, 75, p. 247, April 19, 1994.

Finite Difference Time Domain Simulation of the Atmosphere's Electromagnetic Response to the Lightning Discharge, Ma, Zhaofeng, C. L. Croskey, L. C. Hale, Fall Annual Meeting, American Geophysical Union, 1994, Abstract in *EOS*, 75, p. 116, December 12, 1994.

Thesis completed:

Rocket payload development for the investigation thunderstorm region electrodynamics, Lee H. Marshall, M.S. Thesis, Department of Electrical Engineering, The Pennsylvania State University, August, 1994, 75 pp.

Finite difference time domain simulation of the atmosphere's and ionosphere's electromagnetic responses to the lightning discharge, Zhaofeng Ma, Ph.D. Thesis, Department of Electrical Engineering, The Pennsylvania State University, May 1995, 156 pp.