P13.11 UNMANNED AIRCRAFT OBSERVATIONS OF AIRMASS BOUNDARIES: THE COLLABORATIVE COLORADO-NEBRASKA UNMANNED AIRCRAFT SYSTEM EXPERIMENT

Adam L. Houston* [1], Brian Argrow[2], Jack Elston[2], and Jamie Lahowetz[1]

[1] *Department of Geosciences, University of Nebraska, Lincoln, NE*
[2] *Research and Engineering Center for Unmanned Vehicles, University of Colorado, Boulder, CO*

1. BACKGROUND

Unmanned aircraft systems (**UAS**; the aircraft along with the communications and logistics infrastructure required for their operation) can provide observations of atmospheric phenomena that are either difficult or impossible to attain with existing platforms. It is for this reason that facilitating the maturation of this relatively new technology has become a high priority in the atmospheric sciences. This position is reflected in the 2007 National Research Council Decadal Survey which states that unmanned aircraft technology “should be increasingly factored into the nation’s strategic plan for Earth science”. Moreover, the FY08 budget for NOAA features an increased investment in UAS to “evaluate the benefits and potential of using UAS”.

The earliest application of UAS in the atmospheric sciences was in the Atmospheric Radiation Measurement Unmanned Aerospace Vehicle (ARM-UAV) program in the mid-90’s (Stephens et al. 2000). Originally proposed in 1991 as part of the DOD/DOE funded Atmospheric Remote Sensing and Assessment Program (ARSAP), ARM-UAV was responsible for several “firsts” including the first unescorted flight of a UA in class A airspace. The principal focus of the ARM-UAV experiments was on the radiative processes within the mid/upper-troposphere. Thus, experiments were conducted using a high altitude, long endurance (HALE) aircraft configuration. Most recent applications of UAS have also utilized the HALE configuration (Blakeslee et al. 2002; Corrigan et al. 2006; Lin 2006; Ramanathan et al. 2007).

The utility of smaller unmanned aircraft (**UA**) with more limited altitudes and ranges has only recently begun to be explored. The principal advantages of these types of systems over HALE UA or manned aircraft are,

1) They are cheaper to operate, maintain, and replace
2) They are capable of rapid deployment near meteorological targets
3) They are capable of collecting low-altitude observations over land

However, despite their potential benefits, the use of small UA for collecting observations of terrestrial low-level meteorological phenomena is extremely rare.

2. OBJECTIVES

The overarching objective of this collaborative project between the University of Colorado at Boulder (**CU**) and the University of Nebraska – Lincoln (**UNL**) has been to examine the feasibility of using a small UA operating semi-autonomously to observe atmospheric phenomena within the terrestrial boundary layer of the national airspace system. To achieve this objective, a field experiment has been designed that will utilize a UA developed by the University of Colorado’s Research and Engineering Center for Unmanned Vehicles (**RECUV**) to collect *in situ* data across airmass boundaries located over the Pawnee National Grassland in northeast Colorado.

The specific objectives of this experiment (**CoCoNUE** – **Co**llaborative **Co**lorado-**N**ebraska **U**nmanned Aircraft System **E**xperiment) are as follows:

- Demonstrate the targeting of a mesoscale atmospheric phenomenon that has been

---

* *Corresponding author address:* Adam L. Houston, Department of Geosciences, University of Nebraska – Lincoln, Lincoln, NE, 68588. ahouston2@unl.edu

identified with supplemental observing platforms

- Examine flight strategies for sampling airmass boundaries with unmanned aircraft
- Test the rapid deployment of an unmanned aircraft system

3. PARTICIPANTS

The work is led by Drs. Brian Argrow (CU) and Adam Houston (UNL) but also involves personnel from Colorado State University (**CSU**) and the National Center for Atmospheric Research. Dr. Argrow and his staff at RECUV have taken a leading role in the following areas: 1) developing and maintaining an open line of communication with FAA for the purpose of clarifying and integrating FAA regulations, 2) constructing the UA that will be used for CoCoNUE, and 3) developing the command and control system for the UA. Dr. Houston and his group at UNL have taken a leading role in the following areas: 1) developing a decision support system that enables the navigation of the UA and ground-based support vehicles in relationship to an observed airmass boundary and 2) crafting the overall strategy to target airmass boundaries. CSU operates the NSF-supported CSU-CHILL and CSU-Pawnee radars located in northeast Colorado. These radars will be instrumental in the execution of CoCoNUE: real-time radar data will be used to target airmass boundaries over the Pawnee National Grassland and archived radar data will be synthesized to yield three-dimensional wind measurements that can be compared to the observations collected by the UA. NCAR's In-Situ Sensing Facility at the Earth Observing Laboratory has provided miniaturized temperature and humidity sensors for the UA. The sensor was originally developed for use in the MIST (miniature in-situ sounding technology) dropsonde.

4. EXPERIMENT DESIGN

Experiments will be conducted over the western half of the Pawnee National Grassland located in northeast Colorado (Figure 1). The Pawnee National Grassland (**PNG**) was selected because its modest population density obviates the need to operate over major urban areas and because it is positioned to enable dual-Doppler measurements from the CSU-CHILL/Pawnee radars (Figure 1).

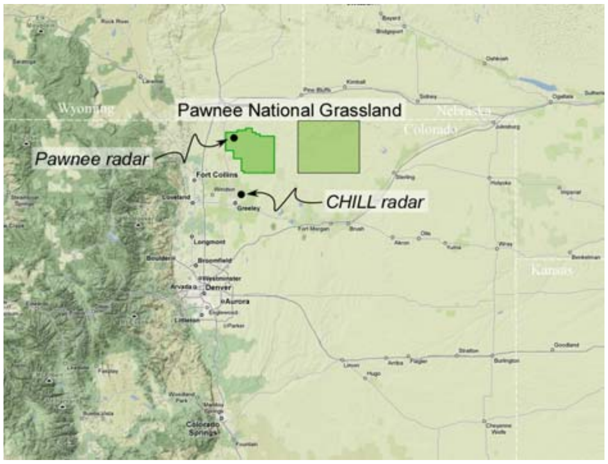


Figure 1. Location of the Pawnee National Grassland and CSU-CHILL/Pawnee radars. Background image courtesy of Google Maps.

For a given deployment, the aircraft will be launched in the PNG from the RECUV Mobile Ground Station. Semi-autonomous operation will commence immediately following launch. The aircraft flight plan is controlled by dynamic waypoints that can be changed in real-time at the ground station. The aircraft will be landed at the location of the ground station.

Deployments will target atmospheric airmass boundaries. An airmass boundary was chosen as the mesoscale atmospheric phenomenon to target for the following reasons:

- Airmass boundaries are ubiquitous.
- An airmass boundary is characterized by a long along-boundary scale on the order of 100s to 1000s of km so it can be easily tracked via the existing network of synoptic scale observations.
- An airmass boundary is characterized by a short across-boundary scale on the order of 1-10 km that can be sampled by UA without requiring flight times at the limit of current small UA capabilities.
- Sampling an airmass boundary does not require operations in precipitation where uncertainties in current UAS capabilities are more acute.
- An airmass boundary is readily apparent in radar reflectivity and velocity data during

the late spring, summer, and early fall through the combination of biological targets and Bragg scattering.
- An airmass boundary can be easily identified and tracked in all seasons using a combination of ASOS surface observations and visible satellite data.
- An airmass boundary should exhibit a clear signal in the thermodynamic and kinematic data measured by the UA.

4.1. Aircraft

The two UA that will be used for this work (not flown simultaneously) are the Hobbico NexSTAR and the Experimental Aircraft Models Velocity-XL. Both aircraft are based on commercially available almost-ready-to-fly airframes. The NexSTAR airframe (Figure 2a) is made of balsa and plywood and has a 5.7 foot wingspan. The Velocity-XL (Figure 2b) has a balsa and fiberglass construction and a 6.7 foot wing span.

Figure 2. a) Hobbico NexSTAR UA; b) Experimental Aircraft Models Velocity-XL.

The Velocity-XL is the principal aircraft for CoCoNUE but the NexSTAR will be flown first. RECUV has already received authorization from FAA to fly the NexSTAR at Table Mountain, CO and thus the path to receiving authorization to fly the NexSTAR over the PNG was shorter than for the Velocity-XL. The Velocity-XL airframe was chosen because, 1) it has a sturdy construction, 2) the canard (front wing) and rear-mounted engine provide an easily accessible volume for payload (and eventual parachute stowage), 3) the canard provides excellent lateral stability and stall control, 4) the pusher configuration provides flexibility for sensor placement ahead of the disturbed airstream, and 5) it is easily configured for operating air speeds of ~25 ms^{-1} and flight times of ~2 hrs. Additional attributes of the Velocity-XL that will be used for the project are as follows:

- Piccolo autopilot for semi-autonomous flight
- Catapult launch capabilities for rapid deployment
- Strobes for improved visual spotting
- Camera for image archiving
- Air velocity sensor
- Miniaturized temperature and humidity sensor

4.2. Boundary position identification

Identification of airmass boundary position and motion will primarily depend upon real-time Doppler radar data from the CSU-CHILL/Pawnee radars. These radars are also positioned to enable *ex post facto* dual-Doppler wind synthesis for data collected over the PNG (Figure 3). Through consultation with the CSU-CHILL staff, a radar scanning strategy has been devised that will provide volumetric data coverage over the PNG, sufficient data coverage within the planetary boundary layer, synchronized scanning between the two radars for dual-Doppler wind synthesis, and a relatively short scan cycle (3.5 min). As illustrated in Figure 3, the CSU-CHILL will scan a 135° sector to the northeast and the CSU-Pawnee radar will scan a 180° sector to the southeast.

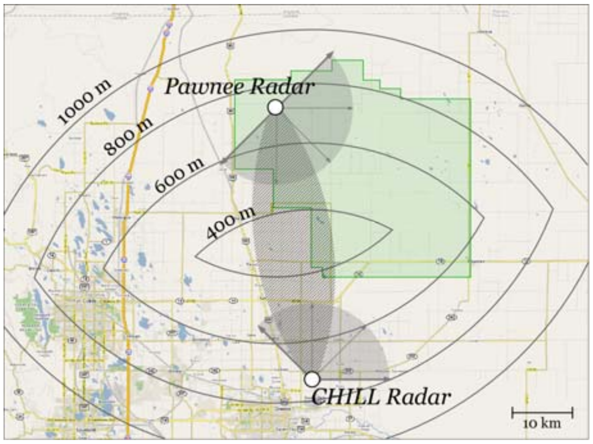


Figure 3. Locations of the CHILL and Pawnee radars relative to the Pawnee National Grassland (green shaded region). The unfilled lenses represent the areas for which radar measurements can be made at minimum altitudes of 300-400 m (labeled "400 m"), 400-600 m (labeled "600 m"), 600-800 m (labeled "800 m"), and 800-1000 m (labeled "1000 m"). All points within the hatched region reside too close to the baseline to allow for reliable dual-Doppler measurements. Scanning sectors are indicated with semi-transparent semi-circles.

4.3. Decision support tool

Navigation of the UA and ground-based observers in relation to airmass boundaries requires the fusion and visualization of meteorological data with UA and ground-based observer telemetries, communication between ground-based observers and the project coordinators, and a means to communicate navigation decisions to the UA. To this end, the Gibson Ridge Radar and UAS Visualization Interface (**GRRUVI**) has been developed. GRRUVI is a decision support tool that integrates radar data, supplemental meteorological data, UA and ground-based observer telemetries, and road networks using the GIS-driven Gibson Ridge Level-II (**GR2**) data viewer[1] (Figure 4). It also provides an interface for communication between ground-based observers and the project coordinators as well as a mechanism for broadcasting the telemetry of each ground-based observer. Finally, GRRUVI enables flight plan modification during semi-autonomous flight.

The CSU-CHILL staff has set up a real-time feed of both the CHILL and Pawnee radar data converted to Level-II format. Additional real-time meteorological data are also made available for situational awareness. These data include 1-km visible satellite images and ASOS observations and are provided through the Unidata Internet Data Distribution via UNL.

4.4. Communication

4.4.1. Network

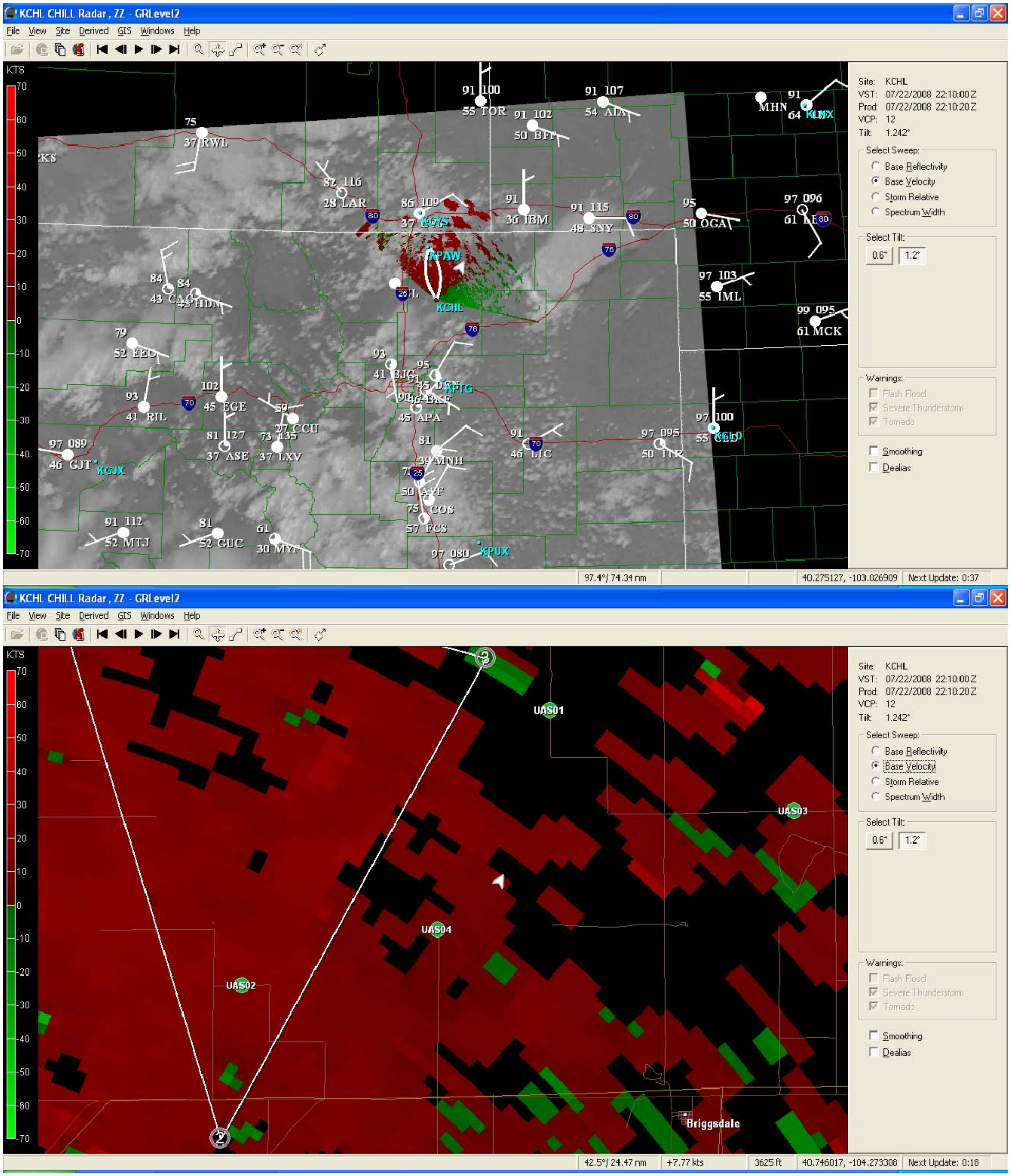
Both communication and data transfer will use the (Verizon) EV-DO (broadband cellular) network in place over the Pawnee National Grassland. Testing has revealed that the coverage is sufficient for communication and optimized data transfer. For purposes of redundancy, direct radio communication capabilities between the base station and the primary ground-based observer will also be employed. This communication will utilize 2 two-way radios provided by CSU-CHILL. These radios operate in the 450-512 MHz band (UHF) and take advantage of repeaters operated by Wireless Advanced Communications and covering the entire PNG. This system will also enable communication between the base station and the CSU radars

4.4.2. Communication interface and telemetry dissemination

GRRUVI's communication interface uses the Internet Relay Chat (IRC) protocol and relies on the EV-DO network. The telemetry of a particular ground-based observer is collected via a GPS receiver tethered to each observer's laptop and then transmitted in GRRUVI via the EV-DO network to the UNL server where it is converted into a format that can be visualized in GR2 (Figure 4). UA telemetry is collected in GRRUVI via the 802.11b (Wi-Fi) network used for command and control of the UA (discussed below) and can also be collected from the UNL server via the EV-DO network. See Figure 5 for an illustration of the flow of information during a deployment.

---

[1] http://www.grlevelx.com/grlevel2/



Site: KCHL
VST: 07/22/2008 22:10:00 Z
Prod: 07/22/2008 22:10:20 Z
VCP: 12
Tilt: 1.242°

Select Sweep:
○ Base Reflectivity
● Base Velocity
○ Storm Relative
○ Spectrum Width

Select Tilt: 0.6° 1.2°

Warnings:
☐ Flash Flood
☑ Severe Thunderstorm
☑ Tornado

☐ Smoothing
☐ Dealias

97.4°/ 74.34 nm | 40.275127, -103.026909 | Next Update: 0:37

Site: KCHL
VST: 07/22/2008 22:10:00 Z
Prod: 07/22/2008 22:10:20 Z
VCP: 12
Tilt: 1.242°

Select Sweep:
○ Base Reflectivity
● Base Velocity
○ Storm Relative
○ Spectrum Width

Select Tilt: 0.6° 1.2°

Warnings:
☐ Flash Flood
☑ Severe Thunderstorm
☑ Tornado

☐ Smoothing
☐ Dealias

42.5°/ 24.47 nm | +7.77 kts | 3625 ft | 40.746017, -104.273308 | Next Update: 0:18

Figure 4. Examples of the Gibson Ridge Level II data viewer that GRRUVI utilizes for data visualization. The UA position is indicated with a white arrow, ground-based observer positions are indicated with green circles, and the waypoints appear as double circled numbers connected by white lines. Radar data from the CSU-CHILL radar is presented here.

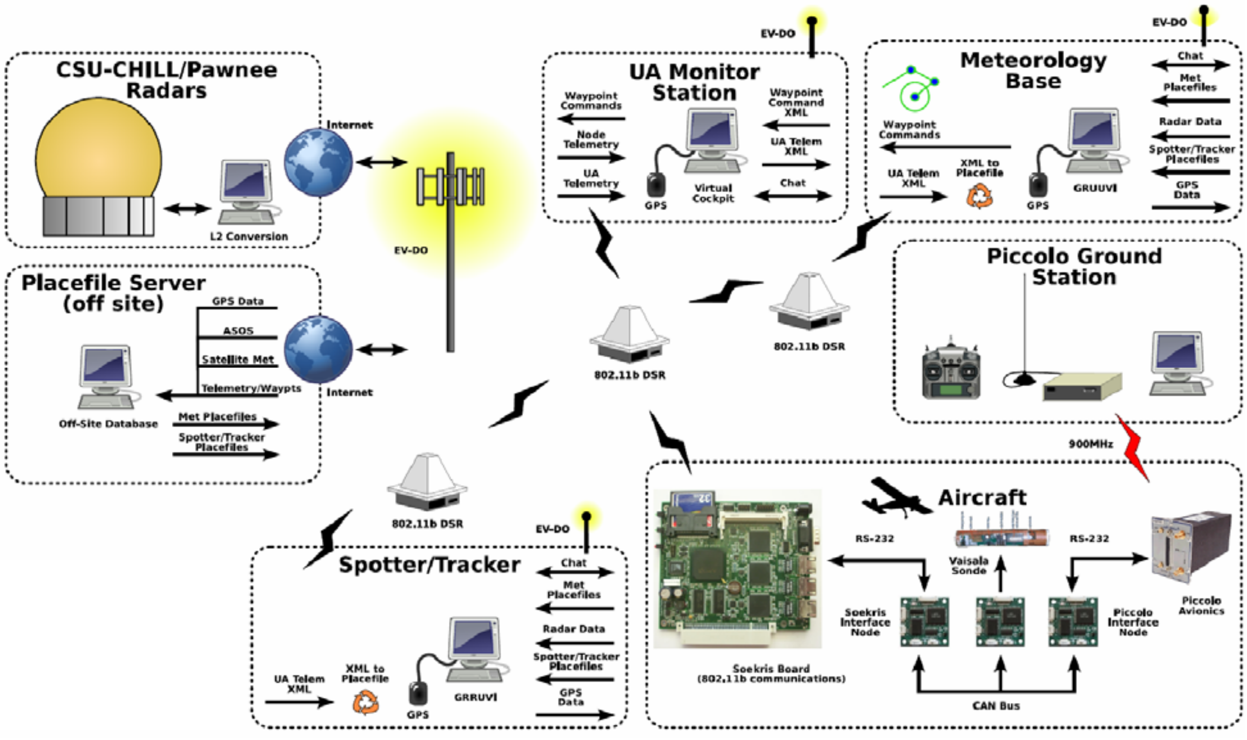
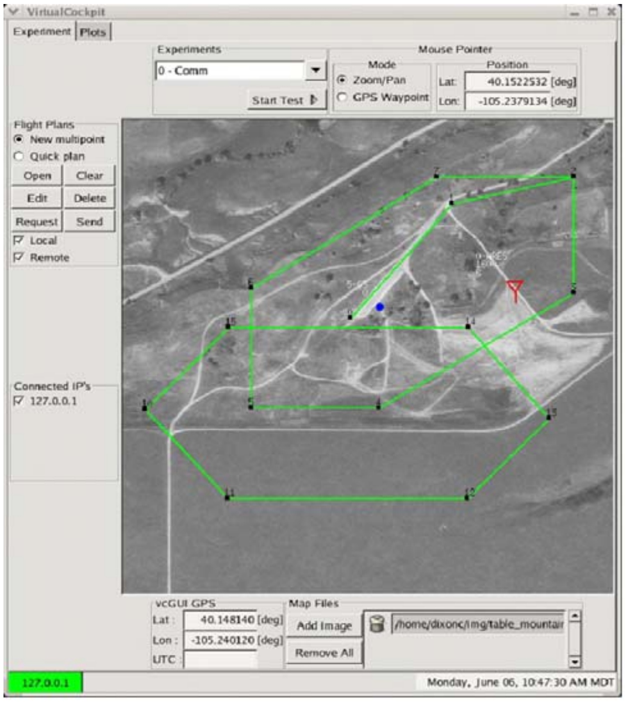


Figure 5. Flow of information during deployment

4.4.3. *Command and control system for UA*

While GRRUVI is able to control semi-autonomous flight of the UA by setting out waypoints, the overall control of the UA occurs through the Virtual Cockpit (Figure 6), a control interface developed at RECUV. Primary command and control (**CC**) of the UA occurs over an 802.11b (WiFi) data link. WiFi nodes will reside in all ground-based observers thereby allowing for CC to utilize the AUGNet (Ad Hoc UA-Ground Network) technology developed at RECUV (Brown et al. 2004). A directional WiFi antenna will also be used at the base station. The UA can also be controlled directly via a 900-MHz control link.



Experiments: 0 - Comm

Mouse Pointer

Mode: ● Zoom/Pan ○ GPS Waypoint

Position: Lat: 40.1522532 [deg] Lon: -105.2379134 [deg]

Flight Plans: ● New multipoint ○ Quick plan

☑ Local

☑ Remote

Connected IP's

☑ 127.0.0.1

vcGUI GPS

Lat : 40.148140 [deg]

Lon : -105.240120 [deg]

UTC :

Map Files: /home/dixonc/img/table_mountair

127.0.0.1

Monday, June 06, 10:47:30 AM MDT

Figure 6. Virtual cockpit.

4.5. *Field crew*

A minimum of 4 vehicles will compose a given deployment:

- RECUV Mobile Ground Station (**RMGS**) [1]
- Tracker [1]
- Spotters [2]

The RMGS is a 10-ft x 6-ft x 8-ft trailer designed to transport and support the UA. The trailer contains a full complement of support tools, a weather station, a computer running the Virtual Cockpit, and a computer running GRRUVI. The Tracker is a ground-based vehicle designed to shadow the UA at all times. This vehicle will be the primary means of maintaining visual observation of the UA. Two mobile Spotters will also be deployed in the path of the UA. Spotters will be tasked with insuring redundant visual observations of the UA. The Tracker and Spotters will be equipped with computers running GRRUVI to enable situational awareness. The flow of information between the various units of the entire system is illustrated in Figure 5.

The crew composing a given deployment will contain the following:

- Pilot in command (**PIC**) [1]
- Meteorologist in command (**MIC**) [1]
- Pilot-at-control for semi-autonomous operations (**PAC-O**) [1]
- Pilot-at-control for manual operations (**PAC-M**) [1]
- Tracker driver, navigator, and UA observer [3]
- Spotter driver and observer [2]

The PIC is the coordinator for UA operations and generally oversees the mission. During operations, the PIC will reside in the field at the base station. The MIC is responsible for making boundary targeting decisions based on meteorological data and will also reside in the field at the base station. The PAC-O is in charge of controlling the UA (using the Virtual Cockpit) and the PAC-M is in charge of controlling the UA manually. Both PACs will reside in the field at the base station.

4.6. *Example deployment*

In each deployment, the UA will be focused on collecting data within a zone extending from ~10 km on the "warm" side of the airmass boundary's density demarcation to ~15 km on the "cool" side and will stay below 1 km AGL. This zone across the boundary has been chosen because it generally contains the largest gradients in thermodynamic properties and the largest accelerations. The UA will fly transects across the boundary as illustrated in Figure 7.

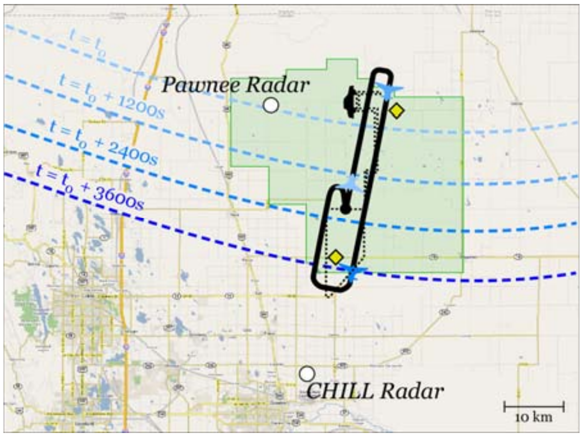


Figure 7. Deployment scenario for CoCoNUE. Track of the UA is indicated with a thick black curve, location of the UA at t0, t0+1200, t0+2400, and t0+3600 is indicated with blue aircraft symbols, boundary positions appear as dashed blue curves, the locations of Spotters are noted with yellow diamonds, and the track of the Tracker (car symbol) is indicated with a dotted curve.

5. FAA COMPLIANCE

The regulatory environment for UAS has radically changed since the execution of the ARM-UAV experiments in the mid-90's. The operation of UA by public entities now requires a Certificate of Authorization or Waiver (**COA**) issued by the FAA. The COA is crafted by the FAA "with terms that ensure an equivalent level of safety as manned aircraft". The COA application asserts the air worthiness of the UA and the emergency procedures that will be executed for many possible contingencies. It is issued for a particular aircraft and a particular geographic region.

For CoCoNUE and similar projects, the FAA mandates the following for UA operation:

- UA must remain within visual contact of an observer (ground-based in this experiment) at all times. This is required to enable deconfliction if other aircraft enter the nearby airspace. Binoculars can be used to assist in spotting aircraft.
- A notice to airmen (NOTAM) is a sufficient mechanism for notifying pilots of impending operations.
- It is necessary to maintain the ability to communicate with local air traffic control and manned aircraft.
- If multiple UA are operated, each UA must have a dedicated PAC-O, PAC-M, and support communications equipment

The approval of a COA application can take as long as 3½ months. Figure 8 illustrates the process of COA application/approval.

RECUV has obtained a COA to operate the NexSTAR at Table Mountain, CO and, at the time of this writing, has executed 51 flights and nearly 6 hours of flight time. The COA application to operate the NexSTAR over the PNG is in the process of being validated and thus the COA should be issued in less than 60 days. The COA application to operate the Velocity-XL over the PNG has just been submitted.

6. PILOT PROJECT DURING VORTEX-2

Drs. Argrow and Houston along with collaborators Erik Rasmussen (Rasmussen Systems), Jerry Straka (University of Oklahoma), Eric Frew (CU), and Katharine Kanak (OU) have received NSF funding to conduct a pilot project in 2009-2010 aimed at advancing the use of UAS for studying supercells and their environments. This project will involve two principal components: 1) deployment of UAS in the vicinity of supercells during the execution of the second phase of the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX-2) and 2) identification of an aircraft design and deployment strategy capable of collecting in-situ observations within a supercell RFD.

7. SUMMARY

Ultimately, the complicated marriage of engineering, meteorology, and policy involved in using UAS to observe atmospheric phenomena in the NAS terrestrial boundary layer has meant that the feasibility of this endeavor is unknown. This is particularly true for atmospheric phenomena that require UA operation beyond visual line of sight of the operator. The full benefits of UAS cannot be realized until this application of UAS is demonstrated. The Collaborative Colorado-Nebraska Unmanned Aircraft System Experiment (CoCoNUE) will provide this demonstration by using UAS to target airmass boundaries over the Pawnee National Grassland.

8. ACKNOWLEDGEMENTS

The authors are grateful to Dr. Patrick Kennedy and his staff at the CSU-CHILL radar for their invaluable assistance throughout this project. The authors would also like to thank Terry Hock and Dean Lauritsen of the In-Situ Sensing Facility at NCAR’s Earth Observing Laboratory for providing the miniaturized temperature and humidity sensor, for reprogramming the sensor board, and for offering guidance regarding optimal installation locations on the UA. Funding for this work was provided through NSF grants ATM-0715875 and ATM- 0715941.

9. REFERENCES

Blakeslee, R. J., D. Mach, M., M. D. Desch, R. A. Goldberg, W. M. Farrell, and J. G. Houser, 2002: The Altus Cumulus Electrification Study (ACES): A UAV-based science demonstration. *1st Technical Conf. and Workshop on Unmanned Aerospace Vehicles, Systems, Technologies, and Operations*, Portsmouth, VA, American Institute for Aeronautics and Astronautics, Paper 2002-3405.

Brown, T., B. Argrow, C. Dixon, and S. Doshi, 2004: Ad hoc UAV ground network (AUGNet). *3rd Unmanned Unlimited Technical Conf.*, American Institute for Aeronautics and Astronautics, Paper 2004-6321.

Corrigan, C., V. Ramanathan, M. V. Ramana, D. Kim, and G. Roberts, 2006: Chasing black carbon using autonomous unmanned aerial vehicles. *American Geophysical Union*, *Fall Meeting*, San Francisco, CA, #A43A-0106.

Lin, P.-H., 2006: The first successful typhoon eyewall-penetration reconnaissance flight mission conducted by the unmanned aerial vehicle, Aerosonde. *Bull. Amer. Math. Soc.*, **87,** 1481-1483.

Ramanathan, V., M. V. Ramana, G. Roberts, D. Kim, C. Corrigan, C. Chung, and D. Winker, 2007: Warming trends in Asia amplified by brown cloud solar absorption. *Nature*, **448,** 575-579.

Stephens, G. L., and Coauthors, 2000: The Department of Energy's Atmospheric Radiation Measurement (ARM) Unmanned Aerospace Vehicle (UAV) program. *Bull. Amer. Meteor. Soc.*, **81,** 2915-2937.

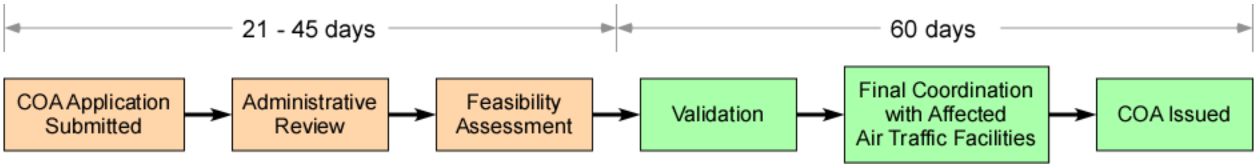


Figure 8. COA process