Unmanned Aircraft Systems for Sampling Severe Local Storms and Related Phenomena

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I. INTRODUCTION

To understand and predict the dynamic behavior of our planet’s environment over multiple spatial and temporal scales remains an outstanding scientific challenge [1], [2]. More than 50 years of investment and advancements in remote weather sensing systems (satellite-based as well as ground-based radar) have resulted in remarkable capabilities, however these systems cannot deliver observations to meet current requirements for timeliness, positional precision, and the acquisition of data that can only be obtained in situ. Highly mobile observations systems are needed to deliver in situ data that are critical for the verification and validation of current models and simulations. This is the challenge to “engineer the tools of scientific discovery,” one of the 14 Engineering Grand Challenges of the 21st Century posed by the National Academy of Engineering [2]. This article addresses specific challenges to designing and deploying unmanned aircraft systems for sampling severe local storms.

Robotic sensor systems will enable fundamentally new science with in situ measurements from autonomous platforms that actively assimilate and explore in places too hostile or too remote for people [2], [3], [4]. Unmanned vehicle technology has advanced to the point where platforms perform persistent surveillance missions far from remote operators [4]. Likewise, complex environmental phenomena can be simulated in near real-time with increasing levels of fidelity [5], [6]. Combining unmanned platforms with real-time environmental models enables the adaptive sampling by autonomous robotic sensor systems of data essential for examining the fundamental behavior of complex phenomena. Robotic sensor systems have been deployed successfully in a variety of applications that include: hurricane sampling [7], underwater ocean observation [8], pollution monitoring [9], tornadic storm penetration (Figure 1) [10], water condition mapping [11], and harmful algal bloom tracking [12].

The National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) have recognized the benefits that unmanned aircraft systems (UAS) provide for atmospheric sampling [13]. Based on field experience utilizing a diverse set of measurement capabilities [7], [13], [14], [15], [16], NOAA has suggested that current efforts with UAS should be expanded to further enhance climate study and characterize meteorological processes [3]. UAS are potentially useful for the study of a wide variety of atmospheric phenomena and processes, including thunderstorm outflows and gust fronts, land-falling hurricane boundary-layer circulations, planetary boundary-layer fluxes (particularly those relevant to climate dynamics), atmospheric responses to fires, pollutant dispersion, and terrain-driven circulation systems.

While UAS have primarily been deployed to study atmospheric phenomena that persist for days or longer [7], [9], [13], [14], [15], [16], there is immediate utility in UAS for facilitating new knowledge through observations of atmospheric phenomena with representative timescales on the order hours or minutes [17]. Severe local storms are good examples of such phenomena [18]. These types of storms and the phenomena that they produce are challenging to observe and study because of their intensity, small spatial scale, and tendency for rapid development [18]. Two examples of severe local storm phenomena are presented below.

Tornadogenesis: Effective advanced warning systems could drastically reduce the loss of life and damage
caused by tornadoes. Unfortunately, understanding of tornadogenesis will not progress until there are in situ measurements of the thermodynamic and microphysical properties aloft in the vitally important rear-flank region of supercell storms [17]. The process of tornado formation occurs in regions 1-10 km wide, within a few kilometers of the ground, and in less than 20 minutes after the first manifestations of tornado potential. Recent hypotheses suggest that thunderstorm downdrafts must be negatively buoyant aloft, but arrive at the ground with nearly neutral buoyancy through compressional warming, in order to promote tornado formation [19], [20]. Unmanned aircraft systems are exceptionally well-suited to measure these buoyancy characteristics in an environment with flow variations too extreme for manned aircraft observations.

**Airmass Boundaries:** Airmass boundaries (e.g., drylines, cold fronts, and thunderstorm gust fronts) are ubiquitous phenomena in the atmosphere and can play a significant role in the development of supercell thunderstorms and tornadoes [21]. Previous methods for collecting in-situ measurements of airmass boundaries do not provide significant spatio-temporal sampling [22]. Airmass boundaries are characterized by a long along-boundary scale (100s to 1000s of km) so they can be easily tracked via existing observation networks. However, the processes associated with airmass boundaries that are relevant to storm initiation and intensification are mainly dependent on ~10 km scale cross-boundary gradients of density and moisture [23], [24] that are amenable to sampling with UAS [25].

Autonomous targeted observation of complex environmental phenomena is enabled by a planning framework that combines real-time science driven control with online high resolution modelling and data assimilation. For severe local storms, targeted observation can be enabled by the integration of multiple sensor systems (Figure 2) such as mobile Doppler radar that can provide three-dimensional wind fields [26] for energy-aware path planning by in situ aircraft and data assimilation in the online models. Underwater [8], [12], terrestrial/surface [11], and airborne [7], [9], [10] domains present unique challenges for the robotic sampling systems performing targeted observation, however these challenges can be broken down into three main categories: regulatory, logistical, and technical.

This article discusses specific challenges to developing UAS for sampling severe local storms and related phenomena [27]. The development of the Tempest unmanned aircraft system [10] will be used as a guiding example (Figure 1) for this article. The Tempest UAS was deployed as part of the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) [17] to sample the rear-flank gust front of supercell thunderstorms [10]. The Tempest represents the state-of-the-art in airborne sampling systems due to its networked command and control architecture and concept of operations for flight in the U.S. National Airspace System (NAS). The major challenges described here played a role in the design of the Tempest UAS and will shape future robotic airborne sampling systems.

II. REGULATORY CHALLENGES

The operation of unmanned aircraft systems in the U.S. National Airspace System is governed by the Federal Aviation Administration (FAA), with guidelines established in Interim Operational Approval Guidance 08-01, Unmanned Aircraft Systems Operations in the U.S. National Airspace System (Policy 08-01) [28]. This document was created to define requirements and procedures for the operation of unmanned aircraft systems. It specifies that special approvals are required for UAS operation in the NAS (outside of active restricted, prohibited, or warning areas) because unmanned aircraft systems are not compliant to many sections of Title 14 of the Code of Federal Regulations (14 CFR) [29]. A recent FAA Aviation Rulemaking Committee [30] reported “a comprehensive set of recommendations for small UAS regulatory development,” but these regulatory recommendations have yet to be adopted, even in part.

UAS compliance with 14 CFR is demonstrated by receiving a certificate of waiver or authorization (COA) or by obtaining a special airworthiness certificate–experimental category. For public institutions, defined as one that is intrinsically government in nature, approval is obtained through the COA process [28]1. A COA defines operational requirements, emergency procedures, airworthiness requirements, an area of operations, and ground crew proficiency requirements for the operation of a single class of UAS. The overarching goal of the COA application is to demonstrate that the UAS operations have an equivalent level of safety of manned operations. The regulations that must be satisfied for the operation of UAS remain those developed for manned aircraft resulting in a COA application process for UAS that is not straightforward.

Although the FAA’s Unmanned Aircraft Program Office (UAPO) has worked to clarify regulations and submission requirements, rather than define a complete set of sufficient conditions for receiving a COA, the UAPO approach is to evaluate submitted COA applications individually. Often a COA application must be submitted, revised, and resubmitted multiple times before it is accepted. In some cases the COA might be issued for

1By this definition, public universities are able to receive COAs while private universities are not.
the original submission, but with modifications inserted by the FAA. For example, the COA applications for the Tempest UAS in VORTEX2 requested a flight ceiling of 3000 ft above ground level, but the certificates were issued with a ceiling of 1000 ft [31].

Certificates of authorization are issued for a given aircraft class in a given area for a given duration (typically one year). In order to provide notice to air traffic control and potential air traffic, UAS operators are generally required to file a Notice to Airmen (NOTAM) 72-48 hours in advance of operations. The NOTAM specifies the location and time of the flight within the COA area. The concept of operations required for sampling dynamic phenomena like supercell thunderstorms makes it impossible to issue NOTAMs 72-48 hours in advance; therefore, the size of the COA areas must be relatively small to minimize the workload on air traffic controllers who must notify pilots approaching active COA airspace. The COAs mandated the use of a stationary ground control station for the aircraft operator and pilot in command. To achieve see-and-avoid capability, the FAA allowed a qualified observer to maintain visual sight of the aircraft at all times while also maintaining voice communication with the ground control station. As a result, a third "Tracker" vehicle was incorporated into the system (Figure 3). The Tempest UAS flight computer was fed the position of the tracker vehicle and was commanded to orbit it while the tracker was driven into the storm outflow or beneath the storm where measurements were to be obtained [10]. Although this strategy was suboptimal in terms of storm sampling [32], it was the only viable method to satisfy the regulations that were imposed at the time.

III. LOGISTICAL CHALLENGES

Logistical challenges depend heavily on the specific mission and can vary greatly. In general they will be directed by two main factors. First, the science mission
For the VORTEX2 mission, favorable conditions could be identified a few days in advance, with specific storms evolving over the course of several hours and travelling with ground speed sometimes exceeding 30 m/s. The specific location of storm formation and the path of the storm as it evolved were extremely difficult to predict. Tornadogenesis within a supercell thunderstorm has been observed to occur in as little as 13 minutes from the first manifestation of potential tornadic activity [34]. As a result, tracking storms required highly nomadic sensing with rapid (re)deployment capabilities.

The concept of operations (CONOPS) for a typical deployment during VORTEX2 consisted of a time period that began 36 hrs before flight and ended one hour after launch [10] (Figure 4). The CONOPS developed for the mission was 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, several sampling scenarios were developed that proved to be useful and accommodated most supercell intercepts. COA boxes were approximately 20 x 20 miles for all deployments during VORTEX2, though storms never passes directly through one area and all flights into supercell storms were limited by the COA boundaries [10].

Compliance with the COAs directly impacted the operations starting approximately four hours before the eventual launch of the Tempest UAS. As indicated in Figure 4, final decisions about the probable location of targetable storms would be made in the time leading up to the issuance of the NOTAM, two hours in advance of the launch [10]. This challenged the abilities of the meteorologists to predict the evolution of the storms. Their forecasts had to ensure that the UAS team could issue NOTAMs to activate the appropriate COAs (no more than 4 at one time) two hours in advance of the targeted area of a storm entering an activated COA area. This proved to be a tremendous logistical challenge, particularly given the unpredictable nature of supercell evolution, the speeds at which they can travel, and their nonlinear trajectories. One of the achievements during VORTEX2 was the agreement of the FAA to reduce the NOTAM filing requirement from the original 72-48 hours to two hours. This greatly increased the ability of the UAS team to activate appropriate COAs and to position itself for supercell intercepts.
Fig. 4: Timeline for one deployment during the VORTEX2 campaign. The lower timeline provides an expanded view of times from $T - 1$ hr to $T + 1$ hr on the upper timeline [10].

IV. TECHNICAL CHALLENGES

A. Sensing

Sensing challenges for atmospheric sampling missions are derived from three sources: the need for in situ wind field measurements to augment sampling of thermodynamic variables (available from commercial sensor products), real-time derivation of storm scale wind field from mobile Doppler radar, and onboard monitoring of aircraft energy state and health. Serendipitously, improving sensing for the first two sources can also improve capabilities for the third.

The total energy state of the UAS is determined from the sum of the kinetic (based on true airspeed), potential (based on altitude), and internal (based on battery state of charge) energy. The total energy state of the UAS, including instantaneous power consumption and stored-energy levels, must be accurately determined for any energy-management feedback control algorithm. The principal sources of error in determining the energy state are based on the accuracy in the measurement of 1) true airspeed, 2) altitude, and 3) stored energy. During the VORTEX2 deployments, the greatest energy-monitoring challenge was accurately monitoring instantaneous power draw and battery state of charge [10].

The true airspeed of a low-speed aircraft is computed from the dynamic pressure measured with a pitot-static probe, standard equipment in most UAS autopilot systems. The aircraft velocity in the fixed-ground reference frame is estimated from the autopilot inertial measurement unit (IMU) data, supplemented with GPS. Comparing this in-situ airspeed measurement with the IMU velocity estimate and filtering the result gives an estimate of the local wind velocity. Using this method the wind velocity is only observable if the aircraft makes a curved maneuver, which may not be practical given mission constraints. Multi-hole probes [35] have been miniaturized to fly on small UAS and can improve the wind field estimates. The autopilot flown on the Tempest UAS provided wind estimates, but the quality of these estimates could not be validated and results from hardware-in-the-loop experiments, using simulated supercell wind fields, showed that the autopilot estimates were far from the requirements of science-grade measurements [25], [10], [32].

A robust, storm-scale wind field is essential to any atmospheric model for online planning. Mobile Doppler radars can collect radial velocity data capable of resolving meso-$\gamma$ scale and micro-scale atmospheric phenomena. The techniques of computing 3D wind fields from two or more Doppler radars are well established [36]. When the data from multiple radars are combined, triangulation of radial velocities can yield 2D (x-y) wind fields and through mass continuity, the third (vertical) component of the flow can also be deduced. However,
these analyses have never been produced in near real-time in the context of mobile radar operations.

For more than a decade, wind-field estimation has been a focus for small UAS applications, both for atmospheric science and for energy extraction strategies to enhance small UAS mission capabilities [37], [38], [39], [40], [41]. Research has focused on atmospheric phenomena that include thermals, wind shear (vertical velocity gradients), and gusts from atmospheric turbulence as wind-energy sources to be exploited. Inspired by soaring birds, static and dynamic soaring are well established methods to extend the endurance of unpowered gliders, of both manned and unmanned aircraft, and radio-controlled (RC) model aircraft.

Dynamic soaring during supercell intercepts in the VORTEX2 deployment was evident several times when the UAS operator reported that the autopilot had reduced the throttle to zero while the Tempest UAS was flying into a strong headwind, and gaining altitude. In instances where significant soaring was observed, the propulsion battery returned with more energy than non-soaring flights of similar duration. While it was obvious that the duration of Tempest UAS missions could have been extended, no strategy was available to capitalize upon the unintended energy extraction that occurred.

B. Networking

In order to enable environmental monitoring by UAS, a robust communication, command, and control (C3) architecture is needed that: i.) provides situational awareness of the UAS to all users and operators; ii.) provides real-time telemetry and control to the operator; iii.) returns sensor data as quickly as possible; and iv.) is easy to establish, monitor, and maintain [10], [32]. Safety and assurance are the primary motivators for the design of the networked communication system. The same conditions that motivate the use of robotic systems over manned systems create challenges for networked communication.

In the foreseeable future UAS performing atmospheric sampling will be operated in a semi-autonomous mode whereby a person provides mission-level decision making. In order to enable this semi-autonomous mode, the C3 architecture must support a combination of different human supervisors: end-user scientists focused on the information gathered by the system and UAS pilots focused on the telemetry and health of the system. These different supervisors may be collocated in the field or they may be dispersed across remote locations. As a result, the C3 architecture must support net-centric operation such that data flows seamlessly between multiple dispersed network participants.

Mobile ad hoc networking [42] is critical to enable real-time communication in the highly dynamic environment likely to be encountered during atmospheric sampling. By forming a multi-hop communication network, information can be shared efficiently between the sensor platforms and operators, increasing the overall mission capabilities and operational range of the robotic system. As the scope of sampling missions expands, the principal requirements of communication technologies will be flexibility, adaptability, and controllability of the data flows. Specifically tailored middleware can then enable service discovery, dissemination of data, and application-layer control algorithms. This tight coupling between communications, mobility, and sensing is central to a C3 architecture for atmospheric sampling.

In addition to the overall architecture, mission performance also depends on low-level components such as radio hardware, network protocol, and antenna technology. System endurance is directly coupled with onboard energy use and system range is directly coupled with communication range, so any technology that can reduce power consumption while increasing communication range will improve mission performance. Current radio transmissions are regulated by the Federal Communication Commission, which provides some unlicensed radio bands that can be used, e.g. the Industrial, Scientific, Medical (ISM) bands that includes common bands such as 900 MHz, 5.8 GHz, and the 2.4 GHz channels used in IEEE 802.11 (WiFi) and IEEE 804.15 (Zigbee) protocols. The FCC constrains the amount of power that can be transmitted at these frequencies and thus limits the communication range. Directional antennas can increase the range of the system at the expense of added control complexity. Likewise, satellite communication can be used, but links can be slow and unreliable.

The Tempest UAS communications, command, and control was designed using a modular communications architecture. The C3 architecture provided ad hoc networking, service discovery, and a publish/subscribe data capability across a system of multiple heterogeneous network nodes (Figure 5). In Figure 5, each arrow represents a directed data stream that is provided and managed through the service discovery functionality [43]. Figure 5 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 communication architecture provided seamless transitions between configurations. The communication architecture provided network connectivity between multiple types of platforms (airborne, moving ground node, stationary ground node, remote server) over multiple communication protocols (IEEE 802.11 WiFi, 900 MHz direct wireless modem, broadband (cellular) internet service) to multiple dispersed users and operators (UAS pilot, UAS observer, head meteorologist, VORTEX2 field coordinator) [10]. The
Fig. 5: System diagram for Tempest UAS including remote data sources. All components for the mobile ground control station, unmanned aircraft, and tracker are unique to the UAS VORTEX2 effort. [10]

communication architecture worked well in the field and was critical to enabling quick responses to the changing environment and to allowing rapid troubleshooting [10].

C. Path Planning

Aircraft guidance and path planning in complex atmospheric phenomena presents several challenges, particularly when maximum aircraft speeds are less than the peak wind speeds encountered by the aircraft. In these cases the aircraft are unable to travel directly upstream in some locations so large regions of the environment may be inaccessible depending on the initial position of the UAS. Guidance-layer planning problems are characterized by the presence of background winds which move the aircraft even when the control inputs are zero, making them examples of control affine systems with drift [44]. Techniques do not address general optimal control for these systems and instead motion planning algorithms can be used based on specific problem formulations. Recent approaches using wavefront expansion via level sets [45], fast marching methods [46], and “sliding wavefronts” [47] have been applied to linear and control affine systems with drift, especially in the context of autonomous underwater vehicles operating in strong current fields [46].

The wavefront expansion methods are well suited to the planning problems considered here. These methods generate solutions quickly by interpolating over discrete grid representations of the environment with approximation error decreasing as the mesh spacing is decreased. In general these methods are not applied to aircraft because wind data is difficult to obtain. However, the mobile Doppler radar systems [17], [26] deployed to study severe storms provide this information at discrete points in the regions of interest and can therefore be incorporated easily by the planning methods. In fact, wind data is averaged over some volume and output only at volumetric centroids, so planning methods must interpolate between grid points. Aircraft kinematic constraints and environmental constraints due to terrain can also be included in these methods [46].

Though not fielded during the actual VORTEX2 deployments, backward propagating wavefront expansion algorithms were developed based on ordered upwind methods [49] for use as design tools and path planning [48]. Feasibility analysis was performed on a static wind field to assess baseline performance expectations (Figure 6). Ingress planning was also demonstrated in simulation for a dynamic wind field using a receding horizon control approach to adapt the flight path in response to environmental changes [48]. Given the relatively large size of three-dimensional wind data derived from radar measurements, it becomes computationally expensive to plan using all available data. The expense is compounded
V. RESULTS FROM THE VORTEX2 DEPLOYMENT

The Tempest UAS represents the first step toward autonomous targeted observation of severe local storms. The regulatory challenges associated with operating an unmanned aircraft in the U.S. National Airspace System were the greatest by far and drove many of the logistical and technical design decisions. The FAA provided extensive guidance and exhibited remarkable flexibility throughout the COA application process and during the field deployments. As a result, interactions with FAA during the field campaign required continual refinement of the concept of operations and will continue to be the primary design driver in the foreseeable future [32].

The Tempest UAS was successfully deployed as part of the VORTEX2 field campaign from May 1 to June 15, 2010 [10]. A total of six flights were made that sampled supercell thunderstorms, with one of the storms producing two different tornadoes. Major accomplishments of the Tempest UAS include the first use of a UAS to collect data in close proximity to a supercell storm on May 6, 2010, the first sampling of the rear flank gust front of a supercell storm by a UAS on June 6, 2010, and the first sampling of a supercell rear flank downdraft airmass by a UAS on June 9, 2010 [10]. These flights demonstrated the ability to overcome regulatory, logistical, and technical challenges while also revealing other limitations discussed in this article. Current efforts are assessing the data obtained by the Tempest unmanned aircraft system during the VORTEX2 mission and cross-validating the data with measurements from the other participating sensor platforms.

The interplay between the regulatory, logistical, and technical challenges was highlighted during a deployment on June 10, 2010 [10]. After tracking several storms east of Denver, CO throughout the day, the Tempest UAS team along with the rest of the VORTEX2 instruments chose to deploy into a storm near Deer Trail, CO. As required, a NOTAM was issued and the Denver Air Route Traffic Control Center was notified 2 hours prior to flight. The team was able to position itself for launch before this time period elapsed, but because of the notification requirement the Tempest aircraft had to sit on the ground while two different tornadoes were observed. Once airborne, the tracker vehicle leading the aircraft headed toward the storm to intercept its rear flank gust front (Figure 7). The UA flew

when considering dynamic environments. The complexity of the computations increases as $O(M \log M)$ with the size $M$ of the dataset, so decreasing the size of the dataset significantly impacts calculation time. Methods were explored to reduce the number of points needed to characterize the wind while still providing near-optimal planning [50].

Fig. 6: Cost maps obtained using an ordered upwind method for backward wavefront expansion, target indicated by an asterisk. Shading correlates with time in minutes required to reach goal location. Each plot depicts a different vehicle speed, and an example path from the same starting location is shown on each plot as a dashed line. Plot (a) does not contain a path as it is impossible to reach the goal location within the 30 minute time frame [48].
semi-autonomously above the tracker, but because of
the regulatory constraint that the aircraft remain within
0.5 miles of the observer in the tracker vehicle the
path planning algorithms could not be implemented.
Real-time radar reflectivity data showed that the tracker
vehicle and aircraft were slightly ahead of the storm,
thus the head meteorologist coordinated with the tracker
vehicle to loiter for several minutes as the storm moved
past. Once clear, the tracker vehicle led the aircraft
across the rear flank gust front. The Tempest was able
to traverse the rear flank gust front several times before
the storm left the operations area defined by the Certificate
of Authorization (gray lines in Figure 7), ending the
sampling mission.

VI. CONCLUSION

Future unmanned aircraft systems will be fielded to
provide targeted observations of severe local storms and
related phenomena by combining science-driven
autonomous control with online modelling and data
assimilation. Regulatory, logistical, and technical chal-
ленges exist that will need to be overcome in order to
put these systems into practice. The Tempest unmanned
aircraft system demonstrated proof-of-concept for in situ
sampling of severe local storms. Experiences with the
Tempest highlighted regulatory, logistical, and technical
challenges in the context of supercell thunderstorm pen-
etration, and inform the development of future airborne
autonomous sampling and targeted observation systems.

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REFERENCES

[1] National Research Council, Earth Science and Applications from
Space: National Imperatives for the Next Decade and Beyond,
[2] National Academy of Engineers, Grand Challenges for
http://www.engineeringchallenges.org/
weather and climate prediction,” Bulletin of the American Meta-
investigation at gusev crater, mars,” Science, vol. 305, no. 5685,
[5] D. J. Stensrud and Coauthors, “Convective-scale warn-on-
forecast system,” Bulletin of the American Meteorological So-
of radar data and other mesoscale observations within a collabora-
tive forecasting research environment,” Weather Forecasting,
sance observation of typhoon longwang (2005) with unmanned
aerial vehicle, aerosonde,” Journal of Atmospheric and Oceanic
F. Zhang, “Coordinated control of an underwater glider fleet in
an adaptive ocean sampling field experiment in monterey bay,”
[9] M. Ramana, V. Ramanathan, D. Kim, G. Roberts, and C. Cor-
rigan, “Albedo, atmospheric solar absorption and heating rate
measurements with stacked uavs,” Quarterly Journal of the Royal
and E. W. Frew, “The tempest unmanned aircraft system for in
situ observations of tornadic supercells: Design and vortex2 flight
results,” Journal of Field Robotics, vol. 28, no. 4, pp. 461–483,
2011.
river navigation using the hamilton-jacobi framework for un-
deractuated vehicles,” in IEEE Conference on Robotics and
[12] R. N. Smith, Y. Chao, P. P. Li, D. A. Caron, B. H. Jones,
and G. S. Sukhatme, “Planning and implementing trajectories for autonomous underwater vehicles to track
evolving ocean processes based on predictions from a regional ocean model,” International Journal of Robotics
http://crses.usc.edu/cgi-bin/print_pub_details.pl?pubid=646
http://uas.noaa.gov/
[14] G. J. Holland, P. J. Webster, J. A. Curry, G. Tyrell, D. Gauntlett,
G. Brett, J. Becker, R. Hoag, and W. Vaglienti, “The aerosonde
robotic aircraft: A new paradigm for environmental observa-
tions,” Bulletin of the American Meteorological Society, vol. 82,
of aerosondes in the arctic,” Bulletin of the American Metroe-
[16] R. J. Blakeslee, D. Mach, M. D. Desch, R. A. Goldberg, W. M.
Farrell, and J. G. Houser, “The altus cumulus electrification study
ACES): A uav-based science demonstration,” in 1st Technical
Conf. and Workshop on Unmanned Aerospace Vehicles, Systems,
[18] Office of the Federal Coordinator for Meteorological Services
and Supporting Research, National Severe Local Storms