This paper reports results from field deployments of the Tempest Unmanned Aircraft System, the first of its kind of unmanned aircraft system designed to perform in situ sampling of supercell thunderstorms, including those that produce tornadoes. A description of the critical system components, consisting of the unmanned aircraft, ground support vehicles, communications network, and custom software, is given. The unique concept of operations and regulatory issues for this type of highly nomadic and dynamic system are summarized, including airspace regulatory decisions from the Federal Aviation Administration to accommodate unmanned aircraft system operations for the study of supercell thunderstorms. A review of the system performance and concept of operations effectiveness during flights conducted for the spring 2010 campaign of the VORTEX2 project is provided. These flights resulted in the first-ever sampling of the rear flank gust front and airmass associated with the rear flank downdraft of a supercell thunderstorm by an unmanned aircraft system. A summary of the lessons learned, future work, and next steps is provided. © 2011 Wiley Periodicals, Inc.

1. INTRODUCTION

State-of-the-art tornado warning systems give an average of 13 min of lead time, with a probability of detection of 75% (Erickson & Brooks, 2006). This relatively short lead time directly results from an inability to accurately predict tornado formation and evolution. The primary objective of the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) was to increase understanding of tornadogenesis—the process of tornado formation (National Oceanic and Atmospheric Association, 2010). During the spring of 2009 and 2010, VORTEX2 fielded more than 100 scientists and 40 science and support vehicles (collectively referred to as the “armada”) in a fully nomadic campaign to study the formation and evolution of tornadoes over the central Great Plains of the United States. The goals of the experiment were “…to further the understanding of tornadogenesis, sample the near-ground wind field in tornadoes, determine relationships between supercell thunderstorms and their environments, and to enhance storm-scale numerical weather prediction” (VORTEX2 Steering Committee, 2007).

A consensus of research in the past 25 years makes it clear that a small downdraft of a few kilometers width, known as the rear flank downdraft (RFD), plays a causative role in tornado formation (Markowski, 2002). Improved conceptual models for tornadogenesis can be constructed with better understanding of the thermodynamics of the storm, particularly in and around the RFD (VORTEX2 Steering Committee 2007). Access to the RFD for remote and in situ measurements continues to be a significant challenge. Although weather radar can return detailed precipitation and wind-field data, it cannot return directly measured thermodynamic data. Balloons cannot be constrained to a sampling region after release and provide only serial ascents. Whereas flows around the RFD have been sampled by manned aircraft (Marwitz, 1971), manned assets for storm sensing are hard to obtain, are relatively expensive, and risk human life.

Unmanned aircraft systems (UAS) have been identified as a promising solution for obtaining in situ measurements in the supercell RFD (Burgess, 2008). UAS have already been utilized for a variety of meteorological applications (Blakeslee, Mach, Desch, Goldberg, Farrell, et al., 2002; Hipskind, Tyrell, Holland, & Curry, 2002; Lin &
Lee, 2008), particularly when there is an unacceptable risk to manned aircraft. Small UAS are capable of achieving the airspeeds necessary to penetrate the RFD while carrying relatively lightweight sensor packages to sample thermodynamic properties. Furthermore, recent simulations show that the RFD of a typical supercell thunderstorm can be accessed by a properly guided aircraft (Elston & Frew, 2010). Despite these promising advantages, key developments must be made to enable the study of supercell thunderstorms by small UAS. The fast evolution of the storms presents a set of challenges fundamentally different from those faced in previous work performed on typhoons and hurricanes. Furthermore, the regulatory environment for the operation of small UAS has changed significantly in the past few years, particularly when considering operations over land in the U.S. National Airspace System (NAS).

Over the past 3 years, a first-of-its-kind UAS and concept of operations (CONOPS) have been developed for in situ atmospheric sampling in supercell thunderstorms. The creation of this Tempest UAS was driven by a variety of factors including storm dynamics and Federal Aviation Administration (FAA) regulations. Other factors included science objectives as articulated by the VORTEX2 steering committee, a compressed time frame from project start to field deployment, and the need for a cost-effective solution given the significant risk of aircraft loss. Lessons learned from preliminary operations during the Collaborative Colorado–Nebraska Unmanned Aircraft System Experiment (CoCoNUE) (Elston, Argrow, Houston, & Lahowetz, 2009; Houston, Argrow, Elston, Lahowetz, & Kennedy, 2011) informed the design of the Tempest UAS for the VORTEX2 field campaign. Given the lack of atmospheric, and hence aerodynamic, data in the thunderstorm environment, the Tempest UAS was developed primarily from existing airframe and autopilot technologies with proven reliability. The resulting UAS combines a highly modified off-the-shelf airframe; a customized networked UAS communication, command, and control architecture (Elston, Frew, Lawrence, Gray, & Argrow, 2009); and multiple ground support vehicles.

The purpose of this paper is to present the Tempest UAS and report on results from the field during the VORTEX2 campaign. The Tempest UAS performed the first-ever sampling of the rear flank gust front (RFGF) and air mass associated with the RFD of a supercell thunderstorm by UAS. This accomplishment was enabled by the novel integration of multiple vehicles via a networked communication, command, and control architecture and the development of a new CONOPS for highly mobile, rapidly deployable, semiautonomous UAS within the NAS of the United States. The networked architecture provided seamless interoperability and flow of critical scientific and engineering data across multiple heterogeneous platforms (aircraft, stationary ground vehicles, mobile ground vehicles), communication protocols [900-MHz direct point-to-point link, 2.4-GHz IEEE 802.11 (WiFi) ad hoc networking, cellular broadband], and data sources (payload sensor, aircraft autopilot, ground vehicle telemetry, National Weather Service server, etc.) in remote, challenging, radio-frequency environments. In turn, the robust network architecture supported a novel CONOPS that incorporated the coordination of one unmanned aircraft, a stationary ground control station, two mobile ground vehicles, and multiple dispersed operators and end-user scientists.

This paper describes the unique components of the CONOPS, airframe, mesh network, software suite, electrical subsystems, and ground support vehicles developed to conduct targeted sampling of a supercell thunderstorm by a small unmanned aircraft system. Mission results are reported from the 6-week field campaign from 1 May through 15 June 2010, with emphasis on six particular deployments into or in proximity to supercell thunderstorms. Additional discussion is devoted to unsuccessful attempts to intercept thunderstorms, which in the case of this campaign were always due to the combination of storm motion and FAA restrictions, not UAS performance. Lessons learned are also presented based on empirical, qualitative experiences during the field campaign.

2. MAJOR DESIGN DRIVERS

This section describes the major design drivers for the Tempest UAS. The system design and CONOPS are primarily driven by three factors: the dynamics of a supercell thunderstorm, the desired science return, and FAA regulations and policies.

2.1. Supercell Thunderstorms

Supercell thunderstorms are a class of thunderstorms characterized by a deep and persistent storm scale vortex known as a mesocyclone (Markowski, 2002). Supercell thunderstorms are generally tens of kilometers wide. The presentation of supercells in radar reflectivity data is often characterized by a “hook echo” (indicated by the H marker in Figure 1), a pendant of reflectivity (typically characterized by rain) that extends southward (in the northern hemisphere) from the main precipitation region. The hook echo (or simply, hook) is generally recognized to be a manifestation of the mesocyclone’s rotation. The airflow in a supercell is characterized by a dominant updraft (indicated by the U marker in Figure 1) and two downdrafts: the FFD and the RFD.

Supercells are most prevalent in the United States across the Great Plains. Favorable conditions can be identified a few days in advance, with these storms evolving over the course of several hours and traveling with ground speed sometimes exceeding 30 m/s. The specific location of storm formation and the path of the storm as it evolves are extremely difficult to predict. Tornadogenesis within
a supercell thunderstorm has been observed to occur in as little as 13 min from the first manifestation of potential tornadic activity (Erickson & Brooks, 2006). As a result, tracking storms requires highly nomadic sensing with rapid (re)deployment capabilities.

2.2. Scientific Goals

The scientific mission goals for the Tempest UAS during the VORTEX2 experiment were to fly across the RFGF into the RFD, where in situ thermodynamic observations (temperature and moisture) were to be collected. Furthermore, the intent was to fly multiple transects across the RFGF (into and out of the RFD) at different altitudes, thereby collecting a pseudo-two-dimensional (2D) slice across the RFGF and RFD. In light of this, three sampling scenarios were developed, which can be seen in Figure 2. The gray area in each panel is a representation of the precipitation field that would be identified by weather radar. Each path of the unmanned aircraft (UA) is indicated as a colored line, with each color representing a different flight altitude. In each scenario, the UA is launched from the ground control station (GCS), which is stationed a safe distance from the storm. The aircraft is directed to make as many transects of the RFGF as possible, each at a different altitude, and then return to the GCS for landing.

Each scenario was developed for a particular relative positioning of the GCS to the storm. In the first scenario [Figure 2(a)], the Tempest UA flies transects out to 5 km either side of the RFGF at different altitudes for each pass, starting from a launch point ahead of the storm. This is the preferred scenario, as it provides the best opportunity for performing multiple transects before the storm moves out of range. However, in the case that this launch position cannot be achieved, sampling of the RFD can be achieved from the south, with UA travel perpendicular to storm motion [Figure 2(b)], or from the outflow behind the storm [Figure 2(c)].

2.3. Regulatory Issues

The operation of UAS by public institutions in the NAS is regulated by the FAA. Authorization to fly in specific parcels of airspace is obtained through a certificate of authorization (COA). The original technical and safety reviews for the Tempest UAS operations are based on the UAS Interim Operational Approval Guidance 08-01 (Davis, 2008), which covers operational requirements, emergency procedures, airworthiness requirements, a specific area of operations, and ground crew proficiency. Note that this operations policy document was recently superseded by
The FAA requires that UAS operations satisfy the see-and-avoid requirement specified in the Federal Aviation Regulations (FARs) and mandates the use of a stationary primary GCS to maintain command and control of the UA throughout the flight. To achieve this, a qualified observer must maintain visual sight of the UA at all times. The FAA codified this with a requirement that the Tempest UA always be flown less than 1 mile horizontally and 1,000 ft (305 m) above ground level (AGL) from the observer [for several COA areas these limits are reduced to 1/2 mile (0.8 km) horizontally and 400 ft (122 m) AGL; see Figure 3(b)]. The stationary GCS ensures that command, control, and communication is maintained from a fixed location by the pilot in command (PIC) and the UAS operator. The summary of relevant FAA provisions and requirements based on Davis (2008) along with special provisions written in the COAs specifically for the VORTEX2 operations include the following:

- **Weather minimums**
  - Visibility of 3 statute miles (4.8 km).
  - Cloud separation: UA must maintain 500 ft (152 m) below and 2,000 ft (610 m) lateral separation from clouds.
  - Daytime operations only: 1 h before sunrise until 1 h after sunset.
- **Operational requirements**
  - Single UA operation only.
  - No dropping anything from the UA.
  - No loitering in Victor airways. Victor airways must be transited quickly.

Figure 3. Areas defined by the 59 COAs used in the VORTEX2 campaign. (a) A rough boundary for the 2010 VORTEX2 armada operations in red, along with the UAS operations area outlined in green. (b) A zoomed-in view for easier identification of the particular COA areas. The areas with a 400-ft (122 m) AGL ceiling are indicated in red; areas with a 1,000-ft (305 m) ceiling are in green.
3. UNMANNED AIRCRAFT SYSTEM

The Tempest UAS (Figure 4) consists of a total of four vehicles: (i) the UA, (ii) a mobile GCS used to command the UA, (iii) a ground “tracker” vehicle tasked to observe the aircraft, and (iv) a “scout” vehicle outfitted with a mobile mesonet (Straka et al., 1996) sensor suite used to provide situational awareness for the ground station.

3.1. Aircraft

The Tempest UAS (RECUV, 2010) was designed as a first-generation, low-cost UAS for collecting in situ data in supercell thunderstorms. Two key mission requirements were the ability to launch within 10 min of arrival at the launch site and to maximize sampling time while operating in an expected range of severe atmospheric conditions. The UA was required to fit into a trailer or van but be large enough to contain an electric propulsion system powerful enough to overcome the updrafts and downdrafts anticipated in the vicinity of a supercell thunderstorm. These performance and portability requirements were met by the use of removable wings that can be quickly attached to the fuselage and battery-powered, electric-motor propulsion, which, compared to gas engines, best addresses the balance between the instantaneous power available for maneuvers, the total energy requirement for endurance, and the reliability requirement for rapid deployments. Quick, repeatable launches from previously undetermined sites are achieved through bungee-cord “high-start” catapult or hand launching.

The Tempest UA fuselage [Figure 5(a)] is primarily fiberglass with spruce and balsa core construction utilizing a carbon-fiber composite for reinforcement in the wing spar and the lower surface of the wing. The detachable wings have a full span of 3.2 m with a maximum gross takeoff weight of 6.8 kg. A smooth undersurface and a folding propeller enable landing in grassy fields and road surfaces with no landing gear. These features enable quick deployments with rapid turnaround. The UA is flown semiautomatically with a Piccolo SL autopilot (Cloudcap Technologies, 2005), and in situ meteorological data are collected with a Vaisala RS-92 sonde (Hock & Franklin, 1999). The nomadic nature of the mission required aircraft maintenance to be relatively straightforward and possible to be performed utilizing the tools and facilities available in the mobile ground station. Pre- and postflight checks were performed with every flight. The durable and simple nature of the composite airframe required only minor routine maintenance of the control surface hinge gap seals as the hinges loosened with use. Throughout the project, only minor repairs were necessary for scratches in the structure from rugged landings. All components were installed using commercial off-the-shelf (COTS) hardware. Several spares were carried for all components, most of which were...
commercially available, including servos and propulsion system elements. If any anomalies were found during pre- and postflight checks, hardware could be quickly replaced. Additionally, two airframes were carried in ready-to-fly condition, ensuring that any last-minute problems with one airframe would not scrub a deployment on a storm.

Other airframe requirements include the need to operate in high humidity and precipitation and the ability to handle strong aerodynamic forces while retaining aerodynamic efficiency. The Tempest airframe was developed to combine the aerodynamic efficiency of a high-aspect-ratio wing [evident in Figure 5(a)] and the structural efficiency of the materials used in high-performance gliders to meet the airframe requirements for endurance and gust survivability, respectively. To reduce development time and to take advantage of the materials and techniques used in the manufacture of competition model sailplanes, the Tempest airframe is based on a modified COTS sailplane design purchased from Skip Miller Models (2010). The construction techniques used in remote-control dynamic soaring in which aircraft routinely obtain high air speeds and accelerations (RCSpeeds, 2011) provide sturdy and durable aircraft. The Tempest airframe, detailed in Figure 5(b), utilizes an in-runner electric motor with a gearbox manufactured by Neu Motors, a Castle Creations ICE speed control, a Graupner folding propeller, and a 10,000-mAh lithium polymer battery manufactured by MaxAmps providing endurance of approximately 45 min.

3.2 Mobile Ground Control Station

A mobile GCS is used to support the deployment of the UAS by providing the necessary tools for operation and maintenance of the system. The mobile GCS used for the VORTEX2 project [Figure 6(a)] is a customized 15-passenger van. In its nominal state, the GCS provides the space to transport two Tempest airframes, their support systems, and the crew to launch and operate the UAS. This crew consists of a driver, meteorologist, UAS manual pilot (who can control the UA through joystick commands from a conventional radio-control handset), UAS operator, UAS technician, and PIC. For the experiments outlined in this paper, the tasks associated with PIC and UAS manual pilot are performed by the same person.

The van contains several aftermarket systems that facilitate quick deployment and streamline field operations. First, voice communications radios have been installed in a console and combined with an intercom system that allows occupants to speak clearly through headsets and to use a VHF radio to communicate with the tracker, the scout, and the team leader. During transport, the meteorologist uses wide-area network (WAN) access and VHF voice communications to determine the status of the research group and the current storm situation. A second VHF radio is included for communication with VORTEX2 team leaders and the field coordinator. Additionally, a hand-held VHF radio is maintained by the PIC and is tuned to the frequencies of nearby airports. This enables quick communications with local air traffic should the need arise.

UAS command, control, and communication is provided in the GCS by two computer systems and a WAN interface that accommodates two types of cellular connections [Figure 6(b)]. This provides an interface to the Internet, which allows the head meteorologist to make navigation and targeting decisions based on real-time radar data using the Gibson Ridge Level 3 (GR3) (GRLevelX, 2010).
software package. It also allows for visualization of the positions and real-time data of other assets in the VORTEX2 armada using the SASSI tool (Rasmussen, 2010) for severe weather situational awareness. Communication with other UAS team members and the rest of the armada can also be made through the SASSI chat interface to complement the VHF voice communications. The Internet is also used by the UAS operator for dynamic map requests and for the real-time publication of the UA location and meteorological measurements. A small Linux single-board computer (SBC) is also connected to the LAN and provides global positioning system (GPS) and magnetometer readings. Through these measurements, the UAS operator and meteorologist are able to know their position and heading relative to the UA, tracker vehicle, and target storm.

To maintain communications with the UA up to the 10-mile (16 km) operational range, two tracking antennas, a mechanical system with a high-gain, 900-MHz patch antenna and a phased array for directed 802.11 communications, are positioned on the roof of the GCS. The Linux SBC automatically points the antennas using GPS feeds from the GCS and the UA in conjunction with local magnetometer readings. This helps to ensure continuous communications over the range of operations, and although the GCS typically remains stationary during a scenario, this enables the GCS to be moved during the UA flight in the case of an emergency while maintaining communications with the UA.

The UA airframes are stored on wall-mounted racks in the rear of the van to enable the subsystems to be powered during transport to the deployment site. This allows the UAS operator to perform system initialization and operational verification before arrival at the launch site. This preparation while en route to the launch site enables launches quickly after the GCS van is parked.

3.3. Tracker Vehicle

To satisfy the FAA see-and-avoid requirement, the UA is commanded to orbit within 1,000 ft (305 m) vertically and 1/2 mile (0.8 km) horizontally of the observer inside the tracker vehicle, whose location is transmitted continually to the aircraft. Despite limiting the flight speeds and directions of the UA, orbiting the tracker is vital to satisfying the see-and-avoid requirement. The observer performs a constant visual scan for other air traffic. Should any traffic enter the UA airspace, the observer coordinates with the UA operator over VHF voice communications to perform avoidance maneuvers. The tracker carries a dedicated driver, secondary meteorologist, the observer, and an assistant to the observer. The secondary meteorologist provides the head meteorologist (in the GCS) with field observations of the storm and looks for visual cues to indicate the UA’s position relative to the storm. The assistant observer maintains an interface to the UA, providing telemetry to augment the observer’s situational awareness and a secondary command and control link for emergency situations.

The tracker [Figure 7(a)] contains two systems that allow the UA to follow with a high level of autonomy and that free the observers to focus on airspace monitoring and UA observation. The first system is a small Linux SBC, also called a mesh network radio (MNR) (Elston, Frew, et al., 2009), designed to participate on an ad hoc network. The MNR contains a GPS receiver and provides the location of...
Figure 7. (a) Tracker vehicle pictured during the VORTEX2 deployment. Two large VHF antennas were placed on a ground plane toward the front of the vehicle, and the two 802.11 antennas were placed at the very back. (b) Scout vehicle with the mobile mesonet sensor suite installed on the roof.

the tracker, vehicle to subscribers. By allowing the UA flight computer to subscribe to this GPS location, a controller on the UA can track and orbit the tracker. This provides two advantages: the UA remains within the required distance of the tracker, and the sampling of the storm is simplified to directing the driver of the tracker using voice commands over a VHF radio, which indirectly moves the UA. The second system is a laptop computer running the networking software and a limited-functionality graphical user interface (GUI). This interface provides the status of the system and position of the UA at all times, allowing the personnel in the tracker to provide an offset to the UA orbit. This tracker-relative orbit is chosen to allow easy, full-time observation by one of the designated UA observers through a side window or sunroof. A 2009 Ford Edge was specifically chosen for the tracker because its panoramic sunroof enabled the observers within the vehicle to maintain visual contact with the UA and the surrounding airspace.

3.4. Scout Vehicle

To aid the head meteorologist in choosing a route for the tracker, the scout is used shortly before deployment to examine the intended path for the tracker and identify potential hazards (such as downed trees and rough or non-existent roads). During the flight of the UA, the scout is instructed to lead the tracker and UA by approximately 1 mile (1.6 km) to allow the secondary meteorologist in the vehicle to identify key features of the storm, particularly the gust front. These features are communicated to the head meteorologist in the GCS to help with UA path planning. The scout is also responsible for communicating meteorological hazards, particularly hail, occurring ahead of the tracker and the UA.

For meteorological observation, the scout is outfitted with a mobile mesonet (Straka, Rasmussen, & Fredrickson, 1996) sensor suite installed on the roof [Figure 7(b)]. This allows measured values to be combined with qualitative observations and helps to identify significant storm features. These observations, along with any observed hazards, are relayed to the head meteorologist through a VHF radio. During operations, measurements made by the sensor suite are recorded and can be used to augment the airborne data set.

4. COMMAND, CONTROL, AND COMMUNICATIONS

Communications between all vehicles is critical to mission safety and success and required significant innovation for this application. The highly dynamic nature of the CONOPS required a dynamic and extensible communications architecture, the selection of the appropriate hardware and routing protocols, and modifications to be made to the existing GUI to support display of information pertinent to the VORTEX2 flights.

4.1. Communications Architecture

The UAS’s core command, control, and communications (C3) is supported by a modular communications architecture that has been instantiated through the NetUAS software (Elston, Frew, et al., 2009). This software provides mechanisms for meshed, ad hoc wireless networking; service discovery across the network; and the ability to easily add interfaces to new transport media, sensors, or other physical devices.
The CONOPS for sampling supercell storms required the most complex incarnation of the NetUAS architecture to date (Figure 8) and required the addition of several new software interfaces. In the figure, each arrow represents a directed data stream that is provided and managed through the NetUAS service discovery functionality. Figure 8 represents the complete, ideal system configuration during the mission. In practice portions of the data streams would go down, e.g., from loss of connectivity due to separation, and the NetUAS architecture provided seamless transitions between configurations. Functionality was added to accommodate control of two tracking antennas on the mobile GCS using a Linux SBC, use of the 900-MHz autopilot link as a backup to the ad hoc data network, the addition of two GUIs for use by the PIC and head meteorologist, and a WAN interface to a server at the National Severe Storms Lab for providing UA telemetry and meteorological data to all VORTEX2 participants (Rasmussen, 2010).

4.2. Communications Hardware and Routing Protocols

The CONOPS dictate that communications must reliably support flights up to 16 km from the GCS. This is a significant increase from previous operations that rarely exceeded 2 km from the GCS (Elston, Argrow, et al., 2009; Houston et al., 2011). Also of paramount importance to the system is the ability to create ad hoc networks. Without this ability, all nodes in the system would have to retain a static set of routes. Should one participant leave the network, this could result in a loss of data for many of the other participants. Because the CONOPS for storm sensing requires several
vehicle configurations, it is possible that the GCS would need to communicate directly with the tracker or use the UA as a relay.

Given time and fiscal constraints, a COTS solution was chosen for the networking hardware. Unfortunately most long-range radio solutions are typically designed for static network configurations and do not have the capability to perform true meshing, requiring all traffic to move through a coordination node. For this reason, COTS 802.11 cards were used to create the C3 backbone, and a reactive routing protocol was used. For all missions there was line of sight for this link. The aircraft radio was amplified to 1 W and transmitted through a vertical (relative to the Tempest body frame) 1/4-wave dipole antenna.

Following the recommendations presented in Abolhasan, Hagelstein, and Wang (2009), the implementation of the B.A.T.M.A.N. (Better Approach To Mobile Ad hoc Networking) protocol (Open-Mesh, 2010) was chosen over the AODV (Chakeres & Belding-Royer, 2004) that was used in the CoCoNUE project (Elston, Argrow, et al., 2009; Houston et al., 2011) and that presented problems in initial Tempest UAS test flights. In several experiments conducted both in the laboratory and in the field using mobile and stationary nodes, the functionality of B.A.T.M.A.N. was verified for identifying and properly selecting routes.

4.3. Graphical User Interface Enhancements

A GUI was created to manage all nodes and links participating in a networked UAS (Figure 9 shows a screenshot of the GUI taken during 26 May 2010 operations). Given that each node communicates with its neighbors periodically in order to provide a routing table, by building the GUI on top of the network, the system can provide the users with statistics on a per-node basis. A list of the connected nodes, along with their associated services (telemetry, link statistics, etc.) is contained in a panel on the left. Most of the GUI is used to display several layers of georeferenced data.

![Figure 9. Annotated NetUAS GUI screenshot taken during 26 May 2010 operations. The left panel contains a list of connected nodes and their respective services, along with a list of displayable layers. The right panel shows the overlay of WSR-88D image of the supercell, COA boundaries, and locations of other deployed VORTEX2 vehicles.](image)
The lowest layer contains one of several selectable forms of maps: satellite imagery, road network, topographical, and aviation charts. The upper layers contain node icons and contextual information (node name, altitude, current target waypoint), flight plans, and established network links. From this, the operator can quickly deduce the number of nodes connected on the network, their current location, node type (fixed, mobile, UA), and some simple node context information.

The GUI also allows the user to interact with each participant on a per-node basis. The user chooses which data streams to subscribe to from each node and can issue commands and monitor data stream values through pop-up windows that contain node-specific information and interactions. As an example, the window for the Tempest node contains several tabs, one for each capability. These capabilities include streaming autopilot telemetry and changing control loop values; visualizing the data from the pressure, temperature, and humidity sonde; visualizing the wind data (which are also displayed as wind barb “bread crumbs” on the map window); and affording the ability to select a target node to orbit along with the orbit parameters. Limited interactions can also be performed through the main window, such as uploading or changing waypoint patterns shown on the map.

The NetUAS GUI was further enhanced to satisfy the needs of the atmospheric sampling mission. This was done by adding several new layers and functionality. The new layers include real-time WSR-88D weather radar data, National Weather Service warnings, flight region boundaries, VORTEX2 vehicle locations [available through SASSI (Rasmussen, 2010)], and real-time UA wind measurements. The functionality enhancements include support for geocoded searching, quick flight plan generation, and the ability to send waypoint plans to all vehicles (including ground vehicles). Geocoded searches were added to center the map on a search string, enhancing the ability to follow travel instructions from the VORTEX2 field coordinator, which were commonly given as small town names. Quick flight take-off and landing plan generation was added to reduce setup time and to accommodate occasions when the UA must be landed quickly or out of sight of the GCS. The ability to send waypoints to ground vehicles was added to address the issue that giving directions to the tracker using only voice commands over the VHF link is tedious (especially when road names do not exist).

5. VORTEX2 EXPERIMENT

System development and flight testing for the VORTEX2 project required 2 years and 69 flights of the Tempest UAS. During each of the flights, in addition to recording pressure, temperature, humidity, and wind information, logs were kept of all traffic through the NetUAS system, routing and network statistics, the locations of the vehicles, telemetry from the autopilot, and data from the electronic speed controller (ESC). The field component of the VORTEX2 project was composed of the final 21 of the 69 Tempest UA flights and used two different aircraft from 2 May to 10 June. Performing the flights during the experiment required 8,500 miles (13,700 km) of driving and 15 flight days. Significant statistics for the Tempest UAS and VORTEX2 UAS Team are shown in Table I.

<table>
<thead>
<tr>
<th>VORTEX2 project statistics.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tempest UAS</td>
</tr>
<tr>
<td>Flight hours</td>
</tr>
<tr>
<td>VORTEX2 UAS team</td>
</tr>
<tr>
<td>Days with flights</td>
</tr>
<tr>
<td>Days with VORTEX2 armada in COA area</td>
</tr>
<tr>
<td>Flights with armada</td>
</tr>
<tr>
<td>Flights in proximity to supercells</td>
</tr>
<tr>
<td>Aircraft lost</td>
</tr>
</tbody>
</table>

5.1. Deployment Phases

The CONOPS for a typical deployment during the VORTEX2 campaign consisted of a time period up to 36 h before a deployment and 1 h after, as depicted in Figure 10. This timeline has been broken into three phases: (1) forecasting and tracking supercells, (2) storm relative positioning and UAS predeployment, and (3) UAS flight operations, recovery, and turnaround. In Figure 10, each phase is indicated on the timeline using a separate color, with the 2 h from $T - 1$ to $T + 1$ expanded above the full timeline to show more detail.

The first of these phases starts a day prior to a sampling mission and consists of examination of various data sources and numerical weather prediction models to predict the location and probability of supercells and tornadoes the following day. This decision-making process is performed through a collaboration of VORTEX2 principal investigators and sets the location for overnight staging of the entire armada. The following morning, the decisions are reexamined given current observations and the latest model runs. A tentative travel target and travel timeline are constructed. Starting approximately 8 h before deployment, the entire armada begins a coordinated migration to the travel target. During this process, SASSI enables each vehicle to share its location, examine radar products, and coordinate with the rest of the group through chat and map annotations.

About 2 h before deployment, Phase 2 and the tasks specific to the UAS begin. Based on the evolution and motion of possible target supercells and/or the most likely location of new supercell formation, the head meteorologist collaborates with the VORTEX2 field coordinator (FC) to
Figure 10. Timeline for one deployment during the VORTEX2 campaign. The lower timeline provides an expanded view of times from $T-1$ h to $T+1$ h on the upper timeline.

determine whether the armada will be targeting a supercell within the UAS domain. If so, the UAS team continues to coordinate with the armada. Otherwise, the UAS team separates from the armada in an attempt to target supercells predicted to pass through a COA area. The head meteorologist then coordinates with the UAS team leader and PIC to activate up to 4 of the 59 COA areas with the highest probability of a supercell intercept. The COAs are activated by issuing a NOTAM for each area 2 h before a UA launch. If the storm track changes, or a new target is chosen, the NOTAMs can be individually canceled and another one issued for a different area with a new 2-h NOTAM UA launch. By balancing these activated spaces with the storm track and a desire to coordinate sensor coverage with the rest of the armada, the UAS team determines a location for conducting flight operations.

Approximately 1 h before deployment, the UAS operator activates the computer systems inside the GCS and on-board the UA and begins the preflight preparations. This includes setting of mission parameters (e.g., lost communication waypoints) and system status checks to minimize the preparation time once the GCS is parked and the UA is prepared for launch. Between $T-30$ min and $T-10$ min the head meteorologist and the PIC select a deployment location and prepare the flight plan, accounting for the supercell motion, the local road network, and the COA boundaries. The flight plan is communicated to the rest of the team via SASSI and GR3. The team arrives at the deployment location, and the scout begins to drive the route to determine road conditions. Outside the GCS, the driver and the UA technician assemble the UA while the UAS operator establishes a take-off flight pattern and performs final preflight checks.

Phase 3 begins with the launch of the UA. During launch and climb-out, the UA is controlled by the UA manual pilot using a handset. Following verification that all systems are functioning appropriately, the UA is switched to autopilot control and tasked to orbit the tracker. The head meteorologist then uses his GUI with telemetry overlaid on radar products to issue driving commands to the tracker and to position the UA relative to the storm. During the sampling, the UA operator monitors the status of
the UA from the GCS and performs altitude changes as directed by the head meteorologist. The decision to instruct the tracker to return to the GCS is made based on the estimated UA energy consumption and the completeness of the data collected. Once the UA enters visual range of the GCS, it is commanded into a holding pattern from which the UAS manual pilot takes control and lands the aircraft. Following landing, the UA operator issues commands to automatically collect data from all mobile nodes. The UA is then disassembled and loaded into the GCS van, where it is prepped en route to another deployment.

5.2. VORTEX2 Supercell Intercepts

All flights during the VORTEX2 campaign occurred without incident despite being near and beneath supercells and other severe convective storms and through light precipitation. A total of six flights in the proximity of supercells were performed, including one flight (10 June) conducted shortly after the supercell produced two tornadoes. The location for each of these flights has been identified in Figure 11, and the flight path and storm relative positioning for the supercell intercept are shown in Figure 12. Basic information for each flight is provided in Table II, which includes date, aircraft flown, time of flight, COA area for flight, and whether the UAS team was performing the mission in coordination with the rest of the VORTEX2 armada. This coordination is significant as it provides the opportunity for UAS data to be combined with measurements of the storm taken from the rest of the armada. The UAS team was not always able to coordinate with the armada given the limited area for UAS operations compared to the entire range of the VORTEX2 project as was shown in Figure 3(a). The following section presents a brief summary for each of the six supercell intercepts.

Figure 11. Deployments for the VORTEX2 project from 1 May to 15 June 2010. Operations with supercell intercepts have been identified in yellow; all other operations are shown in orange.
Figure 12. Composite radar, flight path, and COA boundary for supercell intercepts during the VORTEX2 campaign.

Table II. Summary of significant VORTEX2 deployments.

<table>
<thead>
<tr>
<th>Date</th>
<th>Aircraft</th>
<th>Coordinated with armada</th>
<th>Flight time (mins:s)</th>
<th>COA area</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 May 2010</td>
<td>Tempest 1.5</td>
<td>Yes</td>
<td>44:15</td>
<td>2009-CSA-37</td>
</tr>
<tr>
<td>26 May 2010</td>
<td>Tempest 2</td>
<td>Yes</td>
<td>45:01</td>
<td>2009-WSA-23</td>
</tr>
<tr>
<td>6 June 2010</td>
<td>Tempest 1.5</td>
<td>No</td>
<td>19:35</td>
<td>2009-WSA-13</td>
</tr>
<tr>
<td>7 June 2010</td>
<td>Tempest 1.5</td>
<td>No</td>
<td>27:30</td>
<td>2009-CSA-9</td>
</tr>
<tr>
<td>9 June 2010</td>
<td>Tempest 1.5</td>
<td>Yes</td>
<td>33:30</td>
<td>2009-CSA-6</td>
</tr>
<tr>
<td>10 June 2010</td>
<td>Tempest 2</td>
<td>Yes</td>
<td>34:00</td>
<td>2009-WSA-33</td>
</tr>
</tbody>
</table>

5.2.1. 6 May 2010

The 6 May flight was the first performed in coordination with the VORTEX2 armada. Both the UA position and meteorology data were reported over SASSI in near real time to the rest of the VORTEX2 participants during the flight. The take-off went well, and the mission proceeded as expected. The UA was able to follow the tracker for the entire flight, but the network routing table caused the laptop in the tracker to be used as an intermediary for communications between the UA and MNR. It might have been possible to use a wired interface for the laptop to force a route, but that would have eliminated the redundancy of the ad hoc setup. The tracking antenna on the GCS worked well, but 900-MHz communications were slightly weaker than normal. It was reported that the UA flew through the lobes of a couple of radar scans, so it remains possible that interference caused some of the communications issues. Despite landing within the required daylight hours, the lighting during landing was flat, making it difficult for the human pilot.

5.2.2. 26 May 2010

The storm on 26 May developed many miles from a COA area, so the team had to wait a long time before deploying on the slow-moving storm. Before the storm made it to the
COA boundary, its trajectory shifted north and the mesocyclone and RFGF never made it into the COA. The UA was launched within the inflow but could get no closer than 15 km from the mesocyclone while remaining within the COA. The 900-MHz tracking antenna had an error of about 40 deg at launch, but the error diminished once the plane left the immediate area. Strong head winds (approaching 26 m/s) on the way out provided for a quick trip, but a long return. The tracker reported spotty WiFi communications with the UA for the entire flight, but operations were mostly at 500 m above ground level (AGL) on the way out (the ground height in the COA varied significantly, and all flights were typically conducted 300 m from the highest point in each COA area) and could have been part of the problem. For the return flight segment, the UA altitude was dropped to 250 m AGL, and about half-way back the indicated air speed (IAS) was increased from 22 to 25 m/s. Using the ESC data, it was estimated that the propulsion battery pack was expended to 2,000 mAh beyond the manufacturer’s rating of 10,000 mAh.

5.2.3. 6 June 2010

The 6 June flight included the first sampling of the RFGF by a UAS. The initial plan was to deploy on the early western storms in northeastern Colorado and work eastward toward the armada, which was approaching from the east. A cluster of storms formed northwest of Grover, Colorado, near the Colorado–Wyoming border around 2100Z. The storms rapidly intensified as they traveled southeast generally along CR-390 in Weld County. The team set up the GCS just west of CR-390 and launched shortly after COA WSA-13 went active at 2200Z.

The UA flew out at approximately 280 m AGL and back at 150 m AGL. The UA GPS feed for overlaying its position on the meteorologist’s screen did not work, and neither did reporting of the UA position through SASSI. This was possibly because of a restart of the Tempest inside the van or the long run time of the GUI before deployment. There was a 22% packet loss over the WiFi link from the UA to the tracker; however, the length of the timeouts never exceeded 12 s, which was a significant improvement over the previous few flights. The UA crossed the RFGF on its northwestern leg. The team attempted a redeployment farther southeast on the same storm, but during the time waiting for new COAs to become active, the storm underwent a merger with a left-moving supercell to its south and the merged complex rapidly dissipated.

5.2.4. 7 June 2010

On the morning of 7 June, the armada decided to target storms near Scottsbluff, Nebraska, which remained north of available COA areas. Around 0020Z the UAS team decided to leave the armada and drop south to target storms that were beginning to develop near Cheyenne, Wyoming. These storms rapidly intensified, and around 01Z the southern end of a short line segment assumed supercell structure. At this time, the UAS team was positioned to its east near Dix, Nebraska. The hope was that the storm would travel far enough north into COA CSA-9 so that the team could execute an east–west transect. Unfortunately, the mesocyclone remained on the southern end of the COA without any road options for crossing the RFGF. The team decided to reposition behind the storm and execute a flight from the west, but by the time the team repositioned and set up the GCS north of Kimball, the storm had begun to weaken significantly. At the time the UA was launched, the storm had lost all supercell characteristics.

5.2.5. 9 June 2010

The 9 June flight included the first sampling of a supercell RFD airmass by a UAS. The initial target storms for 9 June developed near Scottsbluff, Nebraska, and moved into low convective available potential energy (CAPE) to the east, north of the northernmost COAs. The supercell that developed just west of Goshen County, Wyoming, around 0Z looked as if it might move into CSA-6, the northwest-most COA. The GCS was set up near the intersection of CR-X and Stegall Road while the scout vehicle attempted to find good east–west roads near the northern end of the COA. Unfortunately, the only viable road option was the north–south Stegall Road (CR-13). The mesocyclone never appeared to make it into the COA, but the team was able to cross the RFGF on the first northerly leg of the flight. The UA appears to have crossed the gust front again on its southerly leg [at 1,650 m above mean sea level (MSL)] and again on its northerly return leg (at 1,500 m MSL). During the flight the 900-MHz tracking antenna had trouble pointing to the South and saw −101 or worse decibels before it was corrected (up to 45-deg counterclockwise).

5.2.6. 10 June 2010

The initial deployment for 10 June was planned for the first target storm east of Denver, Colorado. The GCS was set up 18 miles (29 km) south of Fort Morgan, Colorado, in COA 2009-WSA-23. The aircraft was ready on the launcher before storm development south of the target storm started dropping heavy precipitation south of the hook. This would have made the traditional RFD deployment very difficult. The right-flank development also weakened the target storm. The GCS was (rapidly) undeployed, and the team redeployed on a new target storm near Deer Trail, Colorado. As the UAS team was arriving at the designated spot for UA launch, the target

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1The UA may not have encountered descending air but definitely sampled air that had previously descended in the RFD.
Figure 13. (a) Photo of 10 June 2010 supercell, looking approximately due west, of the first of two tornadoes produced just before UAS operations commenced. (b) Flight path and corresponding radar data. Note the white COA boundary just north of the end of the flight path. This boundary prevented sampling further beneath the storm.

A violent storm produced the tornado, shown in Figure 13(a), that persisted approximately 6 min. After setup for launch and while the UAS team was waiting for the storm to approach the COA area, another tornado developed that also lasted about 6 min and then dissipated before the desired portion of the storm reached the COA area and the UA could be launched. As it approached the COA area, the target storm motion promised to take the Deer Trail supercell across the northwestern corner of COA 2009-WSA-33. Fortunately, the activation of COA 2009-WSA-33 was requested prior to the first (truncated) deployment, so that the storm crossed through the COA when it was active. County road CR-7 offered a good E–W option on the northern end of the COA, but the paved state highway SH-71 was chosen for its improved surface. The Tempest UA was launched approximately 12 km southeast of the storm and flew north to the anticipated track of the southern tip of the hook. The UA loitered at this position for about 10 min until the RFGF passed and then continued north into the RFD airmass [Figure 13(b)]. The UA appeared to cross a second RFGF near the northernmost point of the track. The intercept of a strong updraft upon crossing the second RFGF was also confirmed through visual cues sighted by the secondary meteorologist in the tracker. During the flight, all systems functioned nominally. The UA spent considerable time in updrafts, resulting in a significant reduction in the consumption of propulsion battery power.

6. RESULTS AND LESSONS LEARNED

6.1. Concept of Operations

The CONOPS developed for the mission were refined over the course of the VORTEX2 experiment but remained relatively unchanged. Although sampling was generally done at only one altitude due to limited sampling time, each of the sampling scenarios proved to be useful and accommodated most supercell intercepts. Changing expectations by the FAA required the largest changes to the CONOPS and will continue to be the primary driver of changes to CONOPS in the foreseeable future.

6.1.1. Scientific Goals

Each of the sampling scenarios given in Figure 2 was used during the course of the experiment (Figure 12). As mentioned previously, only three deployments, the 6 June, 9 June, and 10 June 2010 flights, were made close enough to supercells to observe primary features. For each of these intercepts, data were successfully returned that indicated crossing of the RFGF and penetration into the RFD airmass. Figure 14 shows information derived from the gathered data that indicates storm relative positioning for the 10 June 2010 flight. Although this information was derived from postprocessing, experiences in the field indicated that it could prove invaluable for UA path planning and should be made available for use in real time during future missions.

Meteorological data gathered by the Tempest UAS is archived in the VORTEX2 field data catalogue. This catalogue is a repository for the data uploaded from all instruments deployed during the 2009–2010 field campaign and is shared among all investigators. Meteorologists on the Tempest UAS team are currently working to couple the Tempest UAS data with data from several mobile Doppler radars that were scanning along the UA track during
several flights. The 10 June 2010 flight is of particular interest because of the multiple updrafts and downdrafts encountered after the RFD gust-front crossing. Coupling of the pressure, temperature, humidity, and wind-estimate data with the Doppler radar data might lead to some new insight into the atmospheric dynamics behind the RFD gust front. To ensure the integrity of the UAS meteorological data, tests were conducted with a calibrated ground-based system, collocated with the UA that was mounted on a mobile mesonet, approximately 3 m above the ground, to validate the calibration of the MIST sondes while mounted on the Tempest UA.

### 6.2. Unmanned Aircraft

#### 6.2.1. UA Performance

The primary objective for the VORTEX2 UAS effort was demonstration of the feasibility of in situ sampling of the RFD using a small UAS. In particular, the project focused on validating the ability of the UAS to fly in the wind environment of the storm. Of secondary importance was characterization of the magnitude of the winds and turbulence that the UA encountered during transects of the gust front and cross validation of measurements from the onboard pressure, temperature, and humidity sensors.

To characterize the environment that is encountered during the RFD sampling flights, the horizontal wind estimates from the autopilot were recorded during each flight. Figure 15(a) shows a superposition of the time series of measured horizontal winds, utilizing the Piccolo autopilot’s proprietary wind finding algorithm. Whereas it is difficult to characterize the accuracy of this algorithm in the field due to the lack of truth data, hardware-in-the-loop

![Figure 14.](image)

Figure 14. Equivalent potential temperature and altitude (MSL) vs. UTC for (a) 9 June 2010 operations and (b) 10 June 2010 operations. Each labeled region represents travel in a particular part of the storm: A, warm, convective air; B, RFD boundary; C, RFD.
Simulation capability was recently added to the system that should allow for further analysis (Elston, Argrow, Frew, & Houston, 2010).

Average winds were found to be 11.2 m/s over all supercell intercepts with a maximum wind of 26.2 m/s. The UA was still able to make significant headway on all missions with cruise speeds ranging from 18 m/s to just under 30 m/s. Each flight typically covered 30 km to about 45 km round-trip. It should be noted that total range was significantly limited by the fact that the UA always returned to the launch point for recovery. Future work on autolanding will allow the UA to land away from the launch point, thus significantly increasing maximum range and sampling duration. During all flights, the UA was observed from the tracker to maintain a solid wings-level attitude and the GCS showed that it tracked its waypoints adequately. Nominal accelerations and angular rates during flights in the vicinity of the supercells deviated from the mean twice as much as they did during autopilot flights on calm days. This deviation level is approximately the same as that observed in a comparison of manual flights on a calm day to autopilot flights on those same calm days. The UA withstood all operational extremes and showed few signs of wear at the conclusion of the season’s flight operations, indicating that the conditions for the supercell intercepts are well within the limits of the airframe control and structural capabilities.

Figure 15(b) shows a one-dimensional power spectral density based on the calculated horizontal wind velocities from the Piccolo autopilot algorithm and the measured aircraft dynamic pressure. Relating turbulent wave mode, mean velocity, and frequency in the standard way (Roadman, 2009), the characteristic frequency corresponding to a flight speed of 22 m/s and wingspan of 3.2 m is on the order of 1 Hz, placing the turbulent scales of the Tempest UA at the right edge of the figure. Unfortunately, the data were sampled at 2 Hz, not sufficient to realistically capture phenomena on the scale of the Tempest UA. Nonetheless, the power spectrum suggests that the largest energy-containing scales for the atmospheric turbulence encountered are on the order of 1,000 m or more. It is worth noting that the upturn in energy at the right-hand side of Figure 15(b) is a manifestation of the noise in the measurement system and is not a physical result. This anomaly was investigated and verified on a previous project that looked at the energy spectra of various velocity measurement systems under various inflow conditions (Roadman, 2009). A better estimate for the atmospheric energy spectrum could be obtained with higher frequency pressure transducers and a multihole probe in order to measure the full three dimensionality of the flowfield near the UA. Figure 15(b) indicates that the Tempest UA has a flight speed and size that places it well within the inertial subrange of the atmospheric turbulence. Current theory suggests that turbulence scales one order of magnitude larger and smaller than the aircraft wingspan most significantly affect its local flight qualities (Fuller, 1997; Roadman, 2009). Larger scales tend to convect the UA around without affecting its local attitude. Observations of the UA during deployments support this theory. From the ground observer’s point of view, the Tempest UA’s main challenge to maintaining control and making headway derived from the background convecting winds, not the turbulence scales on the order of its wingspan.

6.2.2. Estimating Mission Duration

Another outstanding issue raised by the VORTEX2 deployments was estimation of the expected range and
endurance of the aircraft while sampling. Electric propulsion was used to allow for quick turnaround and fast deployments. However, electric propulsion also limits the range and endurance of the UA compared to expected performance using a gas-powered engine. For preliminary analysis, the sample set of six flights is too small to state conclusions about the impact of headwinds, tailwinds, and deployment locations. Instead, the flights were examined together to parameterize flights conducted to sample the RFD of supercell thunderstorms. Figure 16 represents a first pass at determining parametric equations for bounding range and endurance of the current system configuration.

Gauging when to command the tracker to return with the aircraft for landing required the creation of a rough battery usage estimate to be displayed in the NetUAS GUI. This estimate was determined by integrating in real time a fitted curve of the battery current draw vs. the throttle setting, shown in Figure 16(a). This curve fit was established and updated over the course of the 2010 VORTEX2 deployment using all available data for the aircraft, mainly during cruising conditions. It should be noted that this fit was a rough estimate because it did not account for many secondary effects including airspeed, cruising altitude, or state of battery discharge. Thus, significant variability (approaching 10%–15%) in the estimated battery usage was often observed. More physically accurate correlations that accounted for more of the relevant aircraft physics were investigated but not implemented in time for the 2010 deployment season. Results from the battery-use estimator are shown in Figure 16(b). This figure shows the actual battery usage for each flight as a solid line, with the error of the estimate indicated by the shaded region. Note that on some flights, such as the 45-min flight, the estimator does quite well, whereas with the 35-min flight, battery usage was significantly underestimated. Again this indicates the need for modeling secondary effects and direct access to information available through an interface to the ESC, such as measured current draw. An approximate linear fit of time to battery usage is given in Figure 16(b) for use in rough mission design.

6.3. Command, Control, and Communications

6.3.1. NetUAS Architecture

The NetUAS architecture worked well in the field and allowed for quick changes to be made to the system for needed functionality. As an example, one deployment required the UA operator station in the GCS to be field swapped with a laptop used as a backup in the tracker when the operator station’s graphics card failed. During another deployment, it allowed for the tracker’s entire system to be reconfigured when issues were encountered with the 802.11 networking cards. With no software changes, the MNR was removed from the tracker and its GPS was plugged into the laptop used by the assistant observer. By indicating that the UA was to follow the laptop instead of the MNR through the NetUAS GUI, the system functionality remained the same for both instances. Halfway through the deployments, a third computer was added to the system to give the PIC the ability to visualize components of the data, allowing the UA operator to focus on separate tasks.

The NetUAS also accommodated software changes to increase system functionality in the field. These changes were easily implemented due to the dynamic nature of the system afforded by the service discovery protocol and were quickly coded given the modular nature of the software. During the deployment, a module was added to

Figure 16. (a) Flight data from the electronic speed controller, with postprocessed battery draw vs. throttle approximation. (b) Battery usage vs. flight time for six supercell intercepts with battery usage estimate bounded by the error indicated by the translucent regions.
the operator interface to include battery usage estimates for determining a safe time to terminate operations that afforded enough power to return to the GCS and land the aircraft. A module was also added to the operator station in the GCS that subscribed to UA telemetry and converted it to a National Marine Electronics Association (NMEA) 183 string. This string was transmitted over a USB interface. In this manner, a computer connected to the other end of the universal serial bus (USB) saw it as a GPS device. This allowed for easy integration of UA telemetry into the GR3 software, which already had support for reading GPS devices.

6.3.2. Tracking Antennas

Successful flights across the entire COA-defined areas required constant communications with the aircraft through the 802.11 WiFi and the 900-MHz autopilot link for a distance up to 10 miles (16 km). As mentioned before, this was preformed with a 900-MHz patch antenna mounted on a COTS mechanical tracking antenna and an 802.11 phased-array antenna. Several issues were encountered when attempting to use these systems. First, placement of the magnetometer for measuring the heading angle of the GCS was critical. As it turned out, the entire vehicle produced a magnetic field that was not easily accounted for in calibration (mainly due to heavy-gauge steel roof rack components) and required careful placement of the magnetometer to avoid effects from fields emanating from the van. After resolving these issues, the pointing accuracy of the phased array controlled by the MNR was sufficient, and a constant link of up to 8 miles (13 km) could be maintained, with sporadic packets being received up to 12 miles (19 km).

Pointing the COTS mechanical tracking antenna proved to be significantly more difficult. Rather than allowing for commands to be sent for base-relative positioning, the unit contained its own magnetometer and accepted only magnetic direction pointing commands. This proved to be quite difficult with the changing field of the van and the inability to move the magnetometer inside the antenna a sufficient distance away from noise sources. A changing bias was always present in the antenna pointing and was dealt with by adding an offset box to the GUI to allow the UAS operator to adjust the pointing of the antenna during operations.

6.3.3. IEEE 802.11 (WiFi)

The ad hoc link from the UA to the tracker was problematic in both packet loss and, more importantly, occasional lengthy communication timeouts. This link was critical because it enabled the UA to orbit the tracker. It also enabled the operator in the tracker to offset the UA orbit along with maintaining situational awareness of the position of the UA if visual contact was lost. During these timeouts the GCS could still command the UA; however, if the UA was not tethered to the tracker it was much more difficult for the observer in the tracker to maintain situational awareness of the UA (Elston, Argrow, et al., 2009; Houston et al., 2011). These communication timeouts caused delays in the mission that had the potential to affect the ability of the team to get the UA to the sampling area and collect data. Once in the sampling area, these timeouts affected the real-time pressure, temperature, and humidity data stream that augmented navigation direction decision making by the meteorologists in the tracker and GCS.

Owing to the time constraints of the project, a more thorough investigation of this problematic link was not possible, but several flight experiments were conducted with different hardware configurations to arrive at a solution that worked well enough for VORTEX2 operations. Figure 17 contains four histograms showing the number and length of communication timeouts along with the percent packet loss for four different communication experiment flights. It should be noted that several smaller changes were attempted, but these four illustrate the main configurations. Figure 17(a) involved a MNR placed in the tracker vehicle along with a 1-W amplifier (Fidelity-Comtech, 2009) on the 802.11 WiFi card to increase the range and an external antenna on the roof of the tracker. This setup was found to have too many long timeouts and too many dropped packets to allow operations. Figure 17(b) shows the results of removing the MNR from the tracker vehicle and attaching the external antenna directly to the tracker laptop. This reduced the amount of long timeouts; however, the number of dropped packets, 22.2%, still made operations difficult. Figure 17(c) is the same as Figure 17(b) except that now the 1-W amplifier was reinserted between the laptop and antenna. Figure 17(d) improved on Figure 17(c) by adding a second external antenna with a 1-W amplifier and enabling diversity on the laptop. This final setup had good packet loss, only 10.1%, and the number of longer timeouts was manageable. These four flight experiments did not have identical trajectories. However, all four flights involved the UA orbiting the tracker at a distance up to 500 m at an altitude of approximately 300 m AGL. Thus each flight provided roughly the same relative geometry, so the relative changes in communication performance seen in Figure 17 can be attributed to the changes in the hardware with a high degree of confidence.

The setup shown in Figure 17(d) was used in the field deployments for VORTEX2 and was found to work well enough to successfully complete the scientific experiments. Figure 18 is an aggregate histogram of the communication timeouts for four VORTEX2 deployments that occurred on 6, 7, 9, and 10 June 2010. Over these 4 days there was 17.3% packet loss and only one communication timeout longer than 20 s. It should also be noted that 86.1% of the timeouts were 5 s or less. These experiments showed that 802.11 worked well for the distances involved in the VORTEX2 project.
Figure 17. Four histograms showing the progression of different communication system architectures and the improvement in both length of timeouts and packet loss percentage: (a) MNR in tracker with 1-W amplifier, (b) no MNR, (c) 1-W amplifier connected to laptop, and (d) two 1-W amplifiers connected to laptop for diversity. These are normalized by flight time.

Figure 18. Aggregate histogram of communication timeouts using finalized system over 4 VORTEX2 deployments from 6, 7, 9, and 10 June 2010.

7. CONCLUSION

Through a short time span of slightly over 2 years, the Tempest UAS was developed to provide in situ measurements of tornadic supercells. This system and its CONOPS were incrementally verified through a series of flight tests culminating with the spring 2010 deployment with the VORTEX2 project. Major accomplishments of the Tempest UAS include the first-ever use of a UAS to collect data in close proximity to a supercell on 6 May 2010 and the first-ever sampling of a supercell RFD airmass by a UAS on 9 June 2010. Data were gathered about the storm environment and UAS (such as observed winds, control surface deflections, and control-loop tracking) that will be used as the basis for the design of future unmanned aircraft systems. Progress was made with the FAA to refine the notification and air traffic control process for highly dynamic UAS science missions. Finally, the CONOPS for sampling the RFD of supercell thunderstorms using small UASs was improved and verified through six different supercell intercepts. More detailed analysis of aircraft performance and assimilation

of the science data with other sensor platforms is ongoing.

Experience from work with the system in the field environment provided several lessons learned. First, it was difficult to fly the UA on a waypoint pattern and have the remote observer keep eyes on the aircraft. Either the UA would approach the limit of the visual range, given that its ground-relative speed was generally faster than that of the tracker, or it would be positioned in an area difficult for the observer to see while seated inside the tracker. To alleviate this issue, the UA was commanded to orbit the tracker, and the observer was given the ability to displace the center of the orbit up to 1 km relative to the tracker. Second, accurately estimating the consumption of the propulsion system battery was difficult and should be augmented with direct measurements to increase allowable sampling time while still allowing for the safe return of the UA. Third, the maximum allowable setup time after arriving on station varied significantly but was always greater than the original 5-min estimate. Fourth, the effect of the winds encountered on the UA was less than expected, specifically the updrafts and downdrafts. With minimal human operator input, the Tempest UAS was able to mitigate the wind effects successfully and perform sampling as desired. Finally, although being one of the few COTS solutions to provide true ad hoc networking, the limitations of 802.11 hardware significantly affect network performance when used in highly dynamic networks and over ranges approaching 10 miles (16 km).

The Tempest UAS represents the first step toward semiautonomous targeted observation of severe local storms. Short-term work will focus on the design of a “next-generation” airframe, improving the aircraft’s scientific instrumentation and increasing system endurance. Redesign of the aircraft is driven by the need to balance a lightweight but aerodynamic structure for increased endurance with an airframe suited for typical atmospheric conditions around the RFD. Part of the airframe design will also provide better locations for installing pressure, temperature, and humidity sensors and adding space for additional instrumentation used to collect three-dimensional wind measurements. Endurance will be addressed in the short term by adding propulsion batteries and by modifying the CONOPS to allow the aircraft to land autonomously, eliminating the need to return to the ground station at the end of a flight.

Next steps to continue the effort to provide effective, in situ measurements of supercell thunderstorms will address FAA restrictions, increase the autonomy of each vehicle, and move toward simultaneous sampling by multiple coordinated vehicles. FAA regulations and policy are continuously revisited, and coordination with the program office and ATCs is essential to ensuring the continuation of this type of flight operation. Beyond policy, a few minor changes can be made to alleviate some of the restrictions, such as the increase in range from an observer by increasing the visibility through the use of aircraft strobe lights. Algorithm development is necessary to achieve increased autonomy and mission success. These algorithms will include aircraft guidance for optimal ingress, sampling, and endurance in strong wind fields and data assimilation with high-fidelity simulations. Finally, achievement of the scientific goals will not be fully realized until the regulations and algorithms have been adopted that allow for simultaneous sampling of the RFD by multiple unmanned aircraft.

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