ABSTRACT: Recent research has helped identify, define, and describe the occurrence of transient electrical bursts such as jets and sprites (~10-20 ms duration) in the stratosphere and mesosphere during tropospheric electrical storms. However, it is critical to make in situ measurements within the active electrical region for the primary purpose of understanding the currents responsible for the luminous events, to develop a proper understanding of their cause(s), and of their impact on the atmospheric electromagnetic environment. The transfer of significant quantities of energy between the lower and upper atmosphere during tropospheric electrical storms has long been suspected but never verified until the identification of these type phenomena. It has become important to develop measuring systems which can be used to determine the mechanisms responsible for generating these events, to make a better appraisal of their role and importance in the electrical structure of the atmosphere. The use of unmanned aerial vehicles (UAV) such as ALTUS provides a unique and valuable approach for obtaining the desired information. An important objective of The ALTUS Cumulus Electrification Study (ACES) was to monitor the electromagnetic state of the atmosphere during electrically active (thunderstorm) periods. The program involved several flights of a payload designed to continuously measure the electromagnetic structure near and above thunderstorms for extended periods. It was conducted at the Naval Air Station in Key West, FL during August, 2002. The payload contained instrumentation to measure the time varying and steady state three dimensional vectors for electric (slow antenna and field mills) and magnetic fields (search coils and magnetometer), as well as a Gerdien probe to measure electrical conductivity. The data acquisition system aboard the payload permitted acquisition of short-term bursts with a few microsecond resolution. This work will focus on initial surveys of the AC portions of the package, including preliminary calculations of the upward directed Poynting flux.

INTRODUCTION: In the summer of 2002, an atmospheric electricity package was integrated into the ALTUS uninhabited aerial vehicle (UAV) for a series of flights over southern Florida thunderstorms. There were three primary science objectives to this Altus Cumulus Electrification Study (ACES): 1) To examine the lightning-storm relationship from storm birth to death, 2) determine the storm’s electromagnetic budget including both DC and AC contributions to the global atmospheric electric circuit, and 3) further validate space-based lightning sensors such as TRMM/LIS.

PLATFORM: General Atomic’s ALTUS UAV (Figure 1) is the commercial derivative of the more-recognized Predator drone. With a 24 ft length, 55 ft wing span, 300 lb. science payload capacity, 8 hour endurance capability and 55 kft ceiling, it is an ideal platform for thunderstorm research.

Specifically, to achieve the science objectives, the platform had to remain in the near-vicinity of a potential storm cloud for long periods of time. Fast jet aircraft, like the ER-2, make repeated encounters from distant to near-vicinity regions. Their speed and large turn radius limits the time in close to the storm. In contrast, the ALTUS loiter speed of ~ 70 knots allows the platform to remain continually in the near-vicinity for constant monitoring during storm maturation. On occasion during the ACES mission the platform passed to within a few thousand feet of the thundercloud tops.
INSRUMENTATION: The ALTUS faring was modified to incorporate 6 DC field mills, optical pulse sensors, a slow antenna, a Gerdien conductivity probe, a DC magnetometer, and a Poynting vector system located on a forward-mounted boom (Figure 1). A flight data system (FPDS) obtained and saved measurements from this sensor suite in both slow continuous mode and in fast “triggered” format. The fast-sampling trigger mode captured measurements in pre-defined 16 channels at 200 kS/s in a 1/3 second window, when activated by a specific sensor (signal above a pre-defined threshold). Lightning-generated optical and electrical pulses represented near-perfect trigger sources and over 4300 such fast-sampling snapshots were captured during the mission.

The Poynting Vector System (PVS), the instrument of primary focus in this paper, consists of orthogonal E and B sensors sensitive between 10 Hz and 100 kHz. The electric field sensors are short monopoles with local pre-amps and the magnetic field sensors are search coils with local preamps. In order to reduce noise (from both the forward payload bay and aft engine) the sets of sensors were placed on a 1-m boom extending from the ALTUS nose (Figure 2).

The primary design issue was not low end sensitivity but instead PVS saturation avoidance. In order to avoid large DC field regions and inadvertent lightning strikes to the aircraft, the Project’s original closest approach distance to any cell was limited to 5 km. It was thus anticipated that the AC electric fields could exceed >240 V/m and AC magnetic signals exceed >900 nT at this distance. To accommodate such large fields, the effective length of the monopole (antenna and pre-amp) was designed to be 0.05-m and the transfer function of the search coil to be 2.5 mV/nT at 10 kHz. In fact, during flights, we found opportunities to approach much closer to a storm and still remain in safe DC field conditions.

SORTIES: There were 18 ACES flights, including 7 test flights (4 of which occurred in the Mojave Desert) and 11 formal science flights on site from Key West. Of those 11 flights, 5 flights resulted in very direct and prolonged encounters with thunderstorms. The discussion below will highlight one particular day, and feature the data products currently being produced.

AUGUST 10 2002: A nice example of the usefulness of the platform occurred on this day. This particular sortie was ~4 hours long, with a substantial period of reconnaissance over the south Florida coast to encounter a cumulus in the process of maturation into a thunderstorm. While trailing one particular candidate cloud, a second small cell just southward became electrically active (near 1820 UT). The UAV then began a series of “figure-8” passes over this second storm for the next 45 minutes.

Figure 3 shows the electrical activity for the day, as measured by the PVS’s AC Ex antenna. Shown are the peak VLF magnitudes (from lightning EMPs) in each 5 minute interval, as derived from the triggered data. The triggered data system has its own turn-on criteria, which explains the lack of lower intensity lightning events from weaker sources (like the waveguide, etc.). The sustained lightning VLF peak near 1840 UT is associated with the repeated passes of the UAV over the storm (radar image, Figure 3, lower left panel). Clearly the storm was electrically-active with lightning signals reaching nearly 20 V/m over the storm top. Near 1920 UT, the UAV left this now-disintegrating storm cell to return to Key West. Thunderstorms remained in the near-vicinity during the return, accounting for the ~ 2V/m signal levels between 19:30-20:00 UT. Upon approach to Key West, the AC electric fields again increased (after 20:00 UT) to nearly 20 V/m, this associated with lightning from a mature storm cell located just to the northwest of the Island (radar image, Figure 3, lower right panel).

Trigger data has been processed into “quick-look” plots, and over the course of the month-long mission > 4300 survey plots exist. The PVS data has also been processed to determine the VLF Poynting Vector ($\mathbf{S} = \mathbf{E} \times \mathbf{B}/\mu_0$) for each trigger snapshot. Figure 4 is a example of the measurements at 18:37:13 UT, when the ALTUS was over the storm. We present a portion of our Level-1 data visualization plot, with all three components of both E and B. Note that the search coils (10 Hz –100 kHz) detect a signal near 20 nT, and the E-field system (10 Hz – 100 kHz) detects signals in excess of 10 V/m, including a portion of the near field [Volland, 1984].
The last three panels show the 7-14 kHz Poynting vector magnitude, and the Poynting vector angle of arrival in elevation (90° is zenith) and azimuth (0° is forward). The upward-directed VLF power is approximately 0.05 W/m², and the emission appears to originate below the aircraft (-50°) from the port side. Figure 5 shows the angle of arrival from the UAV perspective.

COMPARISON OF VLF AND DC POWER:
It has been recognized that displacement currents can exceed conduction currents (by factors of 4-5) for short periods of time during and immediately following a lightning discharge [Blakeslee et al., 1989]. While displacement currents are momentarily large, a fundamental question is whether these currents provide large amounts of upward-directed power to the mesosphere and D/E region ionosphere. To obtain radiated power from displacement currents, the Poynting vector is required including the quantification of wave magnetic field strength. For the event near 18:37 UT (Figure 4), we compare the radiated power from the displacement currents (VLF portion) to the upward conductive power from the thundercloud.

The relatively-weak lightning EMP at 18:37:13 UT had a peak flux of 0.05 W/m². Assuming that upward radiation is through a horizontal surface (vertical normal) of 10 km radius, the outward radiated power in the VLF is ~ 10MW. During the overflight of this cell, there were at least 5 such discharges of comparable or larger power levels, including one at 19:09:26 UT registering a maximum Poynting flux of 0.2 W/m² or power of ~40MW through the surface.

For the 1-min period immediately preceding this VLF event, the DC E-field as measured by the field mill (15 km altitude) was small, but immediately after the discharge jumped to ~ 1 kV/m, remaining at this level for about 2 minutes (until the next discharge near 18:39). The conductive (electrostatic) power flux through the same R = 10 km horizontal surface over the storm top in this post-discharge period is

\[ P/A = \int \sigma(z) E_z^2(z) \, dz \quad (1) \]

where the integral limits are from the charge center (6 km) to the UAV altitude (15 km). Since the field is electrostatic, the continuity equation indicates that the vertical conduction current is \( \sigma(z) E_z(z) = \text{constant} \) at all heights.
For a model atmospheric conductivity profiles [Greifinger and Greifinger, 1976] of

\[ \sigma(z) = 6 \times 10^{-14} \exp(z/L) \text{ S/m} \quad (2) \]

with \( L = 6 \text{ km} \), the conduction current is derivable using the measured field mill values at 15 km, \( E_z(z=15 \text{ km}) \sim 1 \text{ kV/m} \), and is \( J_z = \sigma(z=15 \text{ km}) E_z(z=15 \text{ km}) = 730 \text{ pA/m}^2 \). Since \( \sigma(z) \) \( E_z(z) \) = constant at all heights, the electrostatic E-field at lower altitudes is then

\[ E_z(z) = 730 \text{ pA/m}^2 \sigma(z)^{-1} = 12166 \exp(-z/L) \text{ V/m} \quad (3). \]

Placing Eq. (2) and (3) into (1), and performing the integral, we find that the upward conductive power flux over the storm is \( \sim 5 \text{ mW/m}^2 \), much lower than the preceding impulsive VLF power. Assuming a horizontal area above the storm of \( \sim 3 \times 10^8 \text{ m}^2 \), the total vertical-directed electrostatic current flowing to the ionosphere from this cell is \( \sim 0.22 \text{ A} \). As described in Volland [1984], this current is contributing to the global atmospheric electric circuit, and is relatively close to the nominal cell electrostatic current of 0.5 A discussed therein. Table 1 lists the VLF discharge/post-discharge comparison.

<table>
<thead>
<tr>
<th></th>
<th>E (V/m)</th>
<th>J (nA/m²)</th>
<th>I (A) (5)</th>
<th>Duration</th>
<th>Power Flux (mW/m²)</th>
<th>Upward Power (MW)</th>
</tr>
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<tbody>
<tr>
<td><strong>Discharge</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>18:37:13 UT</td>
<td>-2.5</td>
<td>1381</td>
<td>414</td>
<td>~ 100 us</td>
<td>50 mW/m²</td>
<td>15 MW</td>
</tr>
<tr>
<td><strong>Post Discharge</strong></td>
<td>-1000</td>
<td>0.73</td>
<td>0.22</td>
<td>~ 2 min</td>
<td>5 mW/m²</td>
<td>1.5 MW</td>
</tr>
</tbody>
</table>

(1) Measured quasi-horizontal wave component, (2) Measured quasi-vertical DC component, (3) VLF displacement current, \( \varepsilon_0 \omega E \), (4) DC conduction current, \( \sigma E \), (5) For areal area of \( 3 \times 10^8 \text{ m}^2 \), (6) See discussion above.

It is interesting to note that while the discharge VLF displacement currents greatly exceed the conduction currents by a factor of \( 10^3 \), the radiated power only exceeds conductive power by a factor of 10. We conclude that the effective resistance of the radiation is substantially smaller than the conductive resistance between 6-15 km. For \( P = I^2 R \), the effective VLF radiation resistance is about \( 10^9 \Omega \), compared to the conductive resistance of \( \sim 10^7 \Omega \). The effective radiation resistance is of the same order as the radiation resistance of free space (377 \( \Omega \)).

CONCLUSIONS: Even though displacement currents may greatly exceed conduction currents during and after a discharge, it does not automatically imply that radiative power exceeds conduction power. Poynting flux and conductive powers should be compared to determine the energy input to the mesosphere. In the future, we will extend the AC calculations into the ELF and ULF, providing a DC-to-VLF power determination. Poynting flux analysis at lower frequencies will feature the corresponding response of the mesosphere/ionosphere to thunderstorm discharges.


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