The NCAR / EOL Community Workshop on Unmanned Aircraft Systems for Atmospheric Research

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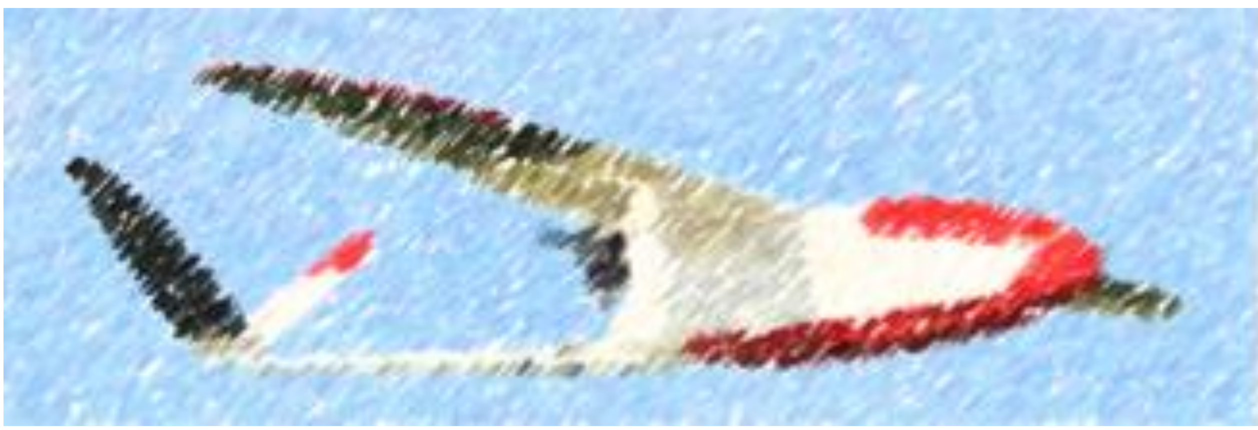
FINAL REPORT



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1 Executive Summary

The NCAR / EOL Community Workshop on Unmanned Aircraft Systems for Atmospheric Research was held from 21 to 24 February 2017 to collect information about the needs of the NSF funded research community in using Unmanned Aircraft Systems (UAS) for atmospheric research and to identify areas in which dedicated support may be most beneficial in fostering the use of UAS in atmospheric science. The workshop brought together over 100 scientists, engineers, and program officers from federal funding agencies to discuss four aspects of UAS in atmospheric research: science, operations, platforms, and instrumentation. Workshop recommendations emphasize the need for wide-ranging community support and address topics such as expert teams and workshops, community platforms, dedicated instrumentation and platform validation opportunities, weather forecasting and support in working within the aviation regulatory framework.

2 Introduction

The use of Unmanned Aircraft Systems (UAS) for atmospheric research has been expanding at a rapid pace for more than a decade, and they have become a popular platform for atmospheric in situ observations. Numerous research studies are being published using observations from UAS platforms, and many of these observations could not have been taken using other airborne platforms. To list just a few examples: The study by Ramanathan et al. (2007) used three well-coordinated fixed-wing UASs to directly measure the effect of pollution coming off the Indian subcontinent on solar atmospheric heating over the Indian Ocean. Reineman et al. (2016) used a long duration shipborne UAS to characterize the marine atmospheric boundary layer well beyond what is normally possible with shipborne measurements. Xi et al. (2016) characterized volcanic SO_2 emissions by in situ measurements inside the plume of Turrialba volcano, Costa Rica. None of these studies would have been easily accomplished with more established techniques. Due to significant advances in UAS for other purposes, the use of these platforms in atmospheric research is expected to continue to grow rapidly as well.

This emerging community is in need for more coordinating activities. Currently, only one dedicated annual conference exists for UAS in atmospheric research (ISARRA: International Society for Atmospheric Research using Remotely piloted Aircraft). A significant number of universities have UAS programs in a variety of research departments. NOAA and NASA each have a dedicated and established UAS program with some parts focused on atmospheric research. The US Department of Energy Atmospheric Radiation Measurements (ARM) program is rebuilding its UAS program and recently acquired a UAS. NSF supports basic research using UAS as well as various engineering developments.

NCAR has a long tradition of conducting and supporting observational atmospheric science research. The mission of NCAR's Earth Observing Laboratory (EOL) is to develop and deploy observing facilities and to provide the expertise and data services needed to advance scientific understanding of the Earth System. EOL manages and operates the largest portion of the National Science Foundation (NSF) Lower Atmosphere Observing Facilities (LAOF) and deploys these instruments primarily in support of NSF-funded observational field campaigns. EOL's airborne program provides unique manned research aircraft and airborne measurement capabilities that address a wide spectrum of needs of the atmospheric research community. Furthermore, EOL has extensive experience in remote and *in situ* sensing technologies, both ground based as well as airborne, and has unique manufacturing capabilities for supporting atmospheric sensing technologies. While NCAR-developed sensors and instruments are already flown on UAS, providing high quality airborne observations, NCAR does not currently support UAS based research directly. The need clearly existed for EOL to evaluate how its mission can include a UAS component and in what ways EOL could support new possibilities the UAS-based atmospheric research may provide.

In the summer of 2016, and as part of the pre-workshop activities, EOL distributed a survey to the larger NSF research community regarding the needs for UAS-based atmospheric research. The results of this survey are given in Appendix 2. The survey collected input from the general UAS community and considered any class of UAS platforms. Not surprisingly, the survey indicated that unmet needs exist within the broader UAS community. Given the complexity of UAS-based observations, access to fully equipped platforms was seen as beneficial, even though there was no clear indication as to which platform or platforms would be most appropriate. Sensor development, calibration, and validation were also seen as highly beneficial. The regulatory framework remains a challenge for UAS-based atmospheric research and the current user community seems to be divided between those who can manage the regulatory framework well and those who find it daunting.

Following the survey, EOL organized the NCAR/EOL Community Workshop on Unmanned Aircraft Systems for Atmospheric Research, to allow an active dialog between the UAS research community, operators, and those developing UAS capabilities. The goals of this workshop were to gather input from active UAS researchers, including key national and international experts, as well as the scientific community at large on highest priority needs in atmospheric and atmosphere interface research that may be uniquely met by UAS.

The workshop was held from 21 to 24 February 2017 over two full and two half days at the NCAR Center Green Facility in Boulder, CO. It brought together 108 scientists, engineers, and program officers from federal funding agencies. The workshop included experts from all areas of atmospheric research, both those actively using UAS as well as those currently not involved but interested in UAS-based atmospheric research. Included in these numbers are 17 students, who were invited to get a broad representation of current and emerging scientists, their interests, and inchoate UAS technologies. In total, 55 institutions were represented including all major U.S. federal research agencies as well as some commercial enterprises.

The discussions during the workshop are summarized in the following chapter, followed by a synthesis of the community needs and recommendations expressed by the participants to support this developing community.

Throughout this report, we use the acronym UAS for Unmanned Aircraft System, instead of the terms Unmanned Aerial Vehicle (UAV), drone, or remotely piloted aircraft, which are also in widespread use. The acronym UAS better expresses that, in addition to the airborne platform, the ground control station and the telemetry link are important components of this system. All components are essential for safe operation of a UAS and for the achievement of the mission’s science goals.

3 Workshop Organization and Discussions

The workshop focused on four topics: i) UAS science, ii) UAS operations, iii) UAS platforms, and iv) UAS instruments. The complete agenda of the Workshop is provided in Appendix 1.

UASs provide a new platform for atmospheric research, which are viewed as complimentary to existing national airborne research programs, but not a purpose in themselves. Atmospheric research using UAS should be driven by science questions. Therefore, the opening topic for the workshop focused on UAS-based atmospheric science. Working within the regulatory environment is a challenge for UAS at present and all UAS operators must be cognizant of the framework defined by the Federal Aviation Administration (FAA) and other regulating government bodies. Technical aspects including instruments, payload integration, and UAS platforms were discussed in detail during the workshop.

Each topic was introduced by keynote speakers, who were asked to prepare and submit white papers on their topics ahead of the workshop. Those white papers are provided in Appendices 3-6. The four topics were subsequently discussed in parallel breakout groups, giving all participants an opportunity to discuss all topics. Science, instruments, and platforms were discussed in two separate breakout sessions each, and UAS operations were discussed in one breakout session. Each breakout session was summarized by a small group of rapporteurs and discussed in plenary. All participants, broken in four parallel groups, contributed to the discussions on all topics. This was done deliberately as these four topics of the UAS-based research are inter-related to a very large degree. In this report, we group results and discussions by the four overarching topics to help the reader.

Although the workshop had not scheduled a formal poster session, a number of participants brought posters, which were displayed for the duration of the workshop. Several participants also displayed airframes and some of the instrumentation they are using. These displays helped stimulate numerous side discussions, which are not necessarily captured in this report.

3.1 UAS for Atmospheric Science

Atmospheric observations using manned aircraft, balloons, and kites have a century-long history; UAS based observations are only two decades old. An important challenge for the UAS community is to understand for what class of problems UASs may be the best means of collecting observations and what type of UAS platform may be most suitable for a given scientific question.

Observations using UAS in the free troposphere and above were not seen as a high priority, especially in terms of developing new capabilities beyond the existing ones. While large UASs, which are capable of reaching the upper troposphere and even lower stratosphere, are viewed to play an important role and enable the community to address important scientific issues, a large majority of key unanswered science questions was found to relate to the lower parts of the atmosphere, the atmospheric boundary layer, and the interface between atmosphere and land, oceans, and ice. The opinions expressed at the current workshop thus confirm what was already stated by the participants of the 2012 NCAR/EOL Lower Atmospheric Observing Facilities workshop titled “Meeting the Challenges of the Climate System Science” (Smith, 2013). The report from that workshop identified UASs as a new tool to study the interface between the atmosphere and solid earth, oceans, and the cryosphere, and these platforms were viewed as an important new approach to survey regions over a few tens or hundreds of kilometers with miniaturized instruments, possibly deployed from land, shore, ice floe and ship.

The UAS Workshop discussions included all types of UAS, including rotary-wing and fixed-wing platforms at a variety of sizes. Due to their special nature, larger UAS systems such as the NASA Global Hawk and NASA Ikhana did not receive much attention in the science discussions. Larger UAS systems are expensive to operate, carry a significant logistical and regulatory overhead, and are operated by very few research institutions. Therefore, a focus on smaller UAS is inherent in discussions within the larger atmospheric research community and not reflective of the value of these large systems.

Developing UASs for atmospheric research should be driven by scientific questions. This means that the development of sensors, platforms, their integration and deployment should use specifications that have been determined to address particular research questions. The specifications include measurement accuracy, spatial resolution, temporal resolution, duration, location, ability to fly in hazardous weather, etc. In reality, there is great value in utilizing UAS in ways for which they were not initially designed. The use of UASs is currently expanding at a rapid pace for many commercial applications: for surveillance, infrastructure inspection, and other terrestrial branches of science to name a few. Many businesses and universities are developing UAS technologies without atmospheric research in mind, which creates opportunities for new systems to be used in creative ways that may not have been conceived otherwise.

One important role for UAS is filling gaps within the existing observing system. The idea is to augment and infill current gaps to address outstanding observational needs without duplicating measurements or capabilities readily satisfied by existing platforms.

3.1.1 Making measurements where other platforms cannot

One of the frequently discussed roles for UAS-based atmospheric science is to make measurements in difficult, dangerous, and/or remote locations, the so-called 'dirty, dull, dangerous' mission. There are also opportunities to fill in gaps in current measurement capabilities, including regions of the atmosphere between towers and the typical flight levels of piloted aircraft, as well as enhancing spatial and temporal resolution.

While it was generally agreed that UAS could fill gaps that are too dangerous for manned flight, it was recognized that there are serious issues that need to be considered. Most UAS do not have the same capabilities as manned aircraft. There are also factors that act to increase the price of suitable UAS systems. These factors include UAS platforms powerful and robust enough to be capable of flying reliably in adverse weather conditions and instruments of sufficient quality to make research-quality measurements. Currently, few UAS can operate in icing conditions and many have problems in high wind conditions; however, they may safely fly closer to the ground or forest canopies than most manned aircraft. As the operational cost of the systems and the logistical overhead in working with the regulatory agencies increase, the disincentive for flying in risky areas also increases. Therefore, there is a need to determine what level of risk is acceptable and how to assess the risk to benefit ratio of missions accurately.

For some dangerous missions, expendable UAS systems may be developed. UAS could also serve to deliver expendable measurement systems, for example dropsondes and Lagrangian drifters. The Coyote expendable UAS for the study of tropical cyclones serves as an example in which UAS are launched from a manned aircraft and flown inside hurricanes until they are lost in the ocean. The cost of these UAS is high, but so may be the scientific value of the observations. So far, these expendable UASs can only be flown over oceans in hurricane environments, since here the risk for persons and property is minimal. It may be difficult to obtain regulatory permission for non-recovered UAS in most other situations; however, such operations will benefit from advances in UAS technology driven by the commercial sector.

Examples of 'dirty, dull and dangerous' environments with the potential for important contributions from UAS include:

- Polar regions
- Fire weather
- Hurricanes, particularly near the sea surface
- Volcanoes
- Thunderstorm environments
- Icing conditions
- Boundary layer, especially near ocean/land surface and in complex terrain
- Forest canopies
- Urban areas

This list of topics is neither complete nor exhaustive, but illustrates the potential that UAS observations may have to add to the existing measurement capabilities.

There are few *in situ* observations that cover the region between surface- and tower-based *in situ* measurements and measurements from manned aircraft. Balloon soundings, dropsondes and tethered balloons, as well as remote sensing techniques, such as radar, lidar, and radiometry, can partially fill these gaps. A need remains for reliable in situ measurements to fill this gap spatially as well as temporally for both research and operational missions. Small UAS platforms may be able to fill some of these gaps. UASs may even be able to expand the spatial coverage of in situ measurements that surface observations and towers cannot cover and may explore interface regimes such as trees and tree canopies, which are very difficult to sample. UASs may therefore provide more spatial information, which in turn may be more representative for small model grid boxes than single point measurements.

Some development projects are designed to operate UAS systems in an autonomous or semi-autonomous fashion for weather and climate monitoring, such as using rotary-wing aircraft to profile the PBL with higher spatial and temporal resolution than currently available by radiosoundings. Developments are underway to build an automated system in which a rotary-wing UAS flies a vertical profile, returns to a base to recharge the batteries, and repeats this program at pre-determined intervals autonomously. These types of observations may substantially contribute to research and operational measurements.

Rapid response measurements may be needed when severe events are imminent or have already occurred. These types of observations may be needed in response to fires, volcanic eruptions, and accidents involving the dispersion of hazardous materials, but also if severe weather events such as tornadoes are expected. Rapid response may mean time periods of hours to several days. UAS can be made flight-ready in a relatively short time and may be transported easily to areas where they are desired. Such observations may provide data needed to estimate the dispersion of pollutants, but also to study the internal chemistry and composition of plumes, or how fires may change their character in response to the changing meteorology. In these missions, safety remains the foremost concern, since the UAS operations must be well coordinated with emergency responders, but also since some events, such as volcanic bombs in a volcanic eruption, may pose a threat to the UAS itself and its ground crew.

The simultaneous operation of multiple UAS has the potential to provide a wider spatial coverage than what can be achieved with a single UAS platform. Stacked UAS flights, in which UAS fly in formation at different altitudes, have already been successfully carried out. Developments are ongoing for users to operate autonomous swarms of UAS, where multiple UAS fly semi-autonomously and in a coordinated manner to accomplish the measurement goals. Although not currently in existence, autonomous UAS swarms could be programmed to look for particular atmospheric conditions in which each UAS within the swarm would have a particular mission that is communicated to nearby UAS and the ground control. This strategy would facilitate deploying a larger number of UAS at one time than would otherwise be possible. However, the effect of other UAS on the measurements must be considered if the number of simultaneous UAS in the air becomes significant. The operation of multiple UAS must also accommodate potentially significant regulatory, logistical and operational cost constraints.

3.1.2 Obtaining measurements in remote and data void regions

Remote regions (deserts, oceans, polar regions), which cover most of our planet, as well as many of the developing countries, which are home to the majority of the world’s population, are historically lacking in data coverage. UAS platforms may be well suited for collecting observations in these regions. Successful missions from ships and in the Arctic have already demonstrated the potential for UAS to collect observations in remote regions. Filling in observations in these remote, under-sampled regions may have potential to improve the understanding of weather and climate in these regions and beyond.

The versatility and variety of operational modes that UASs possess lend them to remote operations. For example, small fixed- and rotary-wing UAS do not need an airfield to operate. Ship-based UAS operations have already been demonstrated using hand-launched or track-launched UAS with recovery into a net or by hooking a wire.

3.1.3 Atmospheric science topics suited to UAS

Many atmospheric science topics may see significant progress with UAS-based measurements. The collection shown below was compiled with little regard to the availability of sensors or the ability of platforms. By no means is this list exhaustive. Rather, it illustrates the variety of research areas that may benefit from UAS based observations.

- Boundary-layer meteorology
- Complex terrain studies
- Canopy flux measurements
- Air quality and emission plumes
- Radiation and radiation profiles
- Severe thunderstorms
- Tropical cyclones
- Wave propagation
- Ocean/atmosphere interface
- Sea ice
- Wind power
- Cloud physics
- Trace gases and chemistry
- Active chemistry of short lived compounds in the boundary layer, in particular over oceans
- Bio toxins and hazard chemical location and source localization
- Fire weather and dynamics, hot spot determination
- Volcanic emissions and eruptions
- Urban meteorology
- Validation of remote sensing
- Validation of model subgrid-scale parameterization schemes
- Particle formation over the ocean surface
- Microphysics of particles in deep convection

Researchers have already demonstrated value and utility of UAS for several of the above disciplines, including boundary layer, severe thunderstorms, wave propagation and tropical cyclones. Other disciplines have nascent UAS efforts that are in need of instrument advances and miniaturization in order to advance further. These include cloud physics, trace gases, and chemistry. All disciplines currently struggle with limitations stemming from the regulatory environment. Some areas that may benefit from UAS research, for example urban meteorology, are not feasible within the current regulatory environment. As agencies progress with the integration of UAS operations into the national airspace system, the regulatory environment continues to evolve and technologies supporting safe operations (e.g. detect-and-avoid technologies) advance.

3.1.4 Improved flight performance

The physical limitations of many UASs themselves pose significant challenges for several of the above listed research areas. This includes endurance, which is more of an issue for rotary-wing UAS than for fixed-wing, ability to lift the available sensing technology, and ability to withstand severe weather. Studies of severe weather are of great interest; at the same time, severe weather strongly influences the flight performance. Strong winds may limit the range a UAS can cover, and in extreme cases may prevent a UAS from returning to the take-off location. Precipitation may affect the UAS electronics and complicates operations, but most importantly reduces the visual line-of-sight. No small UAS and only few large UAS are equipped with icing protection devices. Therefore, icing conditions are an immediate threat to the platform and must be avoided to the extent possible. Mitigating the risks posed by severe and sometimes fast changing weather conditions that can exceed the flight capabilities of UAS is of high priority but challenging due to the limited available power and weight for the operation of the platform.

3.2 UAS Operations

A detailed understanding and appreciation of the operational environment for UAS activities was one of the important goals of the workshop. Atmospheric measurements using UAS must be conducted in a safe manner and must assure that no harm to persons and/or property occurs in the air or on the ground. Focus was given to the operations of small to mid-sized UAS in atmospheric research, although the underlying principles apply to all airborne operations. A challenge is the ability to address high priority needs in atmospheric and related research while operating within FAA, state, and local agency regulations.

The white paper on UAS operations (Appendix 4) provides an excellent summary of the issues and includes a long list of references for rules, procedures, related web sites and articles that provide details on UAS operations in the U.S.

The regulatory and policy landscape for civil UAS operations has changed rapidly over the past five years and continues to change as UAS become ubiquitous. The 29 August 2016 publication of the Rule for Non-Hobbyist Small Unmanned Aircraft Operations, Part 107 of the Federal Aviation Regulations, Title 14 of the Code of Federal Regulations, was the first rule resulting from the many congressional mandates of the FAA Modernization and Reform Act (FMRA) of 2012. One of the important outcomes of these changes was to recognize that regulations and flight procedures by small to mid-size UAS operators are not the same as those used for large UAS (e.g. Global Hawk) or for model airplanes.

The detect-and-avoid rule in the General Operating Rules of FAR Part 91 presents the greatest challenge for the operation of UAS in the National Airspace System (NAS). In lieu of a certified detect-and-avoid system, a UAS can only fly in the airspace regulated by the FAA with special provisions that compensate for the inability of the system to satisfy the Part 91 requirement from an airborne unmanned aircraft. This might include a visual observer (VO) in a chase plane, or a ground-based VO who can provide the visual function required to satisfy the detect-and-avoid rule. An immediate consequence of Part 107 was to eliminate the need for most FMRA Section-333 exemptions for small UAS (sUAS) operations below 400 ft (122 m), making it somewhat easier to operate below this altitude. However, this level remains a large operational hindrance.

The procedures and restrictions explicitly stated or implied in the regulations governing UAS activities are the single biggest constraint to UAS operations. It is essential that UAS operators understand the regulations and their implementation. A key part of a successful campaign (and the permission to operate) is to develop a CONcept of OPerationS (CONOPS) plan, clearly state objectives, identify risks, and identify procedural steps to mitigate those risks. Developing the best approach for taking UAS deployment requests to the FAA is critical. A community best-practices approach may be considered where common responses to address safety concerns, explanation of operational approaches, flight operations safety, as well as risk and risk mitigation are developed and shared.

Competency of the aircraft operators is fundamental in working with the FAA. For new institutions entering the UAS world, this will mean a long process of building and demonstrating expertise. This is generally a slow and drawn out process, which starts with small steps. As the institution gains experience, successfully demonstrates that it can operate UAS within the regulations and at the same time achieve the mission goals, it will increase its ability to build a safety case for more challenging missions, which may require waivers. It is generally advantageous to have a single point of contact for the discussions between the institution and the FAA. In more challenging missions, a single point of contact within the FAA will further help in the design and execution of the mission plan. Currently the best approach for new institutions is to cooperate with other institutions that already have high levels of competency and established trust with the FAA.

Working with the FAA can be a lengthy process and will require substantial resources, as rules, under which UAS can be operated, are likely to evolve further. There is clearly room for interpretation of the regulations and staying informed about the current regulatory environment is essential. Close communication with the FAA is an important part of the process to obtain permissions.

NASA, NOAA, DOE, the Air Force, and other government agencies have UAS programs and work with the FAA on regulatory issues, their implementation as well as their future adaptation to the needs of the UAS community. There is a great need for the atmospheric research community as a whole to coordinate with these agencies to be more effective in the implementation and adaptation of regulations.

Many of these regulatory issues have been resolved for manned aircraft. For applications where manned aircraft are an option, it may be preferable and cheaper to use manned aircraft.

3.2.1 FAA Centers of Excellence for UAS Research

To provide airspace where the integration of UAS into the NAS can be developed, the FAA has defined seven UAS test sites (University of Alaska Fairbanks, State of Nevada, New Mexico State University, Griffiss International Airport (NY), North Dakota Department of Commerce, Texas A&M University Corpus Christi, and Virginia Polytechnic Institute & State University), and created the Center of Excellence for Unmanned Aircraft Systems, Alliance for System Safety of UAS through Research Excellence (ASSURE). The partner organizations combine expertise and infrastructure to address challenges for the integration of UAS into the NAS. The activities are in the areas of UAS Air Traffic integration, the implications of improved UAS airworthiness, aircraft control and communication, detect-and-avoid approaches, human factor implications for UAS pilots, low-altitude operations, safety and pilot training, and certification practices. A key component of ASSURE is the participation of more than 70 industry partners across the US, Europe, Asia, and South America.

3.2.2 Weather information

All UAS operators must consider how weather affects flight operations. It is often the case that weather interferes with planned flight operations (e.g. winds, clouds, or visibility). UAS specific weather forecasts and briefings prior to flight operations are critical to address risk and safety concerns. Currently, the FAA only mandates that UAS operators be informed about operating conditions and potential hazards, without prescribing how this information is obtained. Providing complete and timely weather data to the UAS pilots and crew before and during flight operations is essential.

3.2.3 Beyond visual line-of-sight

The requirement to keep UASs in sight with unaided vision severely limits many interesting applications of sUAS for the science community as well as commercial groups. Operations beyond visual line-of-sight (BVLOS) are complex and issues are wide-ranging, including meeting existing government regulations, public privacy, certification of reliable BVLOS guidance/avoidance systems, and developing viable related operations procedures (e.g. sUAS separation standards, special science observations exceptions). The transition to BVLOS operations is non-trivial. Building a safety case and an effective concept of operations is the key. Components include detect-and-avoid (aircraft and obstacles), airframe certification, communication and data links, mitigation of risks, and communication between observer (radar observer or other) and pilot in command. In certain cases, the extended operations add to the mass and power requirements for additional detect-and-avoid hardware and additional telemetry systems. In most cases, these operations will have a lower telemetry bandwidth available, which must be taken into account during the missions planning.

Several specific UAS flight profiles are only possible if restrictions can be overcome, such as long-duration flights, ship-based operations, and long distance overwater flights from shore. A solution may be possible based on evolving commercial applications requiring overcoming the current BVLOS constraints. This includes remote delivery (Amazon and Google), infrastructure inspection profiles (BNSF Railway), visual line-of-sight operations over people (CNN), or extended visual line-of-sight operations in rural areas. Work within the ASSURE consortium may pave the way for atmospheric UAS operators. One opportunity for collaboration between the atmospheric research community and industry lies in the need for atmospheric awareness in commercial UAS operations. Thus, there is an opportunity to equip a large number of UAS with sensors for atmospheric measurements.

3.2.4 Operations over people

Operations over people in urban/suburban environments require the UAS community to demonstrate safe operation as well as to gain trust from the public to operate in populated areas. Privacy may be the single biggest challenge to making scientific measurements over urban areas. Since cameras are often used on the sUAS for flight profile management, the public needs to be convinced that those cameras will not be pointed into someone's backyard or through a window into a home. The payoff will be addressing science questions related to urban heat island meteorology and pollution. Again, the way forward should include collaboration with industry as they develop UAS-based package delivery capabilities. The workshop attendees noted some possibilities to overcome these constraints including the use of small platforms, restricting flight paths to streets/sidewalks, avoiding private space, and developing strategies for flying in 'urban canyons' as opposed to residential neighborhoods. The sUAS community should work with news media and industry, which are already using UAS in this environment.

3.2.5 Night time operations

Nighttime operations of UAS are severely affected by regulations and the need to maintain visual line-of-sight with a 3-mile minimum visibility. As a result, most UAS operations are limited to daylight hours. It will be a challenge to overcome the perceived risk of nighttime operations versus daytime operations, although some operations have been possible using lighted beacons, strobes, and landing lights on the UAS platform. The FAA may be willing to issue waivers for night operations on a case-by-case basis, such as monitoring the nighttime behavior of an active wildland fire.

3.2.6 Multiple UAS operations

In addition to technical challenges, operations using multiple UAS simultaneously need to overcome regulatory challenges such as the need for multiple observers, pilot back-up, airspace access, or blocked airspace. Even with enough staff (especially a sufficient number of pilots), extended multiple UAS flight operations may be challenging. Some operations with multiple UAS have already been successfully conducted, requiring significant staff to operate and monitor all UAS. The University of Colorado did receive permission to operate within a Certificate of Authorization (COA) but had to have separate pilots and spotters for each of the sUAS. The University of Oklahoma, Oklahoma State University, Scripps Institution of Oceanography, and the French National Center for Atmospheric Research (CNRS) have conducted similar activities within a restricted airspace.

3.2.7 Autonomous/automatic operations

Some specific UAS technical components are being improved to help platform reliability and improve safety. Automatic operations are most common and use technology where the pilot in command is always in control of the aircraft. However, developments are moving towards autonomous operations, where the aircraft is to some level cognizant of the environment and acts without input from the pilot in command. This will be particularly important for operations of multiple UAS at the same time. Many technical and regulatory hurdles still exist that need to be overcome. Autonomous operations are highly desired for commercial operations, and industry is heavily involved in the design of autonomous UAS, which can be safely integrated in the NAS. Detect-and-avoid systems that are implemented in the autonomous UAS are essential as well as some level of geofencing, which assures that the UAS will not leave the permitted airspace. Automatic Dependent Surveillance-Broadcast (ADS-B) systems, which are currently implemented in general aviation, provide a technological basis for UAS to be aware of other aircraft. Real-time weather information, which may limit the operation of autonomous UAS, will play another central part in the design of autonomous systems.

3.2.8 Improvement of hardware/technical capabilities

An additional step towards safe operations is to develop standard procedures for the conduct of autonomous take-off and landings. This could include development of an approach control routine that includes a "two-pass" landing protocol where the landing strip is first surveyed before touch down can proceed. Another aspect of landings is to implement, where possible, a standard emergency and/or a forced landing protocol.

There are so many different UAS platform and autonomous navigation system manufacturers that it is likely that different platform construction and software standards are used. It may be possible for the community to work together to develop guidelines or even standards to help improve reliability and UAS safety. The community should consider the collection of flight operations statistics to see if there are common challenges that could be addressed with a technical solution. They include ground impact studies, the examination of mitigating technologies such as parachutes, developing risk assessment and mitigation strategies and providing training for operators to better identify and mitigate risk during flight operations.

3.2.9 Pilot training

With the need for expertise in the operation of UAS comes the need for developing and maintaining a qualified pool of UAS pilots for the increasing UAS activities. Most pilots operating a small UAS for non-recreational purposes must either hold a FAA Part 107 Remote Pilot Certificate with a Small UAS Rating or be under the direct supervision of a person who does hold a Remote Pilot Certificate (the remote Pilot in Command). Some colleges and universities already offer UAS pilot training programs. It is important that pilot have been trained on the specific platform to help ensure safety in operations.

Currently there is only limited support for active pilots such as provision of preflight weather brief, and 'nowcast' updates during changing conditions. Operational considerations should include planning for alternate landing sites and chase vehicles if visibility is expected to be limited.

3.3 UAS Platforms

The capabilities for UAS platforms available for use in atmospheric research vary in terms of size, maximum altitude, endurance, speed, payload capacity, and method of flight. A platform is often chosen based on factors such as cost, ease-of-use, logistics, or regulations, and not necessarily by which platform is best for answering the science question or for carrying the ideal payload. Researchers face the problem of finding a platform that meets their science needs while working within all other constraints. Closely tied to the platform and its flight-characteristics are the software (autopilot and navigation system) to operate the UAS, the data acquisition and data storage, as well as telemetry and communication needs between ground control and the airborne platform and instrumentation onboard.

3.3.1 Current platforms

UAS platforms fall into one of two categories: fixed wing and rotary wing, each with their own pros and cons, which are summarized in Table 1. Fixed-wing UAS offer longer endurance and larger payloads but require more training. Rotary-wing aircraft are generally easier to fly and may be less expensive but generally allow only shorter missions and smaller payloads. While multi-rotors are the predominant form of rotary wing at small scales, as the platforms get larger helicopters (single rotor) become dominant. An example for each category is shown in Figure 1. Systems are under development that offer the advantages of both, i.e. the endurance of fixed-wing and the vertical take-off and landing capability of rotary-wing platforms.

	Fixed Wing	Rotary Wing
Benefits	Longer endurance Higher altitudes available Flights in higher winds Larger payload/platform ratio Instrumentation from manned aircraft more easily adapted Less flow distortion for inlets and certain sensors	Easier to fly/control Maybe better for pictures/imaging Vertical take-off and landing
Drawbacks	Requires a greater operational learning curve Requires more airspace to operate (especially take-off and landing) May require chase vehicle to maintain visual line-of-sight	Shorter endurance Some measurements more difficult (especially wind, clouds, aerosols) Lower altitude capability

Table 1: *UAS categories*

Figure 1: *Example of a fixed-wing aircraft (University of Colorado, UASUSA Tempest, left) and a rotary-wing aircraft (NOAA, DJI S-1000, right).*

For regulatory purposes, classes of UAS are defined by take-off weight with thresholds at 25 kg (55 lb), 150 kg (330 lb), and 600 kg (1320 lb). According to FAA and NASA, small UAS (sUAS, Category I for NASA) have less than 55 lb and a maximum speed of 87 knots. These are generally limited to altitudes below 400 ft AGL. Currently, the FAA does not specify any difference in classes above 55 lb. NASA considers uses a Category II for UAS between 55 lb and 330 lb and speeds slower than 200 kt, as well as a Category III for UAS over 330 lb and speeds faster than 200 kt. Most UAS within the University research community fall in the small UAS category, whereas NASA, NOAA and DOE also operate larger UAS including Global Hawk.

Table 2 lists examples of UASs currently used by government agencies and universities for atmospheric research. Costs are not included but increase with size of the platform. The maximum payload weight is often a compromise between payload measurement capacity and flight endurance. A noticeable gap is evident in payload weights with most UAS either carrying very small or very large packages. Platforms that may carry payloads in this gap generally cannot get them very high or lack endurance. However, with few exceptions, this type of capability may be better filled with manned aircraft, leaving studies at low altitude using smaller payloads and high-altitude long-endurance type missions (i.e., Global Hawk) on the other extreme to UAS.

Name	Max Altitude (ft)	Max flight duration (hr)	UAS Max Takeoff Weight (lb)	Max payload (lb)
Tempest	400	1.5	18	7
DragonEye	500	1	6	1
IonTiger	1000	48	37	5
SIERRA	12,000	10	400	100
TigerShark	15,000	10	500	100
ScanEagle	19,500	24	40	7
Viking 400	25,000	11	420	100
Predator B	45,000	20	6500	800
Global Hawk	65,000	26	29,000	3000

Table 2: *List of some select UAS platforms used by government agencies and universities for atmospheric research.*

Typical total payload weights are in the range of 10 to 15% of the gross weight and may be as low as a few percent and as high as 30 percent, depending on the fuel system, weight class and endurance of the UAS. Cost and complexity scale with size with large systems generally costing much more and being very complex to operate (both from a training and regulatory perspective). An example of this is the NASA Global Hawk, which can carry 2000 lb of payload but is very expensive and takes a large crew to operate. It also has strict rules that must be followed especially for flights over land.

3.3.2 Platform selection

Three main factors go into the selection of platforms for scientific studies: altitude/endurance, payload requirements, and cost. One challenge for researchers is to match these factors with the scientific observation needs.

Altitude and endurance determine the types of studies that can be undertaken. Three categories of platforms are generally distinguished:

High Altitude, Long Endurance (HALE): These platforms are designed to fly high (above 50,000 ft.) and for an extended duration (longer than 12 hours). These are always BVLOS and have sufficient power for large, complex payloads. Some uses for HALE UASs are synoptic scale, air chemistry, upper troposphere/lower stratosphere, tropical, and climate related studies. Except for take-off and landing, these UAS can avoid most severe weather events affecting flight operations.

Medium Altitude, Long Endurance (MALE): These platforms are designed for tropospheric operations with similar endurance, but lower service ceiling than HALE UASs. Uses for these types of UASs include cloud/aerosol interactions, air quality, and mesoscale processes. MALE UASs are the least utilized of the three categories, at least in the atmospheric research community. These UASs may be able to operate throughout their vertical range and are capable of lower altitude, long endurance missions. They rely on enhanced situational awareness for the remote pilots and need to avoid most icing conditions and other severe weather phenomena.

Small UAS, both fixed-wing and rotary-wing, have an endurance of typically less than 4 hours. This type is most widespread due to ease of operation and lower cost and is mainly used for studying boundary layer processes. Other uses include hazardous environments and high-resolution measurements through the ability to fly multiple platforms simultaneously. The small UAS category contains some noteworthy exceptions, such as the Aerosonde and the ScanEagle, which have achieved flights of more than 24 hours.

The cost of the system must take into the account the cost of the UAS platform itself, the science payload, and the ground support. An autopilot system, which provides accurate mapping of regions and more control, will contribute to the cost. Finally, the level of telemetry needed adds costs. If data needs to be sent back to a home station, the cost may increase in proportion to the amount and type of data that needs to be transmitted.

Icing conditions are a major limitation for all UASs. Currently, little deicing technology exists for UASs due to the power requirements and the high aerodynamic efficiency of most platforms. Few if any UASs are capable of handling more than light icing conditions. This limits the temperature and humidity regime that can be studied by UAS, but also the weather conditions during take-off and landing as well as during flight for long duration operations. Mixed phase cloud studies and flights in strong convection pose a much greater risk for UAS and may not be possible.

UASs may not always be the best solution. They cannot necessarily go to where manned aircraft are unable to and often come with significant cost and regulatory hurdles. Manned aircraft can almost always collect more types of data and have well known instruments with high data quality. In general, if a manned aircraft can do what is needed to collect the necessary scientific dataset, it should be used over a UAS. However, large strides are being made in UAS platform development and those platforms will continue to improve and close the gap with manned aircraft.

Only a few platforms exist that can carry larger payloads and at the same time are capable of operating at low altitudes. These platforms are typically outside the affordability of most universities. Since many research interests lie in the boundary layer and its lowest part, a need remains for a larger UAS platform, capable of carrying a substantially larger payload than most sUAS. Such platform could utilize a modular payload concept to allow a larger spectrum of instruments to be used, which is very difficult to design for sUAS.

Propulsion systems for UAS may be based on battery driven electric motors or gasoline engines. Most sUAS are electrically driven, limiting endurance and the ability to trade payload for fuel. Gasoline driven systems must be designed such that the exhaust and heat generated by the engines do not negatively affect the measurements. Most rotary-wing aircraft use electric motors; while fixed-wing aircraft may use either system with gasoline engines dominating the larger UAS segment. Some fixed-wing UAS have been developed using fuel cell technology, but they have not yet entered the larger market. Some research is under way to utilize environmental energy (thermals, solar panels) for fixed-wing UAS. This concept requires some level of in-flight awareness and autonomy and faces both technical and regulatory challenges.

All UAS require some level of water resistance to be able to fly in rainy conditions. UAS operating in marine boundary layer environments require some protection for sea salt spray, which is highly corrosive to some materials especially electrical components.

Most of the UAS platforms are developed by commercial companies for other civilian and military uses and are later adapted for atmospheric science by the research institution. Therefore, many of these platforms are not optimized for atmospheric research studies. While this approach reduces the development time and cost for a science platform, it leaves open the question, whether a platform serves all needs of a research group. One notable exception is the Tempest UAS, which was designed specifically for the University of Colorado with atmospheric research in mind.

Smaller systems often have lower cost but are also less reliable. On the other hand, they may be disposable and may be used in the most dangerous environments. Some UAS use parachute systems for landing or as safety measure for operation over people. Some systems have been launched from balloons at greater height up to stratospheric altitudes. This may extend the vertical capabilities of small UAS, but faces very complicated regulatory restrictions. UAS can also be launched from ships either as vertical take-off or along a launch rail. Recovery is often more complex requiring the use of hook-in-wire systems or nets. Authorization to operate UAS over oceans is often less restrictive than over land. Development of easy-to-use ship-borne systems is needed.

A core component of every UAS is the autopilot system, which controls the UAS flight. Autopilot systems vary tremendously between platforms. There is a need to assess the different capabilities of autopilot systems and to evaluate how similar autopilot systems are being used on different platforms. Some systems use differential GPS for heading and wind measurements, but do not provide that information to a possible science payload. The atmospheric science UAS community often uses its own software to operate the UAS and the science payload and developing standards may reduce some of the labor involved. Research is ongoing to include additional information into the flight operation of the UAS, such as the sensed phenomena itself or other ground-based observations. However, these adaptive technologies are only in early stages.

3.4 UAS Instrumentation

Atmospheric measurements, which are taken to address scientific questions, require scientific instruments of sufficient accuracy. Due to the limited payload capabilities, UAS borne instruments often originate from other systems and are adapted to UAS to satisfy the weight and power requirements of the platform and to fit the available space. As with all airborne measurements, the platform itself may lead to artifacts, which need to be well characterized.

Many atmospheric parameters may be measured using UAS. Common among almost all UAS applications is the need to measure the atmospheric state variables pressure, temperature, relative humidity, and winds. Many other parameters may be measured and depend on the specific science question.

UAS-based atmospheric measurements are relatively new and growing at a rapid pace. There is little coordination between the efforts at different research institutions and little standardization to guide development of sensors. Furthermore, calibration of sensors, characterization of their behavior on the airborne platform, and validation against recognized references pose significant challenges for every research group.

The most rapid growth of UAS is in the small category, which is the most common category at universities and other research organizations. Due to the 25 kg (55 lb) takeoff weight limit for small UAS, instrument payloads for small UAS are typically limited to well below 8 kg. Few organizations invest in larger UAS, which allow heavier payloads and longer durations.

3.4.1 Atmospheric parameters

For the measurement of the basic atmospheric state parameters of pressure, temperature, and humidity a large array of sensors is commercially available or may be adapted from other uses such as radiosondes. Temperature and pressure measurements must consider dynamic effects, in which the sensor placement plays a critical role. Relative humidity sensors are largely based on small solid-state sensors, which need to be recalibrated frequently and may critically depend on the local temperature at which they are measuring. Only few instruments exist for small UAS to measure atmospheric trace gases and aerosol properties. There are almost no instruments for cloud properties for small UAS, not only due to the typical instrument size, but also due to the extraordinary regulatory overhead for small UAS to fly inside clouds. Some remote sensing instrumentation for small UAS exists, typically those that measure properties of the surface underneath. Thermal IR radiometers, multispectral and hyperspectral spectrometers, small downward looking lidars and radars have been deployed on small UAS. For most parameters, a need remains to miniaturize the instrumentation. In some cases, it may be possible to use multiple UAS in coordinated flights carrying different sensors, which significantly increases the logistical overhead for these types of measurements.

Wind and turbulence measurements from small UAS are still challenging. In addition to measuring the air speed relative to the UAS, the speed vector of the UAS above ground must be measured with sufficient accuracy. In all UAS, the inertial measurement unit (IMU) combined with autopilot software maneuvers the UAS along the desired flight path. This system measures all of the flight parameters; however, these measurements may not be available to the user due to the proprietary technology of the system, or may not be of sufficient quality for accurate wind measurements. Magnetometers used in these systems are very susceptible to magnetic fields generated by the motors and GPS units may not be sufficiently accurate to provide acceptable wind measurements. Turbulence measurements from rotary-wing platforms are particularly challenging, since the wind probes need to be sufficiently far from the influence of the rotors and still sufficiently fast for turbulence measurements. Some IMU and autopilot systems are subject to ITAR restrictions, affecting international work as well as cooperation with international partners.

Common among all instrumentation is the rapid pace of technological development and lack of coordination between the different research groups. There is a strong need for an overview of UAS sensors available to the research community. For example, the European COST action ES0802 on the use of unmanned aircraft systems (UAS) for atmospheric research has created a database on sensors and platforms. This database has been moved to the International Society for Atmospheric Research using Remotely piloted Aircraft (ISARRA, http://www.isarra.org/?page_id=75). NCAR/EOL has created a database on Facilities for Atmospheric and Earth Science Research for the NSF research community. Neither database has been maintained after their initial inception. A new database is being developed by CLOUD-MAP (http://www.cloud-map.org). To be useful to the community, such a database must be kept current. To increase its usefulness, documentation of quantitative sensor characterization studies, along with usage experience may be included.

There appears to be a lack of standardization of sensors and methods of observation within the emerging sUAS community. While no recognized organization exists that could define such standards, expert groups may be set up in which highly experienced scientists could define recommendations and best practices for UAS sensors and operations. These expert teams may provide guidelines for best placement of sensors on various platforms and discuss uncertainty and response-time goals for existing and emerging sensor technologies. A handbook for new users may be developed, which provides an overview of the current state of technology, recommends best strategies for implementing sensor technology into UAS, and provides guidelines for their operation. These best practices would not only ensure a level of quality of UAS-based measurements, but also assist groups developing and testing UAS systems. Such an expert team may also provide an interface to the classical airborne sciences community, where many of these issues have been addressed for the larger platforms.

3.4.2 Sensor characterization

One of the most important instrumentation needs by the UAS community is the characterization of the measurement uncertainty for the deployed instruments. It is well known for manned research aircraft that the quality of observations depends on a number of factors including calibration, sensor placement on the aircraft, flight maneuvers, environmental conditions and others. In all cases, flight-testing and validation against a recognized reference is needed. In some cases, special flight maneuvers may be needed during each flight. Most UASs do not suffer from large Mach-number effects. However, the generally lower airspeeds of UASs (compared to manned aircraft) may cause other physical effects, such as rotor wash, which can have large effects on the measurements.

The first step with sensor characterization is calibration of the sensor in known environments, usually in laboratory wind tunnels and calibration chambers. Although not all UAS operators have immediate access to these facilities, tunnels and chambers are available at a number of research institutions including NCAR/EOL. In some cases, it may be sufficient to characterize only a few sensors of a particular type and to document these tests for the community. In other cases, each sensor of a particular type must be characterized in the lab individually. A key concern for many sensors is their response time. Some measurements, in particular turbulence and flux measurements, require fast sensors, which can operate in the range of 10 to 20 Hz. The response times are best evaluated under controlled laboratory conditions. Since sensors for different parameters typically have different response times, a detailed understanding of how these differences influence the analysis is a key concern.

The second step is to define locations on the airframe where the expected measurement error is minimal. This process may involve computational fluid dynamics and wind tunnel modeling to identify regions of wakes and internal boundary layers on the aircraft in which the measurements would not be expected to represent free-stream values. Furthermore, the distribution of boundary layers and wakes may strongly depend on flight profiles and flight maneuvers. This means that a particular sensor placement, which may be ideal for most flight situations, may still lead to artifacts in some. Consequently, data would have to be treated with caution during these flight segments. This effort is especially needed for rotorcraft. Some corrections to the basic sensor calibration due to systematic errors caused by the airframe may be needed based on these results. As with the lab calibrations, publication of the airflow over a particular platform would be useful to the entire research community, and could lead to some de facto standardization of platforms.

In addition to confirming airframe modeling results, careful analysis of in-flight tests can identify more subtle issues, such as measurement noise due to RF, electrical noise from the motors, or RF interference from the control and data acquisition electronics. For some measurements, such as wind, many pieces of information need to be combined and some may only be available from the flight control system. Optimizing how this information is combined often requires iteration.

Lastly, UAS measurements need to be validated against an independent set of reference measurements. These could come from a well-characterized "standard" aircraft, which operates at a similar range of airspeeds to allow "wing-to-wing" comparisons, in which individual samples may be compared. In some cases, statistical comparisons may be necessary, assuming that both aircraft are operating with similar flight characteristics.

An ideal validation may use reference sensors on instrumented towers. These would be most effective for regions that are horizontally homogeneous, since flight-path-average statistics would need to be compared against temporal averages on the towers. These comparisons have the advantage that tower based instruments are generally well characterized and may easily be recognized as reference instrumentation, if these towers are well maintained. Other ground-based sensors, such as lidars, radars, and sodars may be used to measure the atmosphere in the region of the UAS flights.

Ideally, such ground-based facilities could be available at the existing FAA-supported UAS test-sites, either continuously or during specific campaigns designed for this purpose. Flight tests should be done in a variety of environments to ensure extensibility of their measurements to real-world conditions. Therefore, validation efforts should be conducted multiple times in varying environments either by repeating a validation effort during a different season or at a different location.

It is vital to document the uncertainty estimates in each of these efforts and to analyze how uncertainty budgets propagate from the basic calibration to the in-flight characterization and the validation against references. Furthermore, the temporal resolution of the sensor needs to be documented with the uncertainties. Scientific analyses are only as good as the uncertainty estimates that support them. Sensor calibration and validation are at the core of this effort.

3.4.3 New sensor developments

The workshop identified several specific sensor needs. Many groups are flying integrated pressure-temperature-humidity (PTH) sensors, sometimes taken from existing radiosondes or adapted from other uses. These sensors may not have been intended for long-term UAS operation. In particular, their calibration may change with time and/or exposure to the atmosphere. The UAS community may benefit from a "standard" PTH package, which would have a stable calibration, be capable of easy, possibly in field, recalibration, and come with recommendations for mounting on a UAS for optimal airflow over/through the sensors.

The UAS community may also benefit from a standard turbulence probe. Such a probe requires fast-response and precise wind velocity measurements. Recovering data from such a probe would likely be somewhat system dependent since components (GPS, accelerometers, etc.) of the UAS navigation system might be used to avoid duplication. Some navigation systems even report wind velocity directly, though these would need to be validated. In the case of turbulence measurements, sensor placement is an even more critical issue than with PTH. Computational fluid dynamic modeling and wind tunnel measurements to characterize the airflow over common UASs would be part of the development of such a probe.

In situ sensors for some trace gases or aerosols would be useful, but do not yet exist in forms deployable on small UAS. A small, low power, fast-response water vapor sensor does not yet exist. Fast laser absorption instruments, cooled-fin dewpoint hygrometers, as well as fast solid-state sensors are possible options. However, none has been developed into a sensor suitable for UAS. Small, accurate chemical sensors for a variety of species are needed, along with sensors to characterize the size, shape, and phase of particles. For some of these measurements, small and low-power sensors are now available, though many suffer from calibration stability and/or large time constants. For some instruments a commercial market may exist, which could be stimulated by funding opportunities, such as Small Business Innovative Research (SBIR) grants.

Finally, several UAS-deployable remote sensing systems are now possible. 3D acoustic-based tomography, high-resolution infrared, visible, microwave, and hyperspectral sensors are needed for a wide variety of applications, such as land cover, soil moisture, and sea ice. However, active remote sensors typically use large amounts of power, adding to the difficulty of operation on small to medium sized UASs. As the number and variety of these sensors increases, it would be helpful to have standards for wavelengths being used as well as data analysis tools, particularly for lidars and Synthetic Aperture Radar.

Due to the very limited available space onboard sUAS, installing a sensor module with its associated electronics and data acquisition system on the airframe poses significant challenges. This issue may be alleviated to some extent by creating standard instrument payloads and sensor bays that may facilitate instrument development as well as ease of deployment. However, the large number of UAS platforms and their rapidly evolving designs creates a serious challenge for standardizing instrument packages.

The sensor developments need to be balanced with the platform that is to be used. Expensive, high value instruments are unlikely to be flown on less reliable platforms and vice versa. While the intent is usually to recover the UAS platform without incident, a safety case is always required that also considers the value of the instrumentation and the platform in the case of unforeseen or disastrous events.

Data acquisition and telemetry systems for sensors onboard the UAS need to be well designed. Ideally, all data are immediately sent to the ground control station; however, this approach often faces technical challenges, such as the required data transmission rates, available telemetry frequencies, telemetry interferences and dropouts and BVLOS operations. Therefore, a well thought out plan has to be defined, which balances the telemetry capabilities and the risk of damage or total loss of the entire airborne platform. Software libraries, toolkits, small data loggers and telemetry standards may help reducing the overhead involved in the data handling of UAS sensors.

There are ideas for instruments directly contributing to the control of the airborne platform and flight planning. In studies for plume tracking or storm tracking, the available telemetry link may be insufficient for a remotely piloted UAS to follow a meteorological phenomenon. Strategies could be implemented on the UAS to follow a particular phenomenon autonomously, which may be even more relevant for BVLOS operations; however, such an approach may have significant safety concerns that must be addressed.

4 Community Needs and Recommendations

The atmospheric science UAS community is relatively young, vibrant, and expanding rapidly. Many of its needs and desires were already discussed or mentioned in the discussions above. Some open needs are based on the experiences of individual researchers, while others were repeated throughout the workshop. Few guidelines exist and duplication of effort is widespread within the community. Some of the needs may already be addressed by other communities, in particular the commercial UAS and aerospace engineering communities. Other issues are unique to the atmospheric sciences UAS community.

In the following, we summarize open issues, community needs and opportunities that are shared by a broad cross-section of the atmospheric science UAS community. Dedicated efforts in these areas could provide significant support to the U.S. university research community for future developments and discoveries aided by the use of UAS. The summaries of these topics below are reflective of the workshop deliberations.

4.1 Community building

Expert teams: Currently no guidelines exist for instrumenting and operating UAS and for compliance with regulations. Expert teams could be formed and topical workshops could be held to define "Best Practices" and to provide guidelines on a variety of issues such as:

- UAS sensor calibration/installation/validation
- UAS autonomy and operations in the NAS
- Atmospheric observations using UAS, successes and failures
- Regulations and permissions

Other UAS specific topics exist but are not listed here. Expert teams and workshops to address these topics would require dedicated long-term funding if they were to happen at regular intervals and were to become a lasting support process for the community.

To foster use of UAS in atmospheric research, it is essential that the atmospheric sciences UAS community be well connected with the other UAS communities where developments may be progressing at a rapid pace. An example is the work underway in industry to increase the use of UAS for infrastructure monitoring and product delivery. This connection may be strengthened using dedicated groups that serve as interface between the different communities.

Databases: Most researchers are challenged by maintaining a market overview of platforms, instrumentation, and other technology useful to UAS researchers. Several databases have been created, but these are already out of date due to the rapid pace of technological development. Such a database could be re-initiated but would require ongoing funding support for maintenance and continuous updating. The specifics contained in such a database needs to be defined and may include:

- Catalog of available platforms, including performance charts describing payload, power, gust loads, and battery life so that they can be directly compared.
- Catalog of available instruments, including specifications and installation/placement recommendations for various platforms.

Several examples of such databases are currently under development, including those by EUFAR (www.eufar.net) and CLOUD-MAP (www.cloud-map.org), which may serve as examples or clearinghouses for a larger effort.

Working with the FAA: Operations within line-of-sight, below 400 ft, with a single UAS and a limited payload over rural areas are currently possible in many locations. However, many atmospheric observations require operations outside of this set of constraints. Obtaining appropriate permissions from the FAA going beyond the standard regulations may quickly become a challenge for smaller research groups. Recurring issues for many university groups, which require intensive coordination with the FAA, include:

- Vertical measurements by sUAS above 400 ft
- Night time operations
- BVLOS flight operations
- In-cloud operations
- "Floating restricted areas" to follow an event (e.g. severe storm, pollution plume) with minimal lead-time for NOTAMs
- Exceptions to FAA policy for field deployments involving sUAS facilities

Working with the FAA is a significant challenge for many university research groups. A mentoring program for new research groups entering the UAS community may help the community at large operate reliably within the regulatory framework. Understanding the FAA procedures and coordination protocol may go a long way to simplifying the request and approval of UAS operations. Such a mentoring program may require dedicated funding to be able to support a larger community.

The NSF supported atmospheric research community may need to coordinate with other federal agencies to develop a high priority list of changes/exceptions to the regulations that will most benefit UAS operations for atmospheric science and to work with the FAA on how these changes may be included in the regulations. No such coordinated effort currently exists.

4.2 Weather forecasts for UAS operations

Currently, the FAA only mandates that UAS operators be informed about operating conditions and potential hazards, without prescribing how this information is obtained. Strong wind, rain, icing, and turbulence are just a few factors that may interfere with safe UAS operations. Most UAS flights cover only a limited area and require inherently small-scale forecasts. No dedicated UAS forecast product is currently available but one is desperately needed by the UAS community. This may require additional information on small scales, which could be obtained by the UAS itself. The UAS atmospheric research community may want to approach industry about including standard atmospheric measurements on UAS platforms, which would give industry better forecast/nowcast of weather during their operations and provide additional data for research.

4.3 Community platforms

There is an increasing need for platforms that are too complex to be operated by most university research groups. Small UAS are widespread in the university community, but access to platforms that are capable of carrying larger instrument packages and perform well in the lower boundary layer is limited. Such platforms would require substantial ground support and maintenance, as well as an established record for meeting regulatory requirements. This type of system could be made available to the community in a mechanism similar to the NSF/LAOF community model. The detailed specifications and capabilities of such larger platforms would need to be defined with the goal to provide access to UAS tools needed by the research community.

There is also a need for extreme weather capable platforms, which can fly into or near icing conditions, in high winds, heavy rain, thunderstorms, or dense smoke plumes. No platform currently exists with these capabilities. The Raytheon Coyote air-deployed disposable UAS is currently the only platform that can fly into hurricanes, but only with a minimal sensor package. Most commercial applications may not have much need for such a platform and the design may rely on extensive involvement of the atmospheric research community.

A fleet of small UAS capable of taking coordinated high-resolution measurements over a limited area could be made available to the community. Such a fleet may also be equipped with an array of different sensors to measure more parameters than would be possible with the payload of a single sUAS. Current regulations require one pilot in command for each platform, which implies that significant ground support may be needed. To operate such a fleet of sUAS, advanced communications/guidance capabilities will need to be developed to enable operations that are more autonomous and to enable coordination between the platforms (e.g. swarm technology).

4.4 UAS atmospheric sensors

Many research groups adapt sensors from other applications (e.g. ground based or manned aircraft) and reconfigure them for use on the UAS. Calibration of sensors, proper placement on UAS and validation against recognized standards remains a challenge. There is a need for best practices for the choice of sensors, their calibration and installation into a UAS.

All high-quality sensors require traceable calibration to specified uncertainties. The UAS community could greatly benefit from access to calibration facilities for temperature, pressure, humidity, wind, radiation, and certain trace gases. There are few recognized guidelines for the specification of the sensor performance, including random uncertainty, systematic effects, time response, and operating conditions. These may be defined in cooperation with the calibration facility or as part of a dedicated expert team.

Pressure, temperature, and humidity are measured by many UAS with a wide variety of sensor models. However, there is little agreement about which sensor and installation are best. There is a need for a standard, well-characterized pressure/temperature/humidity sensor module. Expert teams may be tasked to define the criteria for such a standard sensor module and to identify the sensor and platform combinations that may be used for that purpose. Similarly, standard sensor packages to measure turbulence and to measure chemistry and aerosols may need to be defined.

Numerical modeling and flight-testing programs may be required to identify optimal sensor placement locations on a specific UAS. This may be labor intensive, but may be done for the most commonly used platforms and sensors, which may then provide recommendations for similar combinations of sensor and platform.

Validation against recognized standards can be done using reference sensors on tall towers or using a dedicated reference UAS or even a manned aircraft. Reference sensors on tall towers, which are easy to operate during validation campaigns, have well-established uncertainties and may be the preferred choice for validation of UAS sensors. Some commonly used sensors may need to be validated across a wider range of platforms, since the measurement uncertainty is influenced by the behavior of the sensor as well as the exposure to the atmosphere on the moving platform.

5 References

Ramanathan V., M.V. Ramana, G. Roberts, D. Kim, C. Corrigan, C. Chung, D. Winker (2007): Warming trends in Asia amplified by brown cloud solar absorption, Nature, 448, 575-578, doi:10.1038/nature06019.

Reineman, B.D., L. Lenain, and W.K. Melville (2016): The Use of Ship-Launched Fixed-Wing UAVs for Measuring the Marine Atmospheric Boundary Layer and Ocean Surface Processes. J. Atmos. Oceanic Technol., 33, 2029–2052, doi:10.1175/JTECH-D-15-0019.1

Xi X., M. S. Johnson, S. Jeong, M. Fladeland, D. Pieri, J. A. Diaz, and G. L. Bland (2016): Constraining the sulfur dioxide degassing flux from Turrialba volcano, Costa Rica using unmanned aerial system measurements, J. Volcanol. Geotherm. Res., 325, 110-118, doi:10.1016/j.jvolgeores.2016.06.023.

Smith, R. B., 2013 The Lower Atmospheric Observing Facilities Workshop, UCAR/NCAR - Earth Observing Laboratory, http://dx.doi.org/10.5065/D66971M1.

6 Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	Above Ground Level
ARM	Atmospheric Radiation Measurements
ASSURE	Alliance for System Safety of UAS through Research Excellence
BEST	Boulder Environmental Science and Technology
BVLOS	Beyond Visual Line of Sight
COA	Certificate of Authorization
CONOPS	CONcept of OPerationS
COTS	Commercial-Off-The-Shelf
DHS	Department of Homeland Security
DOE	Department of Energy
DRI	Desert Research Institute
EOL	Earth Observing Laboratory
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FASER	Facilities for Atmospheric and Earth Science Research
FMRA	FAA Modernization and Reform Act
HALE	High Altitude Long Endurance
ISARRA	International Society for Atmospheric Research using Remotely piloted Aircraft
LAOF	Lower Atmospheric Observing Facilities
MALE	Medium Altitude Long Endurance
NAS	National Airspace System
NASA	National Aeronautic and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PNNL	Pacific Northwest National Laboratory
PTH	Pressure, temperature, humidity
SBIR	Small Business Innovative Research
sUAS	Small UAS
UAS	Unmanned Aircraft System
VO	Visual Observer
VTOL	Vertical Take-Off and Landing

7 Appendix 1: Agenda

Tuesday, 21 February 2017

12:00 PM	**Registration**
1:00 PM	**Workshop Opening** *Holger Vömel/NCAR*
1:05 PM	**Welcome Address** *Jim Hurrell/NCAR*
1:15 PM	**Welcome Address** *Paul Shepson/NSF*
1:25 PM	**EOL and the UAS Atmospheric Research Community** *Vanda Grubišić /NCAR*
1:45 PM	**Workshop Goals and Logistics** *Holger Vömel/NCAR*
2:05 PM	**Regulatory Enviornment** *Mark Askelson/UND*
2:20 PM	**Invited Talk: UAS Science** *Phil Chilson/OU*
2:50 PM	**Break**
3:20 PM	**Breakout sessions: UAS Science I**
5:00 PM	**Adjourn**
5:30 PM	**Icebreaker** poster and platform/instrumentation displays

Wednesday, 22 February 2017

8:00 AM	**Continental Breakfast** *Session Chair: Cory Wolff*
8:30 AM	**Invited Talk: UAS Platforms** *Matt Fladeland/NASA/Ames*
9:00 AM	**Breakout sessions: UAS Platforms I**
10:40 AM	**Break**
11:00 AM	**Rapporteurs Report: UAS Science I**
11:30 AM	**Invited talk: UAS Instruments** *Jamey Jacob/OSU*
12:00 PM	**Lunch** *Session chair: Scott Ellis*
1:15 PM	**Breakout sessions: UAS Instruments I**
2:45 PM	**Rapporteurs Report: UAS Platforms I**
3:15 PM	**Break**
3:30 PM	**Breakout sessions: UAS Science II**
5:00 PM	**Adjourn**
5:30 PM	**Reception** poster and platform/instrumentation displays

Thursday, 23 February 2017

8:00 AM	**Continental Breakfast**
	Session Chair: Jim Moore
8:30 AM	**Rapporteurs Report: UAS Science II**
9:00 AM	**Rapporteurs Report: UAS Instruments I**
10:00 AM	**Break**
10:15 AM	**Breakout sessions: UAS Operations**
11:45 AM	**Lunch**
	Session chair: Steve Oncley
1:00 PM	**Rapporteurs Report: UAS Operations**
1:30 PM	**Breakout sessions: UAS Instruments II**
3:00 PM	**Break**
3:30 PM	**Breakout sessions: UAS Platforms II**
5:00 PM	**Rapporteurs Report: UAS Instruments II**
5:30 PM	**Adjourn**

Friday, 24 February 2017

8:00 AM	**Continental Breakfast**
	Session Chair: Duncan Axisa
8:30 AM	**Rapporteurs Report: UAS Platforms II**
9:00 AM	**Other Topics**
10:00 AM	**Break**
10:15 AM	**Wrap-up**
12:00 PM	**Adjourn**

8 Acknowledgements

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White Paper UAS Operations: B. M. Argrow and E,. W. Frew
White Paper UAS Platforms: M. Fladeland, S. Schoenung, and M. Lord
White Paper Unmanned Aerial Systems for Atmospheric Research, Instrumentation Issues for Atmospheric Measurements: J. Jacob, D. Axisa, and S. Oncley

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9 Appendix 2: The NCAR Earth Observing Laboratory Survey on Unmanned Aircraft Systems

Authors: Holger Vömel, Cory Wolff

Executive Summary

In summer of 2016, NCAR Earth Observing Laboratory (EOL) distributed a survey regarding the needs for Unmanned Aircraft System (UAS)-based atmospheric and interface research to the larger NSF research community. The survey questions collected input from the general UAS community and considered any class of UAS platforms. We received 53 responses from experienced users of UAS, novices, who are still building experience, and researchers not yet using UAS.

The survey indicates that open needs exist within the broader UAS community. Given the complexity of UAS-based observations, providing access to fully equipped platform(s) was seen as most beneficial to meeting the needs of the survey responders. However, there was no clear indication as to which platform or platforms would be most appropriate. The survey furthermore indicated that sensor development, calibration, and validation are also seen as highly beneficial for the larger community.

The current UAS user community seems to be divided between those who can manage the regulatory framework well and those who find the regulatory framework challenging. The latter part of the community may strongly benefit from regulatory support.

This survey provided a one-way communication with the research community. A follow-up workshop, which allows an active dialog between all parties involved, should help in further refining how the Earth Observing Laboratory may best serve the national atmospheric research community in the use of UAS.

Introduction

Unmanned aircraft systems (UAS) have been used in atmospheric research for decades in small research projects and niche applications. In recent years, the availability of UAS has increased dramatically and many research projects are now being conducted at universities, research institutions, and government agencies, both nationally and internationally. Historically, almost all airborne atmospheric observations have been taken by manned aircraft, free flying balloons, and tethered balloons or kites. The widespread availability of remote controlled fixed-wing and multirotor UAS provide an additional platform to lift sensors for atmospheric and terrestrial observations off the ground, and thereby provide researchers a new path to upper air observations.

The Earth Observing Laboratory (EOL) of the National Center for Atmospheric Research (NCAR) has been one of the leading research institutions for airborne atmospheric observations using balloons and manned aircraft, but has not developed any expertise with UAS. One of the important roles of EOL is to provide a resource for the larger NSF research community and to support atmospheric science through expertise in atmospheric observations.

EOL initiated a series of workshops to examine the Lower Atmospheric Observing Facilities (LAOF) assets and to identify weaknesses in the capabilities of existing and emerging tools, and in the modes of deployment supported by these systems. The LAOF workshop titled Meeting the Challenges of the Climate System Science (Smith, 2013), which was organized and hosted by EOL in June 2012, discussed outstanding research topics within different areas of atmospheric research. Among other results, this workshop identified UAS as an emerging tool, which had not yet received much attention within the LAOF community. The terrestrial-atmosphere interface, the ocean-atmosphere interface, and the cryosphere-atmosphere interface were highlighted as areas where UAS could provide a new approach to survey regions over a few tens or hundreds of kilometers with miniaturized instruments, possibly deployed from land, shore, ice floe, or ship. Observations in the free troposphere and above were not seen as a high priority for observations using UAS beyond the current capabilities.

Other government agencies (NASA, NOAA, DOE) have operated or leased UAS for specific missions. Most UAS platforms require a significant ground based infrastructure and financial support not only for acquisition but also for maintenance and operation. NCAR, as a national center, is uniquely positioned to provide additional capability and services to the university community involving UASs for atmospheric research. It was suggested that as part of this process, NCAR conduct a survey of university UAS expectations to support atmospheric research and hold a workshop including university, industry, and government entities.

Survey

To gain a better understanding of the community needs and capabilities with respect to UAS, we developed a community survey, which was distributed in July 2016. This survey sought to reach scientists and engineers who are using UAS or are interested in using UAS for atmospheric research. The purpose of the survey was to gauge how UAS are currently being used, what accomplishments researchers have achieved using UAS, and what the strengths and weaknesses are in the use of UAS for atmospheric science.

We asked all respondents about their research area and their experience with UAS. Those, who indicated that they are not currently using UAS, we asked about the research topics for which they could envision using UAS and the greatest benefit that UAS may provide. We also asked, which support category, such as flight operations, community UAS platforms, or instrument development, they might benefit from most, if they were to become active UAS users.

Those, who are already using UAS in their research, we asked a more extensive set of questions, probing in greater detail their research area, their level of experience and skill working with UAS based observations, as well as were they saw unmet needs and research potential.

All respondents were asked, whether several research support categories, which EOL could possibly provide, would be seen as complementary, competing, or neither, and what EOL could provide to support or augment the respondent’s research.

The survey was distributed to three groups:

1. UCAR Member University Representatives, with a request to distribute the survey within their departments. This went out twice, once at the beginning of the survey period and again a week before the survey closed.
2. NSF grant recipients, who specifically mentioned research using UAS in their grant application.
3. UCAR employees who were also encouraged to send to interested colleagues.

The survey stayed open until the end of August 2016 and all feedback received by that date was included in the analysis.

Results

Respondents

A total of 53 recipients completed the survey. Of these, 40 were from universities in the U.S., 5 from NOAA, and the remaining from foreign universities, the Desert Research Institute (DRI), NASA, the Pacific Northwest National Laboratory (PNNL), Boulder Environmental Science and Technology (BEST), and NCAR.

Forty-one respondents identified with atmospheric science, five with earth science, five with engineering, one with a private company, and one with system health management. Ocean science was explicitly listed as option to identify the area of research, but was not selected by any of the respondents. Within the respondents who classified themselves as atmospheric science, 23 (56%) identified themselves as current UAS users.

Thirty-three respondents (62%) identified themselves as current users of UAS, while 19 (36%) were not using UAS, but indicated plans to use UAS or expressed an interest in using UAS in the future. One respondent indicated that he was not using UAS and was not planning to do so. This respondent provided no additional input and was excluded from further analysis.

Research Areas

The information available to us prior to this survey indicated a strong focus on UAS for lower atmospheric research. To get a better understanding of the general research areas, we asked respondents, who indicated that they are using UAS, about the research topics they are investigating using UAS. We offered the following choices: boundary layer, turbulence, cloud processes, aerosol measurements, air quality, constituents / atmospheric chemistry, tropical, and other. In the category “other” respondents could provide a free text response to further categorize their research topic and provide options that we had not considered. These responses are included in the charts as appropriate.

For the current research topic, the majority of UAS users categorized their research topic as boundary layer, which is consistent with the preliminary information. Although our survey sample size is relatively small, there is no obvious sampling bias and we consider this result representative of the larger UAS research community. The complete distribution of current research topics of UAS users is shown in Figure 2. It should be noted that Boundary Layer was mentioned in almost all of the responses from those in the atmospheric science community.

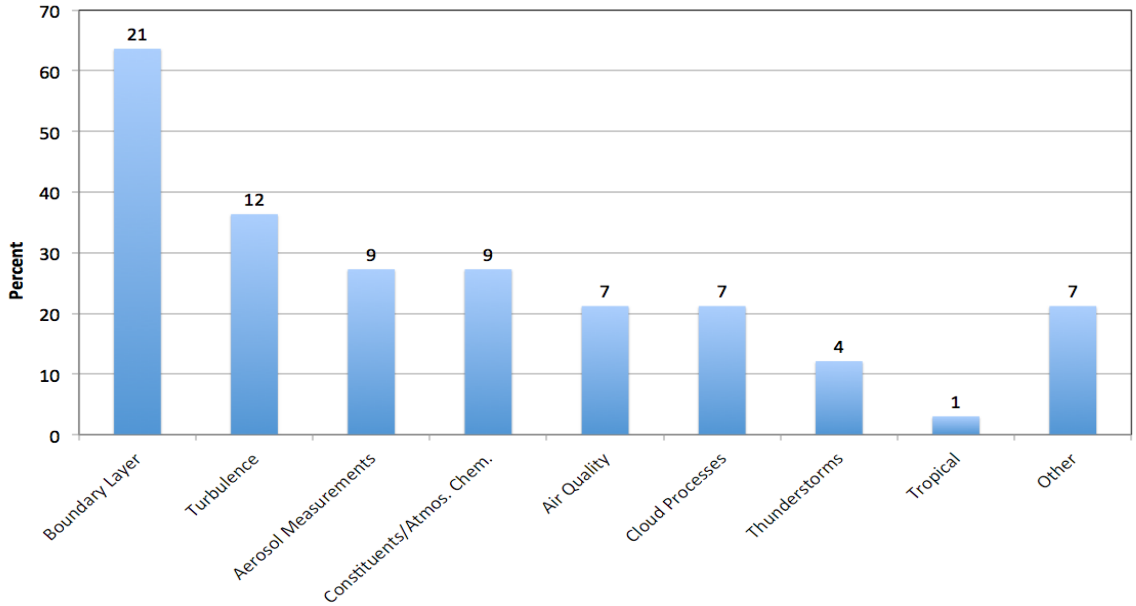

***Figure 2**: Research topics for which UAS are currently being used. The bars represent the percent of total respondents that selected or entered each topic; while the numbers on top of each bar represent the absolute number of times, each topic was chosen or entered.*

We also asked current users of UAS to identify research topics they would like to research with UAS, but are not doing so. The choice of areas of research was the same as those they are currently studying.

Figure 3 shows the distribution of desired research topics. The boundary layer scores high in this group as well, reaffirming that UAS research interests lie mostly within this part of the atmosphere. However, constituents / atmospheric chemistry, air quality, and aerosol measurements rank significantly higher in the topics researchers would like to study compared to the topics, which they are currently studying.

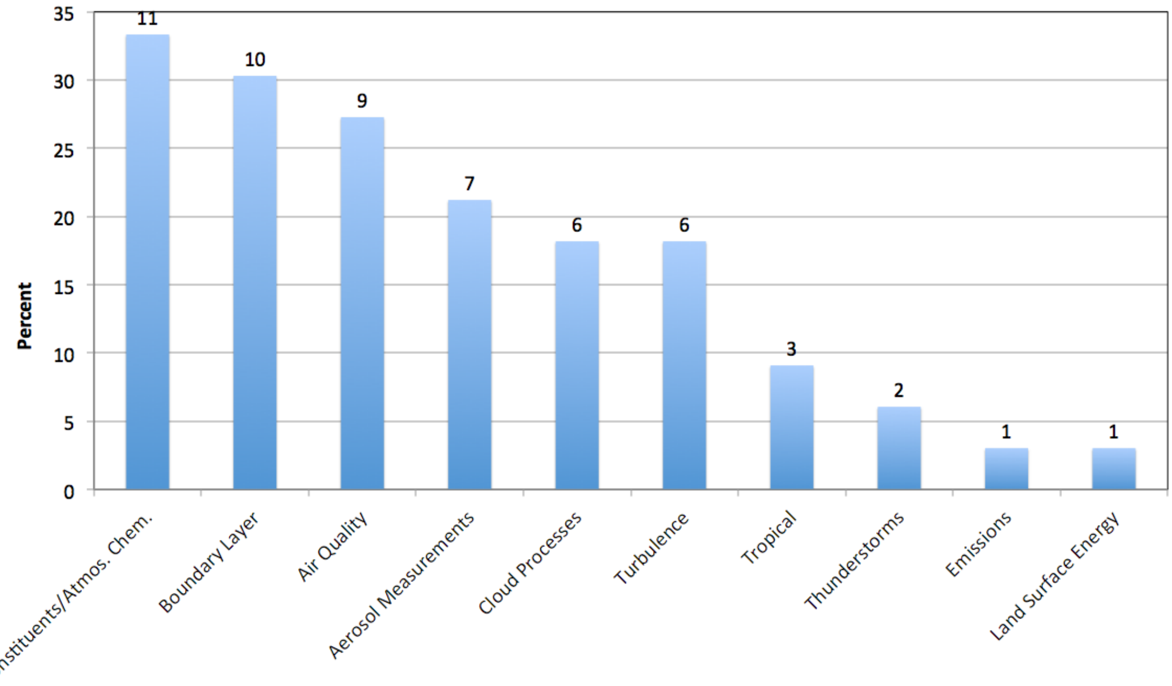

Figure 3*: As in Figure 2, but for research topics for which respondents, who are currently using UAS, would like to use UAS but are not doing so now.*

We also asked non-users of UAS to identify research topics they would like to research using UAS. Their responses are shown in

Figure ***4***. The research topic "boundary layer" again received the highest number of responses, followed by aerosol measurements and cloud processes.

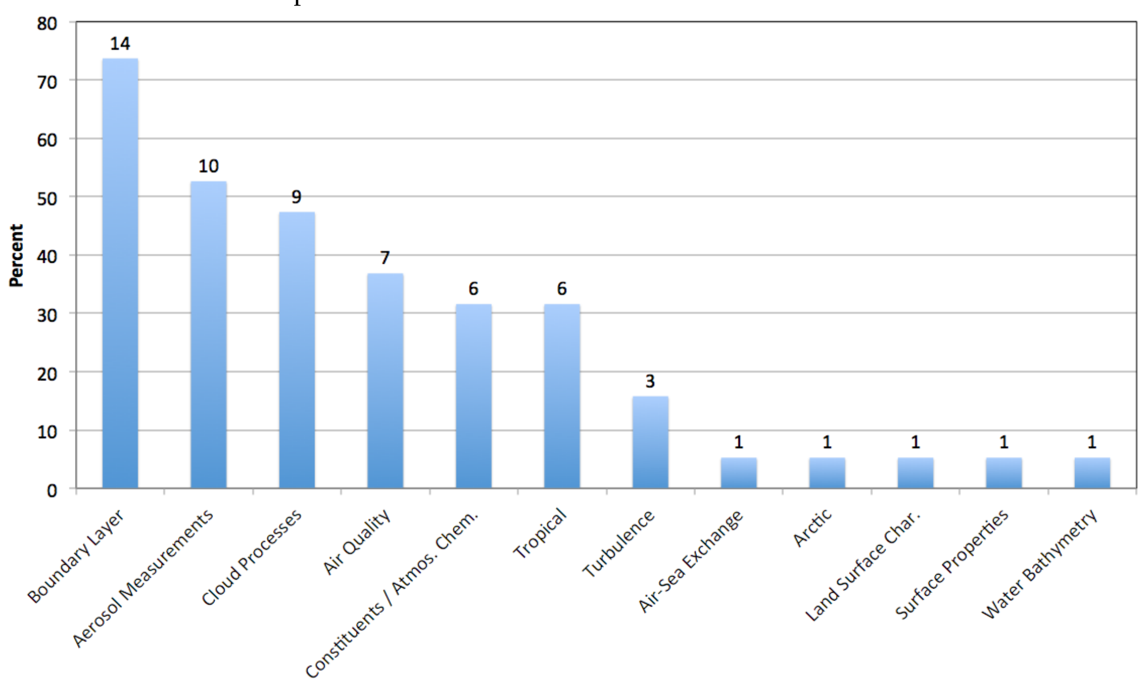

Figure 4*: UAS research topics as in Figure 2, but for respondents, who are currently not using UAS.*

We also asked whether there are any other UAS applications that the respondents think are promising, but outside of their research area. The most common reply to that question was that there are numerous applications outside each respondent's specific area. Although non-specific, this reply indicates that there is still significant potential in the use of UAS, which has not yet been developed. The collaborative multi-UAS measurements was the second most common response, referring to applications, where more than one UAS are flown simultaneously to obtain better spatial and temporal sampling.

Atmospheric parameters

We asked respondents who indicated that they are using UAS which specific atmospheric parameters they are currently measuring. Possible answers were temperature, pressure horizontal wind, vertical wind, turbulence, humidity, cloud properties, aerosols, air quality, constituents / trace gases, fluxes, radiation, and other. The distribution of all responses is shown in

Figure ***4***. Parameters named in the category "other" were aerial photos, electric fields, polar and maritime surveys, topography, multispectral imagery, thermal infrared (IR), and surface temperature. The question obviously implied the existence of appropriate sensors, but did not probe the quality of the measurements.

Observations of the basic thermodynamic parameters temperature, humidity, pressure, and wind are most common and taken in most studies. Other less frequently measured parameters depend on the interests of the individual researcher and the specific research project.

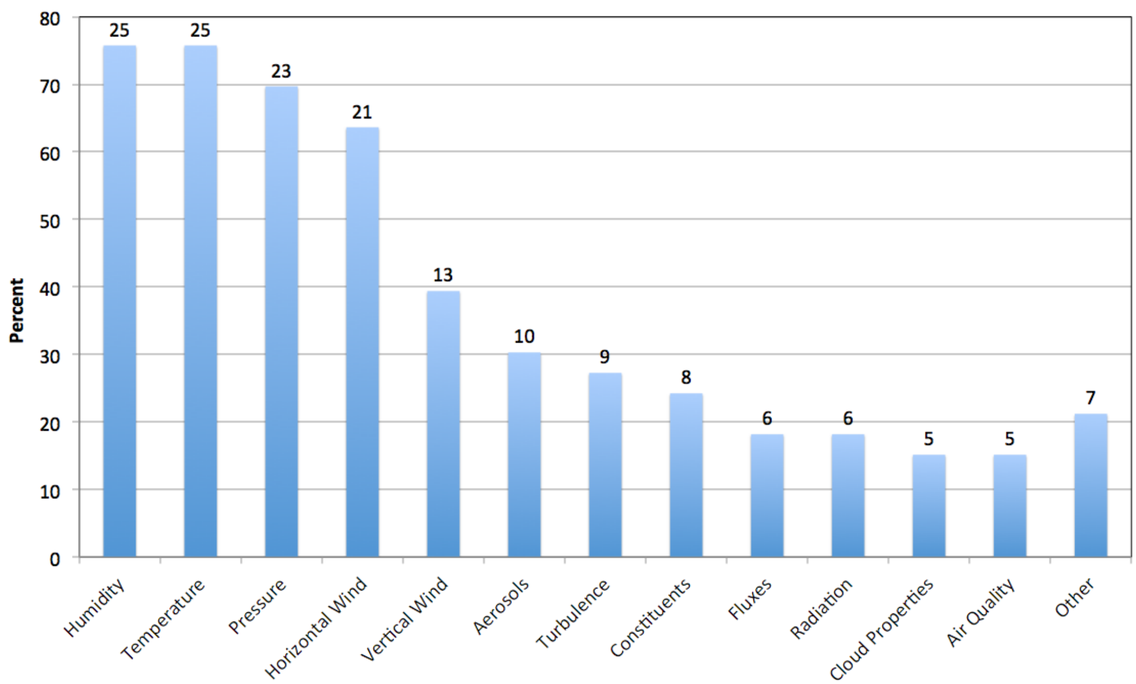

Figure 5*: Atmospheric parameters currently being measured by UAS as a percent of total respondents. The numbers on top of the bars represent the absolute number of responses for each parameter.*

We referred to the same list of parameters when we asked which atmospheric parameters the respondents would like to measure/retrieve using a UAS, but lack the sensors to do so. Here the parameters turbulence, constituents / trace gases, cloud properties, and vertical wind were listed most frequently (Figure 6). However, a substantial need for sensors exists for all parameters, including those for which sensors are already available.

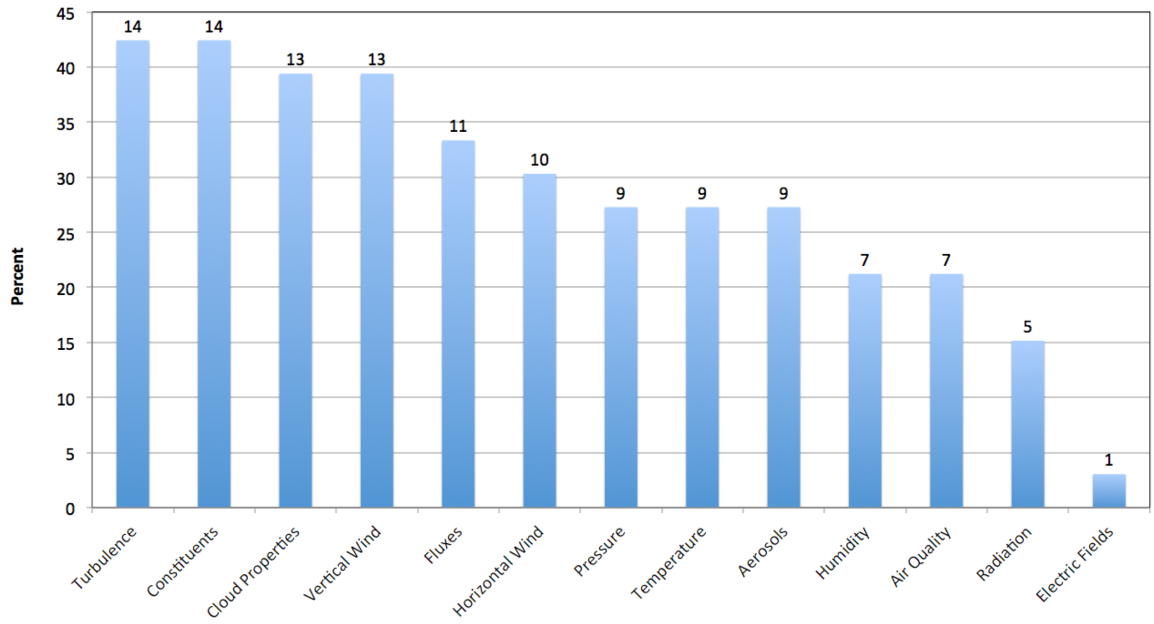

Figure 6*: As in Figure 5 but for atmospheric parameters not currently measured by UAS researchers, which they would like to be able to measure.*

Platforms

We asked for a description of current UAS research platforms and the considerations that went into utilizing the particular UAS. The number of responses was not sufficient to provide a statistically significant distribution of which platforms were chosen, but the responses still provided very valuable information about the scope of platforms as well as the decision process towards a particular UAS.

Platforms being used are divided about equally between fixed wing and multirotor aircraft. Respondents almost exclusively worked with small UAS, i.e. those with a takeoff weight of less than 55 pounds. Within this class of UAS systems, all sizes are represented. Most respondents have utilized more than one aircraft and typically have access to both fixed wing and multirotor platforms.

Researchers using UAS for terrestrial imaging are more likely to use Commercial-Off-The-Shelf (COTS) solutions, which are widely available. For all other applications researchers are more likely to acquire the sensors independently of the aircraft and then adapt those for their planned use, although a few COTS UAS dedicated to meteorological observations exist. Some respondents indicated that they acquired the avionic electronics independently from the airframe. Finally, some respondents indicated that they do not own or operate the UAS themselves, but collaborate with academic or private organizations with that capability.

Figure 7 shows a primary consideration for choosing a particular platform. Payload was the most frequently named consideration, closely followed by cost and size. The responses under category “other” were FAA requirements, endurance, ability to measure in storm environment, fulfill observation requirements, potential to work properly within a thunderstorm, in the mixed-phase region, fairly “simple” operational complexity, and flight duration.

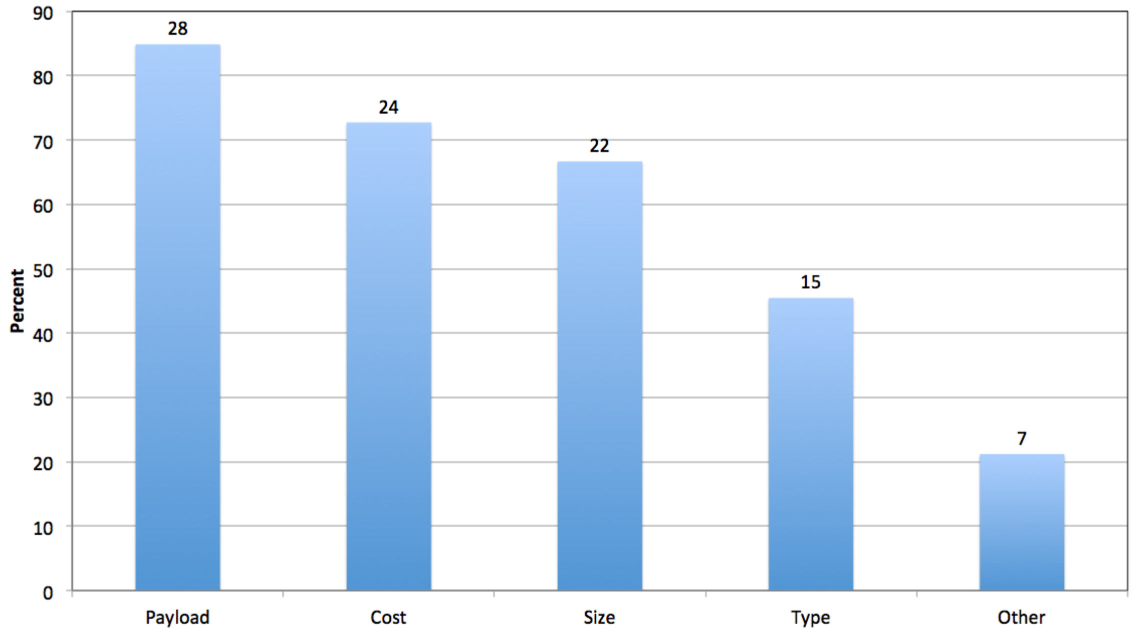

Figure 7*: Percent of respondents who indicated a category as consideration for choosing the UAS with which they are performing research.*

We gave respondents the opportunity to provide other considerations that went into the decision process so that we could gain a better understanding of the motivation to work with a particular UAS. This question did not offer pre-selected options and answers covered a large range of topics. Many responses stated multiple considerations highlighting the complexity of platform selection.

Operational requirements, such as the need for Vertical Take-Off and Landing (VTOL), the need for a runway, UAS recovery options, the ability to operate in a particular environment (e.g. polar regions) or the need for extended flight duration were most frequently listed. Initial cost and ease of use was listed as an important consideration as well. Some researchers, who expressed the need for low cost and ease of operation, expressed that their research plan might evolve to more expensive and complex systems, once sufficient experience with lower cost systems had been acquired. Other respondents highlighted the science question and the choice of sensors as the driver for the choice of platform. Finally, reliability and robustness of the platform as well as a proven track record were given as important considerations. The last category worth noting are legal considerations. One respondent pointed out the need to obtain a Certificate Of Authorization (COA) for the platform of choice and another respondent pointed out the need for open source hardware and software in order to avoid legal export control issues when working with foreign students.

To evaluate which platforms might be replaced by UAS we asked respondents about what other platforms, if any, were considered for the planned observations. Possible categories were tethered balloons, untethered balloons, kites, manned aircraft, towers, remote sensing, none, and other. Figure 8 shows the distribution of alternative platforms that were considered.

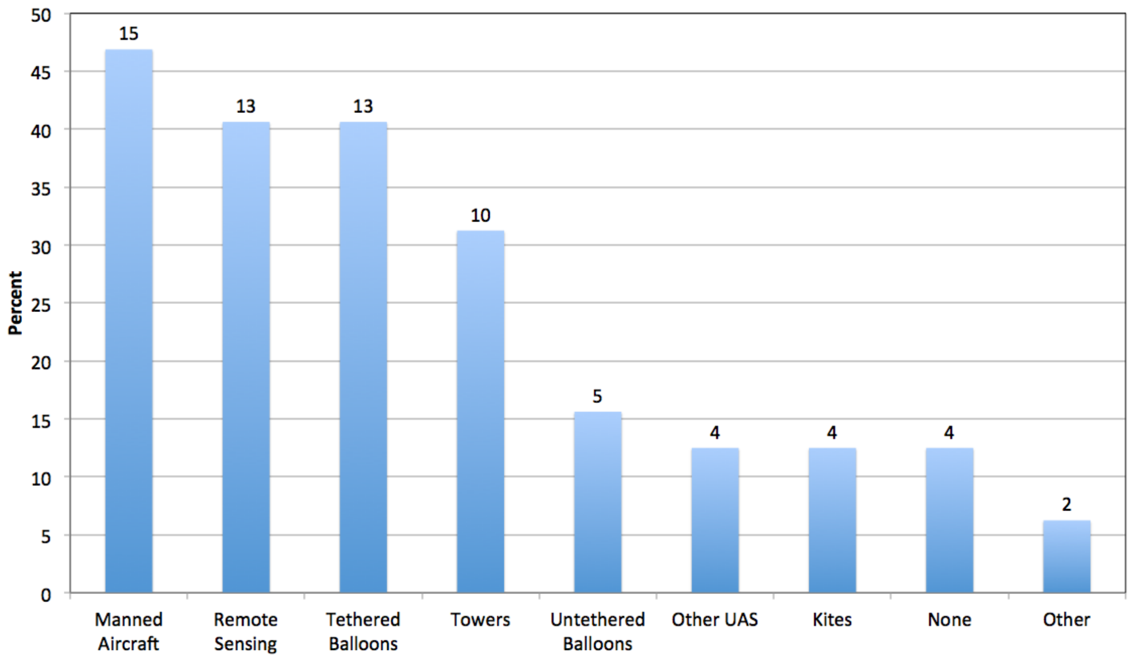

Figure 8*: Alternative platforms that were considered for observations.*

The category "manned aircraft" was listed most frequently followed by remote sensing and tethered balloons. In the category "other" respondents named micro-meteorological ground stations, water vessels, and other UAS. Four respondents replied "none", which is the same number of responses as for the categories kites and one less than for the category untethered balloons.

Lastly, we asked what other methods are respondents currently use in their research that UAS might be able to replace or complement. The responses clearly indicated that UAS is seen as a new and complementary platform, which augments a number of existing observational techniques. The responses also indicated that UAS could possibly replace two other platforms for some research projects: manned aircraft observations, which were also the most frequent alternative platform considered for the observations, and balloon soundings, which on the other hand were not frequently listed as an alternative platform.

Measurements

Measurements onboard UAS often require sensors, which are optimized for low weight and power consumption. Measurements, in particular for air movement, may also be impacted by the specific aerodynamic behavior of the UAS platform. Therefore, it is not obvious that UAS borne measurements have a data quality equivalent to that from manned aircraft or balloon borne measurements. We, therefore, asked how easy or difficult is it to interpret and use UAS data.

Most UAS researchers find that using and interpreting data from UAS is easy to very easy (Figure 9), with only four respondents calling that task difficult or very difficult. Respondents could also provide clear text comments about the difficulty to interpret and use UAS data. Basic measurements such as temperature, pressure, and moisture are seen to be fairly straightforward. However, kinematic measurements such as winds, turbulence and fluxes are seen as more difficult. Some UAS researchers are familiar with observations from other airborne platforms, in particular manned aircraft, and have experience working with this type of data. For these researchers working with data collected by UAS was not seen as fundamentally different. In some cases researchers found that effects from the UAS itself (e.g. downwash from rotors) negatively influence their measurements and makes data more difficult to interpret. The relative ease of deployment of UAS means that significantly more data can be collected, which means significantly more data may need to be analyzed and archived. This aspect is seen to increase the difficulty of working with UAS observations (i.e. "big data" problem).

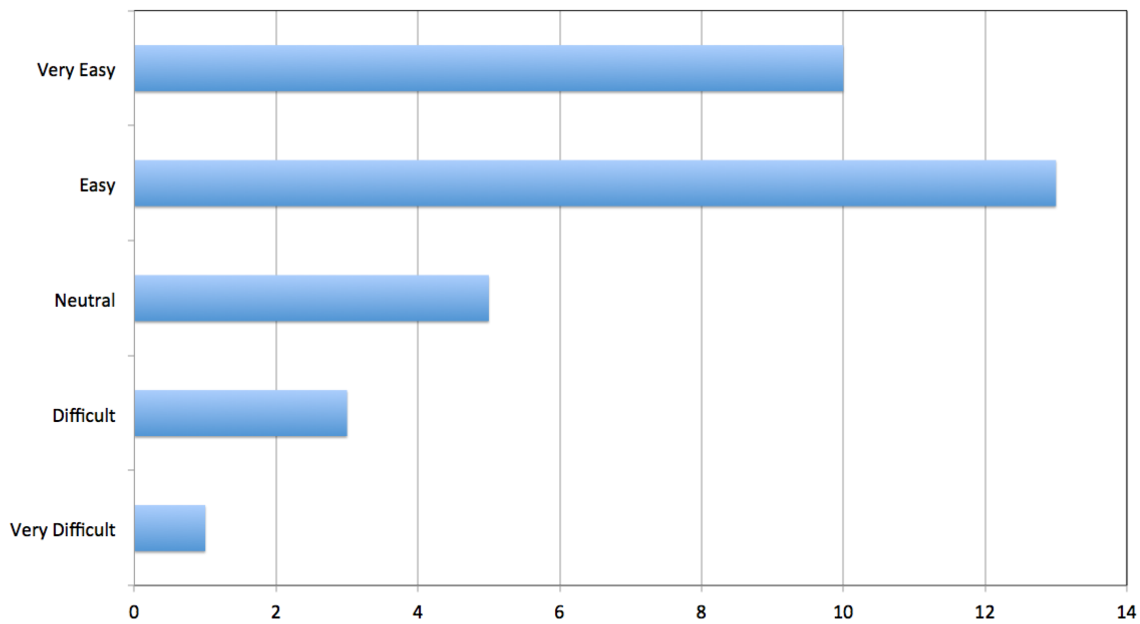

Figure 9*: Difficulty or simplicity of using observations from UAS.*

As with any measurement, it is important to characterize the uncertainty of UAS observations. To better understand the expected data quality, we asked whether respondents, who are using UAS, characterized the uncertainties of their UAS measurements and how this was done. 62% of respondents replied that they did characterize the uncertainty of their measurements. The comments about the methodology indicate that the extent of the characterization efforts depends strongly on the instrument and availability of other systems to measure the same parameter. It is important to note that these replies referred to different measurements without specifically listing those. Laboratory studies of sensor performance were listed most frequently followed by comparisons to ground based instruments and comparisons to tower measurements. Some respondents listed comparisons with remote sensing instruments separately from comparisons with ground based instruments. Comparisons with other aircraft (manned and unmanned) have been used as well as in-flight calibrations and statistical analysis under stable meteorological conditions. Others are just getting started on calibration efforts and the procedures have not yet been defined. We did not ask those not performing *calibrations* about the reasons for foregoing this exercise.

In addition to uncertainty characterization, validation of measurements is an important aspect for any emerging technology. In this context we asked whether respondents had validated their UAS data against established techniques or measurements. Seventy two percent of the respondents indicated that they did so. Most of these validations have been done against ground-based observations, which most likely includes remote sensing instruments, towers, radiosondes, but also other aircraft. Some respondents did not distinguish between calibration and validation and listed the same comments for both questions or entered "See above". We did not ask those not performing *validation* studies about their reasons for not doing so.

Respondents who are currently not using UAS

The level of interest in using UAS from respondents, who are currently not using UAS, is shown in Figure 10. The high interest expressed by these respondents is consistent with their willingness to answer a UAS related survey. It is not necessarily an indication of the level of interest in the larger atmospheric science community as the survey recipients with no interest in UAS-based research were less likely to respond.

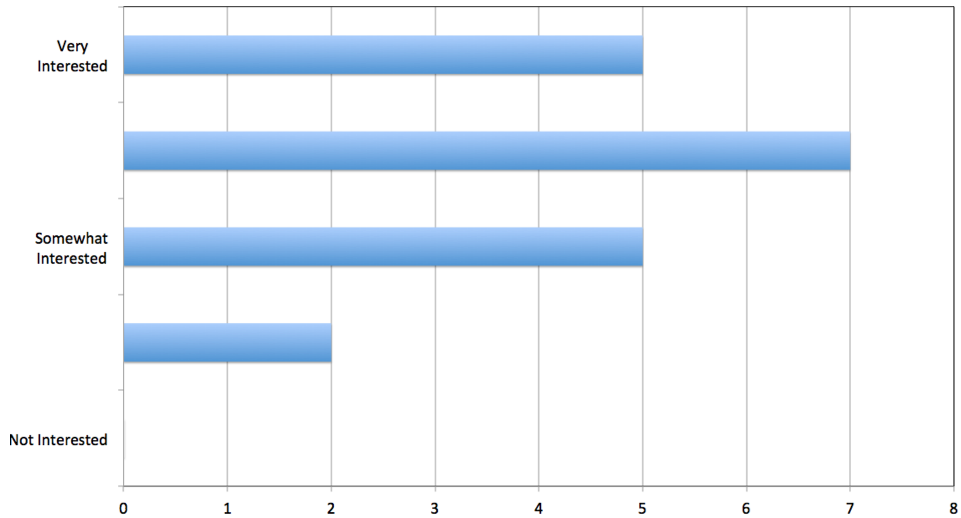

Figure 10*: Level of interest in using UAS from all respondents who are currently not using UAS.*

We asked respondents to indicate the greatest benefits they feel UAS could have for their research and the support categories they could most benefit from. The responses indicate an expectation to be able to reach areas that are difficult to sample either due to their remoteness or due to the difficult access by manned aircraft (proximity to severe storms or low altitudes). Many also indicate that better vertical and/or horizontal coverage than other techniques is expected. Only one respondent indicated an expectation for low cost and easy use of UAS.

We also asked respondents, who are not currently using UAS, what support categories they would most benefit from. The responses are categorized in Figure 11.

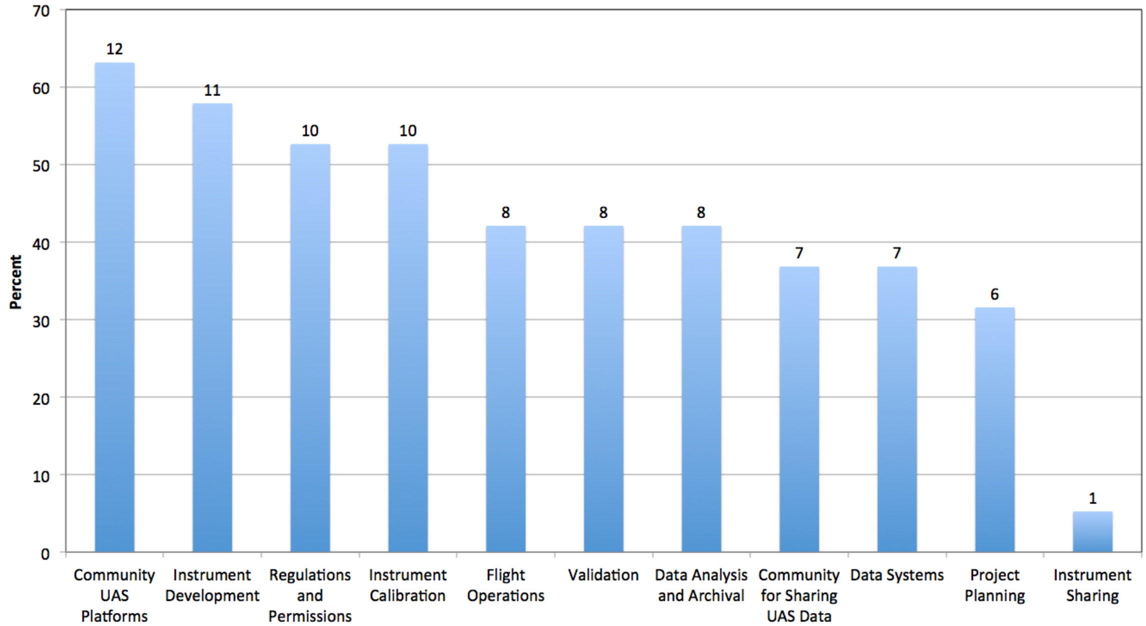

Figure 11*: Support categories for which respondents, who are not using UAS, feel they would benefit from if they were to begin using UAS.*

Most respondents thought that having access to community UAS platforms would be beneficial, followed closely by instrument development, help with regulations, and instrument calibration. Nine categories were selected by more than a third of respondents, showing that a wide range of support would be appreciated by new users.

Potential benefit of EOL activities

EOL's main mission is to serve the larger science community, in particular the NSF funded university research community, by providing access to facilities, which may be outside the capabilities of individual researchers. To gauge how any newly developed EOL program regarding UAS may be accepted, we asked what EOL's relationship would be to the respondent's research if EOL developed any of the following programs: Operate UAS platforms, develop instruments for UAS, provide calibration facilities for UAS instruments, provide site for validation of UAS observations, or provide data services. Respondents could select between the options complementary, competing, and neither. EOL's role in these potential programs was seen as complementary by between 58% and 75% of the respondents. Between 17% and 31% of the responses were indifferent and less than 12% of the responses viewed EOLs role as competing (Figure 12).

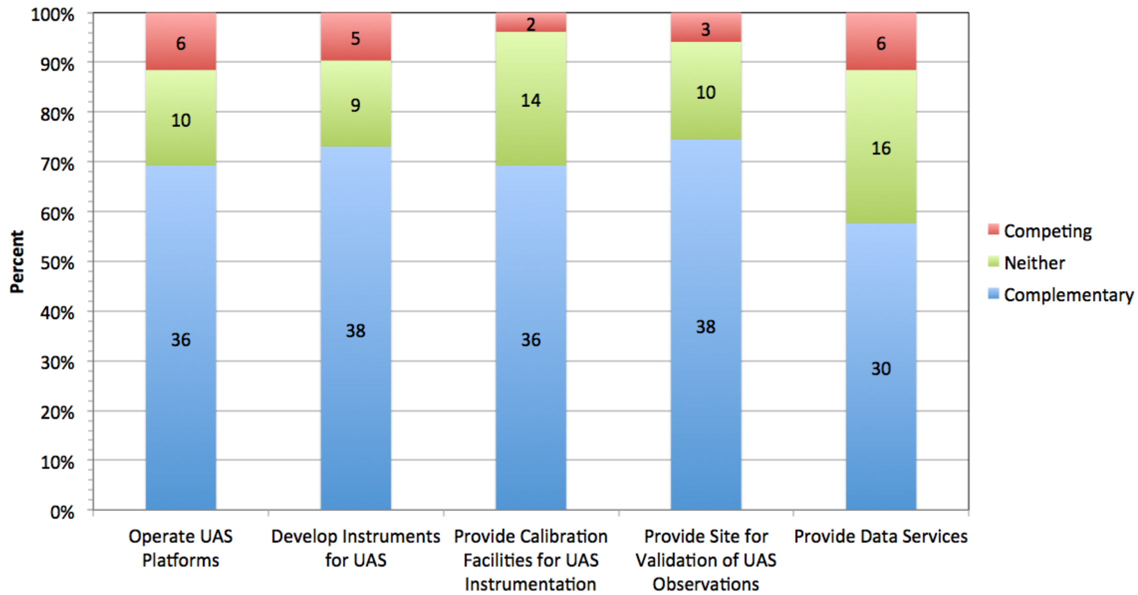

Figure 12*: Percent of respondents who view various services that EOL could provide as complementary, competing, or neither complementary nor competing to their research. The numbers in the bars represent the absolute number of responses for each category.*

The last question we posed to respondents in this section was to list what EOL could provide that would best augment or support the respondent's UAS research. This question did not offer pre-defined answers and allowed respondents to provide free text comments. This question was presented to both current users and non-users of UAS, which here are not further distinguished. The responses were grouped into seven different categories (see Figure 13). The most frequent comment on potential EOL support programs for UAS expressed a need for EOL to provide a community UAS platform, which could be requested similar to other EOL deployment pool instrumentation. However, no clear picture emerged about which UAS platform would be best suited for this function. Suggestions included, but were not limited to, large UAS (> 55 lb.), a fleet of vertical takeoff and landing (VTOL), UAS capable of carrying a 10 kg payload, or simply a community platform with standardized instrumentation.

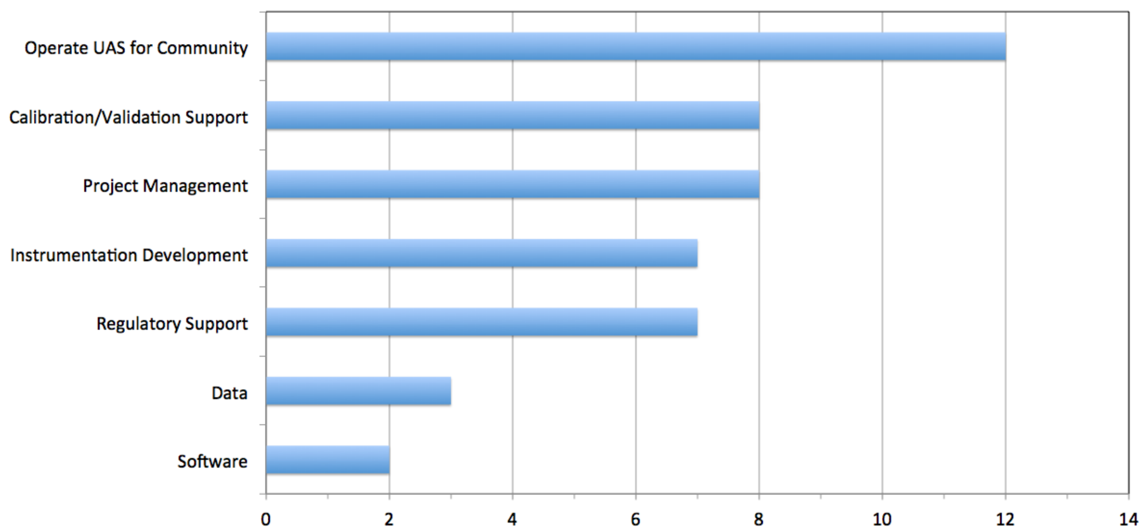

***Figure 13**: Results from what EOL could provide that would best augment or support the respondents UAS research.*

Other potential UAS related programs, which were seen as of high value, are a facility for calibration and/or validation of measurements; project management support, in particular for larger programs involving multiple UAS; support in the development of instruments; and regulatory support. Data services and software support were also mentioned.

Discussion

We asked respondents to think of specific UAS aspects in the context of both their current UAS activities and what they know about the efforts of the larger UAS research community, and asked them to rate how well developed they feel the respective aspect is. The aspects were UAS flight operations, instrument development, instrument validation, instrument calibration, UAS data systems, UAS data analysis, and UAS rules and regulations (Figure 14). Most of these aspects showed a nearly symmetric distribution around somewhat developed. “Instrument validation” and “UAS Rules and Regulations” had a most common response of “less developed”. That instrument validation was rated as less developed is consistent with the previous result that uncertainty characterization and sensor performance may still be improved on average.

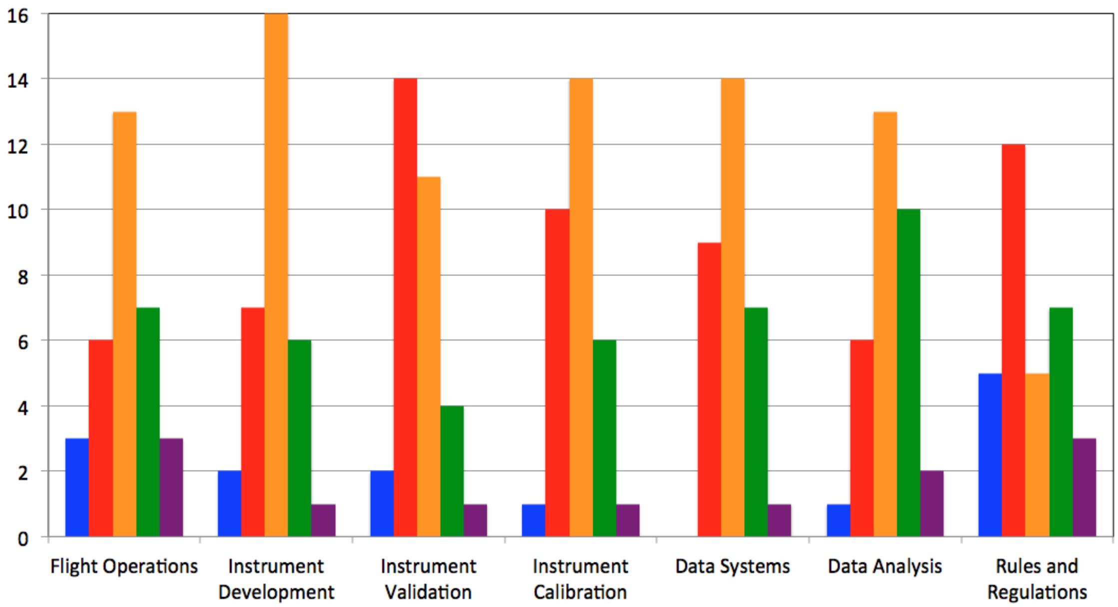

Figure 14*: Subjective level of maturity for different UAS aspects. Color-coding of the bars from left: Blue: not at all developed; Red: less developed; Orange: somewhat developed; Green: more developed; Purple: extremely well developed.*

The responses for the aspect "UAS rules and regulations" showed a split distribution with most responses indicating less developed and a second peak indicating more developed. This indicates that the user community may be split between users who have established relations with the Federal Aviation Administration (FAA) and for whom understanding and complying with regulations may not be a significant burden, and users for whom understanding and complying with regulations may still create a significant burden in the research effort. A follow up question allowed respondents explicitly describing the reasons for choosing why an aspect was not at all developed. Four out of six responses explicitly described the difficulties working with the FAA under current rules, and one of these four respondent commented on the fact that there are some groups that have well established connections with the FAA, while the respondent did not.

To gauge to what extent this new platform may meet expectations, we asked respondents what has been the biggest success in using UAS for research. Although the responses spread over many areas, the largest number of researchers list new observational results, which may not have been possible with other techniques, as their biggest success. Some observations were taken in very remote regions (polar) or in hazardous regions (near thunderstorms). A sizeable number of publications indicates some level of maturity for these observational programs. New sensor development as well as expanding the regulatory capabilities was another area considered a success, which will expand the capabilities of UAS in atmospheric research.

The survey also asked what has been the biggest challenge in using UAS. Here, air traffic regulations and working with the FAA emerged as the most significant challenge in UAS based observations. Related to this, the availability of trained and certified UAS pilots is seen as challenge, in particular for intensive field campaigns, requiring a lot of staff.

Measurements of winds and turbulence were also indicated as significant challenge for current UAS. This is consistent with the answers to our question which atmospheric parameters the respondents would like to measure/retrieve using a UAS, but lack the sensors. Wind measurements from UAS are considered very important measurements and frequently measured, but at the same time, these measurements are seen as somewhat uncertain with current sensor technology.

Basic atmospheric state measurements of pressure, temperature and humidity were listed as the most frequently measured parameters, but also listed as parameters respondents would like to measure/retrieve using a UAS, but lack the sensors. This indicates that even for these basic parameters there is a need for better sensors in some applications, which is currently not being met, despite a wide availability of sensors.

The need for uncertainty characterization and validation is well recognized, but the large variety of approaches and a tendency not to distinguish between the two indicates that there is still a significant need to characterize the quality of observations.

Measurements of cloud properties also appear to be important to respondents. However, these measurements are difficult to obtain because UAS are largely required to stay within line of sight, which implies outside of clouds. Furthermore, there is a significant risk of icing for flights into supercooled and mixed-phase clouds. There is interest in the development of technology for UAS to fly in these conditions, and working with regulatory agencies to collect these types of measurements would be welcome by the community.

Even though not with high priority, data and software services were seen as potential support to respondent's UAS research. Since UAS may provide a multitude of different measurements, the amount and structure of data may be quite complex. Some level of standardization of software, processing, and data flow may be beneficial to the UAS community. Some researchers mentioned a potential "big data" problem in this context without specifying further.

The replies to the question about UAS applications outside the respondent's specific area is consistent with UAS being a relatively new tool in atmospheric science, which has not yet been fully utilized. In particular, UAS operations using more than one platform in a coordinated flight plan appear to be a promising approach, which has been rarely implemented so far.

The fact that roughly half to three quarters of respondents viewed potential EOL programs in UAS research as complementary and only a small fraction of the respondents saw potential EOL programs as competing indicates that there is a significant need for support of the larger UAS community by NCAR EOL and that this support would be welcome.

Access to community UAS platforms, instrument development and calibration, project coordination and aid with regulations are categories where respondents felt they could use the most help if they were to use UAS for their research. However, there is no clear picture, which UAS platform(s) or which set of instruments would be most beneficial for the larger community, because most UAS users typically operate multiple platforms and continuously expand their capabilities. A community workshop on UAS would help with this, as it would allow users to provide more feedback on platforms and instruments and contribute to the shaping of EOL's role in the UAS atmospheric research community.

The previous workshops as well as the responses to our survey focus exclusively on the lower atmosphere. This focus may be representative of the larger university research community; however, it may also be a result of an implicit sampling bias due to the choice of recipients of the survey. Considerations of UAS work in the middle and upper troposphere were explicitly neglected as a result of the previous workshops. Aside from this, we do not suspect any sampling bias in our responses. We expect that whichever path is taken as a result of the outcomes of this survey the NSF research community may be well served by some dedicated UAS support program at NCAR EOL.

10 Appendix 3: White Paper Science Goals for UAS

Phillip Chilson & Greg Roberts

Executive Summary

Unmanned aircraft systems (UAS) are already significantly expanding atmospheric observations. We are currently witnessing a rapidly growing variety of both aircraft and applications with more on the way. For the present discussion, we focus on the use of small UAS (sUAS) for atmospheric research and monitoring. The term sUAS is applied to vehicles weighing less than 55 lbs (25 kg). Moreover, here we will concentrate on those operations pertaining to the atmospheric boundary layer and lower free atmosphere.

We consider a cross-section of various atmospheric research areas being advanced through the implementation of sUAS and provide a look towards some future applications. On account of time and space constraints, it will not be possible to provide comprehensive discussion of this topic, but rather, we will concentrate on several representative applications to initiate discussion on Science Goals for UAS. The focus will be on measurements of thermodynamic and kinematic properties of the atmosphere; turbulence and flux parameters; remote sensing, amounts of trace gasses; and the presence of particulates, including hydrometeors, aerosols, black carbon, and such. The authors are eager to receive inputs from various research groups on their particular science applications involving sUAS.

There are certain regulatory hurdles that must be overcome to ensure compliance with federal and international regulations regarding the operation of sUAS. It is anticipated that these regulations will undergo many changes in the coming years to address safety concerns of manned aviation operations as well as the general public on the ground. The FAA recently established six sites in the United States to test communication and crash avoidance with UAS that are expected to lead to specification of required systems for UAS platforms for operation at various altitudes and weather conditions that might pose threats to manned aviation operations. Meanwhile, current regulations allow for certain low-level operations. In the US, operations can be conducted with an onsite pilot-in-command and other trained spotters at designated sites with Certificate of Authorization granted by the FAA or individuals who have obtained a sUAS pilot license and operate under "Part 107" rules. A more detailed discussion of this topic can be found in the Workshop white paper on the Regulatory Environment.

Finally, when discussing science goals and how they could be achieved through sUAS operations, especially in contrast to traditional research aircraft, we should consider:

- Payload constraints in terms of size, weight, and power (SWaP) and compromises on instrumentation for mission-specific platforms.
- Sampling issues (maximum/minimum altitude, duration, spatial coverage)
- Extended logistics / personnel capabilities (boat launch, operations in remote or dangerous locations, etc.)

Introductory Remarks

Clearly, the availability of quality atmospheric observations is critical to our ability to monitor meteorological conditions and accurately forecast the weather. Meteorological observations fall largely into two categories: in-situ and remote sensing. The former involves the measurement by instruments, which are directly exposed to the atmosphere. In this case, continual observations of the atmosphere are limited to sensors, which can be placed at or near the Earth's surface, e.g., using instrumented towers. To obtain in-situ measurements aloft, balloons, kites, or aircraft must be used. Sensors capable of remotely probing the Earth's atmosphere, such as radar, lidar, sodars, and radiometers, are capable of providing continual observation. However, the number of atmospheric parameters such technologies can provide is limited and the data often must be inferred from other measured quantities, e.g., radar reflectivity. For example, rainfall rates provided by weather radar are estimated based on the strength of the backscattered signal from the precipitation. UAS offers the capacity to make both in-situ and remote sensing observations from a controlled platform capable of operating under conditions and in locations not necessarily possible with piloted aircraft.

As in all areas of experimental research, the evolution of the role of sUAS for atmospheric studies has experienced both the development of sensors and platforms based on specific questions and an aggregation of questions around the availability of sensors and platforms. Some of the sensors in use or envisioned include the measurement of standard atmospheric variables (temperature, pressure, humidity and wind), quantities related to turbulence and flux, common atmospheric chemical constituents (ozone, NO_x, SO_x, particulates and CO_2), imaging sensors (clouds and surface characteristics), rain and cloud particle probes, along with aerosol and particulate probes. Many sensors are currently available off-the-shelf, but most require modification or further development to accommodate size, weight, and power (SWaP) requirements, or to allow the interface with a modular sensor airframe and corresponding telemetry system. Moreover, one must carefully consider such factors as how sensors are placed on the airframe; what is the appropriate response time and sampling frequency; and representativeness of the measurements being collected. These considerations largely overlap with issues related to traditional research aircraft and NCAR has already been filling a community need by helping scientists resolve these issues and when appropriate, providing the needed infrastructure to complete science objectives. In a similar vein, running sUAS operations at research laboratories requires skill sets in aeronautics, sensor development and application, along with state and federal policies and regulations, which not every group will have developed or have the capacity to fulfill within a flight team. NCAR's role regarding sUAS could be similar to the function it plays for manned aircraft in providing the interface between the scientist and technical and logistical issues of operating sUAS.

Sample Applications

The atmospheric boundary layer (ABL) plays a major role in the development of many weather systems. Consequently, there is an ongoing need for improved observations of the ABL and parameterization schemes of the ABL for numerical weather forecasts. For example, height profiles of virtual potential temperature can be used to identify regions of thermal stratification and the degree of atmospheric stability. Moreover, vertical wind shear is capable of producing turbulence and thus turbulent fluxes in the ABL. Overall, processes in the ABL can vary dramatically over a single diurnal cycle.

Currently a significant "measurement rift" exists between tower-based observations of the atmosphere and those provided by manned airborne systems, which is especially acute at critical levels in the boundary layer. Remote sensing systems, such as radar, sodar, and lidar can fill this gap in part, but still do not provide the detailed information, particularly thermodynamic, required for modeling and a complete understanding of the structure and evolution of complex weather systems. Reports from the National Research Council and instrumentation workshops (e.g., NRC, 2009; Hoff, et al. 2012) have recommended that observing systems capable of providing detailed profiles of temperature, moisture, and winds throughout the lowest few thousand meters of the atmosphere are needed to monitor the lower atmosphere, help determine the potential for severe weather development, and rapid changes in the local severe storm environment.

A wide variety of sUAS are currently being used for atmospheric research depending on the particular application or science problem. Platforms in the weight range of 2-5 kg or less have clearly demonstrated that sUAS are capable of producing atmospheric height profiles of temperature, pressure, humidity, and wind, which are important when characterizing the vertical structure of the lower troposphere, and in particular the ABL. They have also been used to monitor certain trace gases in the atmosphere.

The ABL is also crucial to the initiation and further development of severe storms because it provides the moisture, instability, low-level wind shear, and forcing necessary for the formation of severe storms with attendant tornadoes, hail, and dangerous winds. Moreover, within the ABL reside the storm-generated outflows that regulate the strength and longevity of severe storms. Knowledge of these conditions is crucial to improving predictions of severe weather events, yet the highly variable nature of ABL properties on important mesoscale time and space scales is virtually undetected by operational observing systems. Weather radars provide critical information about internal storm structure and processes, but they do not adequately observe the environment surrounding the storms. Satellite data have poor vertical resolution in the ABL. Ground-based remote sensing systems are arguably too expensive if built into a national static observing network. The meteorological community is developing a growing interest in the use of sUAS to help address these issues.

Potential Future Directions

Fixed monitoring sites, such as those in the NWS Automated Surface Observing System (ASOS) and FAA's Automated Weather Observing System (AWOS) provide valuable, high temporal resolution information about the atmosphere to forecasters and the general public. While these are critical data sources, such networks only provide surface observations while most environmental monitoring and forecasting problems are inherently a spatially three-dimensional problem. The deployment of sUAS to collect in-situ vertical measurements of the atmospheric state in conjunction with surface conditions has potential to significantly expand weather observation capabilities. This concept can enhance the safety of individuals and support commerce through improved observations and short-term forecasts of the weather and other environmental variables in the lower atmosphere.

The continuing development of sUAS for meteorological applications requires highly reliable and robust platforms that can routinely perform regular atmospheric measurements in a variety of weather conditions, including day or night operation and during hazardous weather. We must conduct additional research and development on multiple platform types (custom built and commercial off the shelf, rotor craft and fixed-wing platforms), which can be equipped with high-precision and fast-response atmospheric sensors. Moreover, we must adapt miniaturized high-precision and fast-response atmospheric sensors to sUAS platforms. Additionally, we should compare fixed-wing and rotorcraft vehicles as to their suitability for carrying a variety of sensors for the study of ABL properties. Because various properties of the atmosphere are being sensed, the sUAS aircraft, its movements, outgassing, thermal profile, backwash and other properties have the potential to affect sensor data. Future studies will allow us to determine the proper aircraft, sensor position, and sensor suite to use in further research – with the eventual goal of being able to use a heterogeneous system of autonomous vehicles to map critical features of the ABL through both space and time, allowing for a better understanding of this critical set of related atmospheric phenomena.

The development of sUAS as an atmospheric measurement platform is providing better access to regions, which have been traditionally difficult to access, such as, remote and environmentally sensitive locations, volcanoes, forest fires, areas experiencing dangerous atmospheric conditions, and so forth. In this context, we are speaking of the last two components of the "dull, dirty, and dangerous" jobs, for which sUAS are well suited. In some cases, the sUAS could be operated as an expendable resource or serve as a delivery mechanism to deploy other expendable sensors, for example, Lagrangian drifters and dropsonde packages. Along these lines, we can also consider the application of sUAS for aerosol and cloud sampling. For cloud sampling, however, one must consider regulations pertaining to beyond visual line of sight (BVLOS) operations.

We as a community should work towards developing and demonstrating methodologies to overcome some of the most relevant challenges concerning the use of intelligent sUAS to support atmospheric science. To this end we should strive to create solutions which are accessible to researchers with a little specific training in aerospace engineering, robotics, or computer science; self-aware of its own strengths and limitations within the framework of its environment; and able to learn from its own experiences and adapt its behavior. Such systems have the capacity to adaptively monitor the environment and self-aware and self-organizing swarms of vehicles could optimally sample spatially and temporally coherent features such as frontal boundaries, dry lines, clouds, regions of turbulence, outflows, and so forth.

Key challenges and opportunities to be discussed during the Workshop: Here we provide some comments and questions, which could serve to initiate discussion on the role of UAS in the atmospheric sciences

- What are the opportunities for UAS to uniquely address key science questions?
- Does the current suite of UAS platforms adequately serve the needs of the atmospheric science community?
- How do we maximize and manage the utility of UAS in the National / International Airspace System?
- What key science questions are we currently unable to adequately address based on available sensor packages? Is the market large enough to sustain commercial development of these sensors or will they need to be developed in individual laboratories?
- What role could NCAR play in developing and maintaining standard and specialty sensors?
- Do you see a need to have “gold standard” instrumented UAS, which could be used for validation purposes across institutions? Could NCAR play a role in that capacity?
- Is there a coordination function across UAS groups that can improve airspace access, instrument flexibility and access, and measurement quality that is worthy of consideration?
- Are there specific hindrances to the use of UAS and mitigating measures that can be identified?
- How can we define the interface between scientist, instrument developer, and payload engineer?
- How much flexibility exists to test and integrate science payload prior to deployment (ARISTO-type access) – certification / validation procedures?
- Risk assessment (multiple platforms / multiple instruments are needed in case of failure in the field)
- Cross-platform consistency – standardization protocols for sensor measurements when multiple mission-specific platforms have been developed (e.g., T, RH, 3D winds, etc.)
- NASA Aerosonde program (what has been learned from that effort?)

11 Appendix 4: White Paper UAS Operations

Brian M. Argrow and Eric W. Frew
February 2017

Executive Summary

The regulatory and policy landscape for civil UAS operations has changed rapidly over the past 5 years. The 29 August 2017 publication of the Rule for Non-Hobbyist Small Unmanned Aircraft Operations, Part 107 of the Federal Aviation Regulations, Title 14 of the Code of Federal Regulations, was the first rule resulting from the many congressional mandates of the FAA Modernization and Reform Act of 2012 (FMRA; now Public Law 112-095). The FMRA has arguably had more impact on the operations of UAS in the U.S. National Airspace System (NAS), than any other policy statement or event since the creation of the FAA Unmanned Aircraft Program Office in February 2006. FMRA "Section-333" empowered the FAA Administrator (through the Secretary of Transportation) to create a process that enables the Administrator to authorize civil UAS operations on a case-by-case basis. Prior to the FMRA, UAS policies were applied uniformly, regardless of the physical size or performance of the aircraft. Operations of large civilian UAS, such as the General Atomics Predator B and the Northrup Grumman Global Hawk, both military UAS repurposed for civilian agency applications, were subject to the same policies as small UAS (sUAS) weighing in at less than 55 lb (25 kg). Because large UAS are generally operated similarly to manned aircraft of comparable size, their operations are better understood by airspace managers and air traffic controllers, thus the integration of large UAS into the NAS and over international waters has generally been less disruptive than for sUAS that are more akin to "model aircraft" whose operations FAA agreed not to regulate according to the policy published in 1981 in Advisory Circular AC 91-57.[1]

Other outcomes from the 2012 FMRA include the creation of the mandated six FAA UAS test sites, and the creation of the FAA UAS Center of Excellence. To more directly address the immediate interests of the civil UAS industry, FAA also created the Focus Area Pathfinder Initiative with industry partners investigating three focus areas: 1) Visual line-of-sight operations over people, 2) Extended visual line-of-sight operations in rural areas, and 3) Beyond visual line-of-sight operations in rural areas. The industry partners include CNN, PrecisionHawk, BNSF, and recently Gryphon Services, LLC was added under a cooperative agreement.

The 2010 field campaign for the Second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) and the 2013 Marginal Ice Zone Observations and Processes Experiment" (MIZOPEX) project are examples of science missions employing sUAS that pushed the boundaries of FAA policies and procedures for airspace access. The study of these two cases presents lessons that illustrate the need for regulators to adapt policies to accommodate users who satisfy all the regulatory requirements for authorized use of airspace, and the consequences when status-quo and a refusal to acknowledge the demonstrated ability for safe operations is the rule. The cases also illustrate the need for sUAS operators to acknowledge that the penultimate responsibility of airspace regulators and traffic controllers is to first ensure overall airspace safety.

Several opportunities and key challenges for current and future UAS operations are presented for discussion: 1) Increasing Autonomy: Operations without Continuous Human Oversight, 2) Operations Over People and Beyond Visual Line-of-Sight, 3) Nighttime Operations, and 4) Urban/Suburban Operations, and 5) Multiple-UAS Operations.

Summary of Previous Work

As part of the Department of Transportation, the FAA develops and administers airworthiness standards against which aircraft are certified for flight. The FAA also maintains and administers standards for pilot certification through licensure. Standards for the certification of aircraft and pilots, and regulations for the operation of aircraft in the National Airspace System (NAS) are codified in the Federal Aviation Regulations (FARs), Title 14 of the Code of Federal Regulations (CFR). Prior to the issuance of Part 107 in August 2016, there were no FAA regulations for the operations of UAS, nor for the certification/licensure of UAS pilots. Part 107 only addresses

[1] AC 91-57 is now superseded by AC 91-57a, published 2 September 2015.

the operations of small UAS (sUAS) [those weighing less than 55 lb (25 kg)], at a maximum altitude over the ground, or over an obstacle, of 400 ft (122 m). The status of UAS operations in the NAS not covered by Part 107 remains unchanged since the policy changes resulting from congressional mandates in the FAA Modernization and Reform Act (FMRA) of 2012 (now Public Law 112-095). The following discussion first provides a background of some of the more important decisions leading up to the current state of UAS regulations and authorizations that enable UAS operations in the NAS. Since most developments of relevance for the NCAR UAS Workshop have been for sUAS operations, with the exception of a brief discussion of large UAS missions, the remainder of the discussion will focus on sUAS. Also, since the University of Colorado Boulder (CU) has had major influence on the regulatory policies related to sUAS operations, the sUAS discussion will be based significantly on CU experiences.

Certifications and Authorizations

Similar to manned aircraft, UAS are broadly categorized as: i) Civil UAS that are operated for commercial purposes, and ii) Public UAS that are operated by the U.S. or state governments, and their associated agencies [1]. In 2006, FAA stood-up the Unmanned Aircraft Program Office (UAPO) that began to administer applications for Certificates of Waiver or Authorization (COAs) through an online portal. Prior to the 2012 FMRA, civil UAS could only be operated in the NAS, outside of special-use airspace, with a Special Airworthiness Certificate in the Experimental Category. The COA enables a public entity to "self-certify" a UAS with the submission of an Airworthiness Statement prepared according to an accepted standard as described in Ref. [2]. In our experience, over the years the Airworthiness Statement for a custom-built sUAS has evolved from a 30-page document that states line-for-line compliance with the selected standard (e.g., CU has always employed the DoD standard MIL HNBK 516B), to now a one-page statement that attests that the public entity[2] has met the requirements of the standard. Therefore, for circumstances where Part 107 does not apply, the certification or authorization process, and access to the NAS, remains simpler for public UAS. A 2009 Memorandum of Agreement between FAA and the Department of Defense (DoD) streamlined FAA authorizations for DoD UAS flights in the NAS [3]. Because they are under the oversight of state governments, public (state) universities are allowed to operate public UAS with a COA; private universities cannot, unless they are contracted to work under a COA obtained for a public UAS.

Outside the U.S., most member states in the United Nations manage their airspace according to the accepted standards of the International Civil Aviation Organization (ICAO), where again there are no specific ICAO UAS standards. As of this writing, several ICAO-member states have similar policies to the U.S., but generally pursue their own civil aviation interests with processes developed for allowing UAS in their specific airspaces.

The FAA may not regulate airspace in certain a "special use airspace" or a "special area of operation (SAO)" which includes active Prohibited, Restricted, or Warning areas [4]. When active, aircraft operations in a SAO might be conducted based on rules of administered by the airspace manager. Prior to the FMRA, the SAO was usually the easier of the two options for the operations of civil UAS in the national airspace system. In some of the early interactions of CU researchers with the UAPO, an often repeated line was: "if you want to fly these, do it in restricted airspace where we (FAA) have no jurisdiction." The other option is the aforementioned Special Airworthiness Certificate, Experimental Class, which few have pursued because of the onerousness of the process. Ballinger and Bossert [12] present one of the few successes of, which we are aware, for a sUAS special airworthiness certification.

The "see-and-avoid rule" in the General Operating Rules of FAR Part 91 presents the greatest challenge for the operation of UAS in the NAS. Although there has been progress in the development of sense-and-avoid technologies that sometimes rely on non-vision-based sensing systems and automatic decision-making systems, no sense-and-avoid system is yet certified to satisfy the see-and-avoid rule. Murphy and Argrow [5] report on a workshop discussion about the requirement for a UAS to be capable of demonstrating "an equivalent level of safety" to the requirements of a licensed human pilot for the see-and-avoid rule. At that time the machine equivalent was referred to as "sense and avoid" to make it clear that a machine might satisfy the requirement with

[2] In this case, the University of Colorado Boulder, as certified by the Office of the Colorado State Attorney General.

sensors distinctly different from the human eyeball. A subtle change in the argument was suggested to replace "equivalent level of safety" with "acceptable level of safety," since the point is to develop a system that provides an acceptable (likely superior) level of safety as compared to a human pilot.

In lieu of a certified see/sense-and-avoid system, a UAS can only fly in the airspace regulated by the FAA with special provisions that compensate for the inability of the system to directly satisfy the Part 91 requirement from an airborne unmanned aircraft (UA). This might include a visual observer (VO) in a chase plane, or a ground-based VO who can provide the visual function required to satisfy the see-and-avoid rule. Until recently, VOs had to have a class-2 medical certification, which is a greater requirement than the class-3 medical requirement for conventional general aviation pilots in a manned aircraft, however it appears that the class-2 medical may not be required if FAA authorizes VO (and pilot) certification as part of the self-certification process by a public entity.

Large UAS Operations

The resources required to operate large UAS has limited their operations primarily to government agencies, particularly NASA, NOAA, and DHS. Programs of note include a series of NASA programs employing Altus, Altair, and Ikhana (various versions General Atomics Predator-series UAS repurposed for civilian applications) for a series of fire-mapping missions over the western U.S., that started about 2001 [6]. The more recent NOAA "Sensing Hazards with Operational Unmanned Technology (SHOUT) Program is focused on sensing high impact weather-related hazards. In a partnership with NASA, the SHOUT Program has completed several long-endurance, oceanic targeted-observation missions with the Global Hawk UAS [7].

FAA Modernization and Reform Act (FMRA) of 2012 and Section 333 Exemptions

With the passage of the FAA Modernization and Reform Act (FMRA) of 2012 (now Public Law 112-095) [8], the U.S. Congress directed FAA to accelerate its efforts to safely integrate UAS into the National Airspace System. One of the most impactful provisions of the FMRA is *Section 333 Special Rules for Certain Unmanned Aircraft Systems*, that states: "*—If the Secretary determines under this section that certain unmanned aircraft systems may operate safely in the national airspace system, the Secretary shall establish requirements for the safe operation of such aircraft systems in the national airspace system.*" Between the publication of the FMRA in February 2012 and the publication of Part 107 in August 2016, thousands of civil UAS operators gained limited access to the NAS with FAA authorization through FMRA Sect. 333.
With pace of sUAS operations, both authorized and not, the FAA Administrator issued an "Interpretation of the Special Rule for Model Aircraft" [9] to provide an updated interpretation of the 1981 Advisory Circular AC 91-57 that first defined "model aircraft," recognized that they present a potential hazard to manned aircraft operations, and then provided operations guidelines to mitigate the safety risks.

Part 107 Rule for Operations of Small UAS

On 29 August 2017, 14 CFR Part 107 Rule for Operations of Small UAS became active. Although the requirement for UAS registration was the first significant policy change to broadly affect sUAS operations since the COA-online process was established in 2006, as previously mentioned, Part 107 is the first regulation for the operation of a UAS of any size. An immediate consequence of Part 107 was to eliminate the need for most FMRA Section-333 exemptions for sUAS operations below 400 ft (122 m). Part 107 also established clear requirements for a Remote Pilot Certificate and re-affirmed the statutory requirement that all sUAS greater than 0.55 lb (0.25 kg) must be registered. Additional constraints include a requirement for daytime, visual line-of-sight (VLOS) operations only, and a prohibition of flying sUAS over people. However, Part 107 waivers can be sought for any of the prescribed constraints. As of this writing, a number of waivers have been granted that include BVLOS and nighttime operations.

FAA UAS Test Sites, Center of Excellence, and Pathfinder Program

In December 2013, FAA awarded permission to six university-agency consortia to create UAS test sites at locations around the country, as mandated by Congress in the FMRA.[3] This was followed in 2015 with the award of the FAA UAS Center of Excellence (COE) to a university-led team. In addition to the UAS test sites and the UAS COE, FAA also created the "Focus Area Pathfinder Program" [10] with three industry partners to investigate: 1) Visual line-of-sight operations over people (CNN); 2) Extended visual line-of-sight operations in rural areas (PrecisionHawk); and 3) Beyond visual line-of-sight operations in rural/isolated areas (BNSF). These are applications that currently require an exemption or waiver. Since the release of Part 107 it is clear that BVLOS, flying over people, and nighttime flying are primary areas of FAA research focus by the COE, test sites, and Pathfinders. The creation of the test sites and COE appear to enable FAA to be more responsive to the need to conduct research for equipment and operations standards and policies.

Pushing the Limits: Two Case Studies

As mentioned previously, the only UAS-specific regulation is FAR Part 107, which applies to UAS weighing less than 55 lb (25 kg) operated below 400-ft (122-m) altitude. Other UAS operations are enabled through a FMRA Section-333 exemption, a COA, or a Memorandum of Agreement. The following two cases are presented to illustrate the types of interactions that have occurred over the past 10 years, where public sUAS operators have attempted to conduct first-of-their-kind operations that required FAA regulators to assess current sUAS policies and how they addressed the proposed operations.

<u>Case 1: Nomadic UAS Operations</u>

In 2010, the University of Colorado Boulder introduced "nomadic deployments" of a sUAS during the field campaign for the "2nd Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX2)". Stachura et al. [2], describe the interactions with the FAA Unmanned Aircraft Program Office (UAPO) that led to the creation of 59 COAs covering about 24,000 mi^2 (62,000 km^2) of northeast Colorado, northwest Kansas, southwest Nebraska, and southeast Wyoming. Each of the COAs was nominally a box, 20-mi (32 km) on each side, with a 1,000-ft (305-m) AGL ceiling. Four of the COAs had 400-ft (122-m) ceilings because of the proximity of the airspace to approaches to airports; those COAs proved to not be useful. To satisfy the Part-91 see-and-avoid requirement, and the requirement for a fixed ground control station (GCS), a concept of operations (CONOPs) was developed where the UA (the Tempest UAS) was launched at the GCS site, then commanded to automatically track a 2.4-GHz WiFi radio node carried in a ground "tracker vehicle." Inside the tracker vehicle was a driver, a meteorologist, a VO, and a remote UAS operator with limited control of the UA through the WiFi link. The Pilot in Command (PIC) and the UAS operator maintained long-range command and control from the stationary GCS through a 900-MHz GCS-UA link, and VHF radios were used to maintain voice communications between the PIC and the occupants of the tracker vehicle.

At the start of the field campaign, FAA required that COAs be activated with Notices to Airmen (NOTAMs) 72-48 hours in advance of UA launch. Within 2 weeks, this requirement was reduced to up to 4 COAs activated with NOTAMs 2 hours in advance of UA launch. After a review of the CONOPs and procedures with the Denver Area Route Traffic Control Center (ARTCC) at the conclusion of the VORTEX2 field campaign, FAA reduced the COA NOTAM lead time to 1 hour. Since 2010, the original 59 COAs shown in Fig. 1 for Tempest UAS operations have been consolidated into 5 COAs for the operation of the Tempest/TTwistor UAS covering more than 380,000 mi^2 (with 40,000 mi^2 two pending COAs) over seven states of the Great Plains, with a ceiling of 2,500 ft (760 m), and provisions for the simultaneous operation of multiple-UAS. The updated CONOPs eliminates the fixed GCS in favor of a fully mobile GCS carried inside the tracker vehicle with the PIC, a VO, a meteorologist, and a driver. This CONOPs was successfully demonstrated in June and October 2016 with several flights in Colorado, Kansas, Nebraska, and Oklahoma. Multiple-UAS operations will begin in spring 2017.

Lessons learned in working with the FAA during VORTEX2 include:

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[3]For reasons that remain unclear to us, the UAS test site that had been operated by New Mexico State University was not originally counted as a seventh site in addition to the six sites designated in 2016.

1. Prior to submitting a COA application, contact the appropriate liaison at the FAA UAS Integration Office [UASIO; formerly the UAS Program Office (UAPO)] to discuss your intentions and inform the UASIO that you will discuss the operations with the affected ARTCCs to discuss potential air traffic control concerns.
2. During the COA online submission, prepare maps to identify special-use airspace (restricted areas, military operations areas (MOAs), warning areas) and prepare text that states how your activities will be conducted (e.g., “UAS activities will avoid restricted airspace R-XXXX). Once the COA is submitted, be prepared to discuss a plan for how the special airspace managers will be notified prior to operations in their area, and how you will coordinate with airspace managers if the special-use area is active during flights.
3. If relatively small changes are made to the UAS or the CONOPs, submit a “Pen & Ink” request that explains the changes. If properly done, the COA will be updated with the requested changes within a few days, without need for a COA re-submission.

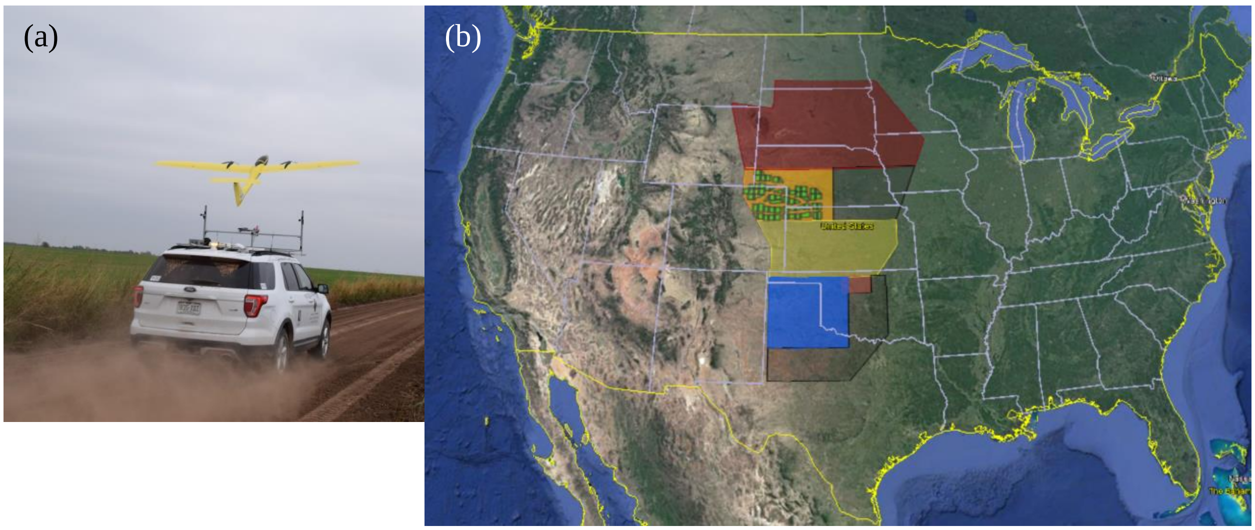

Figure 1 *(a) Roof launch of a TTwistor UA in northern Oklahoma in 2016; (b) original 59 Tempest COA areas during the 2010 VORTEX2 field campaign compared to current Tempest/TTwistor COA areas, the two transparent polygons are pending COA areas.*

<u>Case 2: MIZOPEX and Fully Autonomous UAS Flights—Almost</u>

Maslanik [11] reports on the “Marginal Ice Zone Observations and Processes Experiment” (MIZOPEX) missions that were conducted July-August 2013 from the Oliktok Long Range Radar Station at Oliktok Point, Alaska, about 30 miles (48 km) west of Prudhoe Bay Alaska. Flights begin in Restricted Area R-2204, a restricted flight area of 4 miles (6.4 km) in diameter centered at Oliktok Point and assigned to the Office of Science in the U.S. Department of Energy for atmospheric research purposes. MIZOPEX mission flight paths extended northward through an Altitude Reservation (ALTRV) corridor to international airspace. The MIZOPEX campaign established several important new “firsts” including the first flights of scientific payloads using unmanned aerial system from northern Alaska into international airspace and over international waters.
Over the four weeks, MIZOPEX missions included flights of the ScanEagle and DataHawk instrumented unmanned aerial systems. The ScanEagle was operated by a team from the University of Alaska Fairbanks. DataHawks were operated by a team from the University of Colorado Boulder that included the MIZOPEX Principal Investigator, Professor Jim Maslanik. The following excerpt from the final report [11] recounts the actions of FAA that prevented one of the primary mission deployment objectives:

> *“Our attempts at obtaining a COA for BLOS operation of the small CU DataHawk UAS, or alternatively, an exemption under Part 101 rules (i.e., treatment as equivalent in risk to a small balloon payload), were*

not approved by FAA. The COA was rejected based on the fact that our plans involved operating the aircraft beyond communications range (i.e., in "intentional lost-comm mode"). The reasons for rejecting the Part 101 exemption have not been given formally to CU. Informally, it was suggested that an insufficient safety case was made. A standard within-line-of-sight COA had been granted earlier for DataHawk, but was not needed because we were able to operate within R-2204."

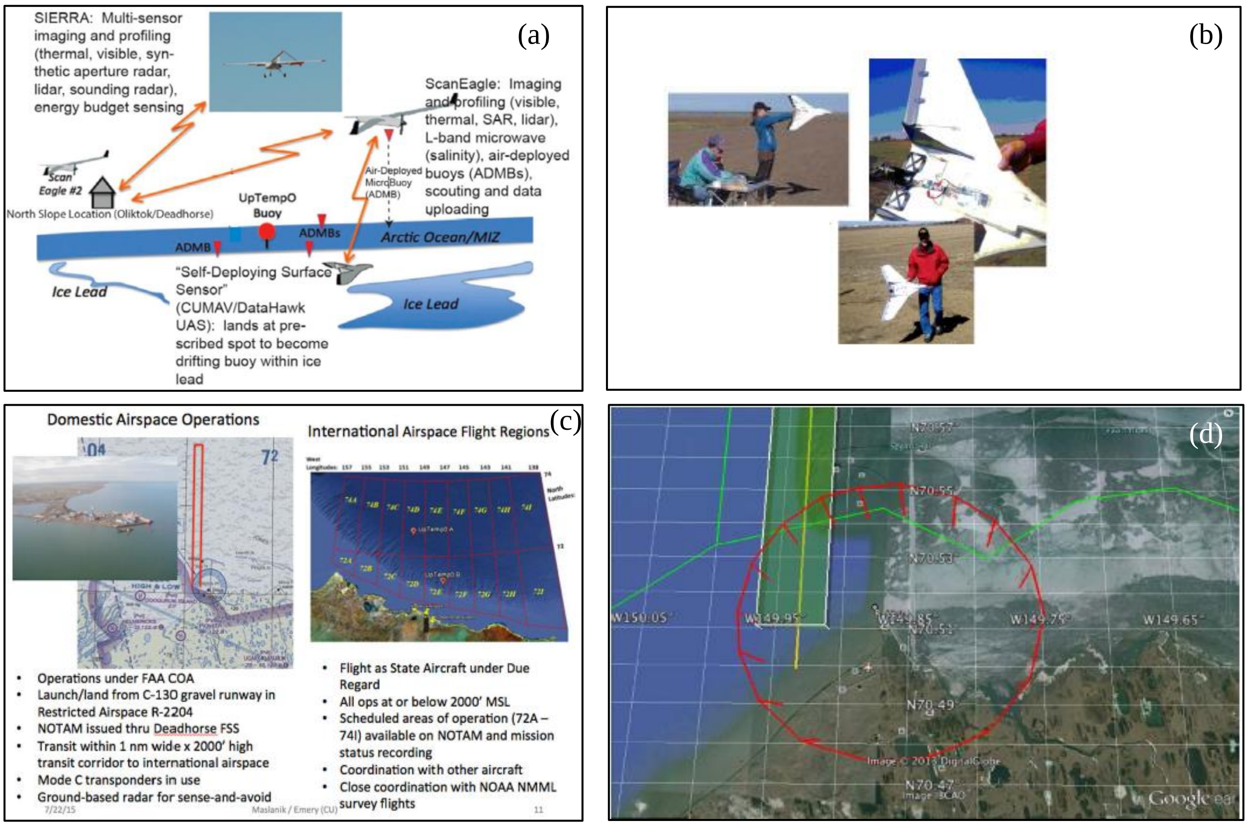

Figure 2 *(a) MIZOPEX concept of operations; (b) Datahawk UAS; (c) planned airspace over domestic and international waters; (d) zoomed view of restricted airspace at Oliktok Point and corridor to international waters*.

As shown in Figure 2, the plan for MIZOPEX was to fly the Scan Eagles over the marginal ice zone, to locate open-water leads. The 1.5-lb (0.68-kg), foam airframe, Datahawk UAS, would then fly through the ALTRV corridor at an altitude not to exceed 50 ft (15 m) above the water, to land in the open water at the designated locations. The Datahawks were equipped with an instrumented tether to be suspended from the foam airframe to become a micro-buoy reporting data to the ScanEagles during periodic overflights. Because the ScanEagles were equipped with satellite radio link, they were allowed to fly beyond visual line-of-sight (BVSOL). Since there was no expectation of recovery, the Datahawks were not equipped with a long-range or satellite link, so once the communications range was exceeded, FAA considered the UAS would operate in an unacceptable "fully autonomous" mode. Given that the airframe is made of foam and small metallic parts, similar to one of the larger radiosondes (e.g., a Vaisala RS-41 Ozonesonde[4]) that are routinely launched by balloon under FAR Part 101, a request was made to operate the Datahawk as a "guided radiosonde" under Part 101. As alluded to in Ref. 11, the Part 101 exemption request was rejected. One of the authors received the rejection correspondence the: "it is not a balloon."

[4] http://www.vaisala.com/en/products/soundingsystemsandradiosondes/radiosondes/Pages/default.aspx

While MIZOPEX was successful by many measures, the investigators failed to receive FAA authorization to fly one of the most low-risk, high-return missions probably ever proposed. In the final report, Maslanik lists recommendations and lessons learned for "campaigns that have challenging and/or unique UAS aspects." A few of these include:

1. As early as possible, designate a single field campaign point of contact (POC) to oversee interactions with FAA.
2. Request that, if possible, FAA provide a complementary single POC to help assure that consistent information and interpretations are being passed to the campaign's POC. This would be warranted for campaigns with special complications, such as those contained within MIZOPEX.
3. Provision of exemptions for very low-risk UASs such as DataHawk under Part 101 (i.e., treating the aircraft as posing risk comparable to a weather balloon) would open up considerable capabilities for sensing using UASs. An alternative would be to allow such aircraft to operate under a COA in fully autonomous mode outside communications range (i.e., in a planned lost-link mode.)

Discussion Topics: Opportunities and Key Challenges for Current and Future UAS Operations

1. *Increasing Autonomy: Operations without Continuous Human Oversight.*

   In 2014, the National Research Council's report autonomy research for civil aviation [13] reviewed the state of increasingly autonomous (IA) for civil aviation, and discussed the "benefits in terms of safety, reliability, affordability, and/or previously unattainable mission capabilities." One of the challenges is encapsulated in the statement: *"… Develop the system architectures and technologies that would enable increasingly sophisticated IA systems and unmanned aircraft to operate for extended periods of time without real-time human cognizance and control.*" Although this is expressed in the context of "civil aviation," it is reasonable to extend this to all "civilian aviation," therefore including the operation of public aircraft that share the airspace. The now overused expression of UAS being appropriate for missions that are "dull, dirty, or dangerous" is appropriate when describing many missions of interest to the science community, where endurance and persistence in potentially hostile environments are exactly the capabilities enabled by increasingly autonomous UAS.

2. *Operations Over People and Beyond Visual Line-of-Sight*

   Following the publication of FAR Part 107, the sUAS community immediately turned attention on the constraints of VLOS operations. Having to keep the UA in sight with unaided vision severely limits some of the applications of most interest. This is being particularly driven by large commercial interests such as Amazon and Google who have been competing to develop "drone" package delivery services that necessarily require BVLOS operations. In addition to the UAS test sites and the UAS COE, FAA also created the "Focus Area Pathfinder Program" with three industry partners to investigate: 1) Visual line-of-sight operations over people (CNN); 2) Extended visual line-of-sight operations in rural areas (PrecisionHawk); and 3) Beyond visual line-of-sight operations in rural/isolated areas (BNSF). While the commercial interests are obvious, eliminating the barriers to these categories of operations would enable a broad range of science applications.

3. *Nighttime Operations*

   FAR Part 107 and most COAs restrict sUAS operations to daylight hours, in part to satisfy the VLOS requirement. This constraint is a major impediment to many science and emergency/disaster response applications. There are many opportunities for low-risk deployment of sUAS for nighttime operations. An example is monitoring the nighttime behavior of an active wildland fire. While there are examples of nighttime sUAS operations under an emergency COA [14], the perceived risk of night operations appears to often be artificially inflated compared to daylight operations, thus is an area for sUAS operators should lobby to increase research opportunities and airspace access.

4. *Urban/Suburban Operations*

   This topic might be considered an extension of the Pathfinder topics described in (2), however, suburban/urban environment includes more challenges than the rural or semi-rural applications described earlier. One of the prevailing issues is increased hardware/software reliability. Standards for sUAS construction and operations are currently in development. Since there are yet no requirements to construct sUAS according to any published standard, reliance on components repurposed from the hobby industry will continue. In addition to the obvious challenges of obstacle avoidance and possible geo-fencing, hardware/software reliability present significant challenges.

5. *Multiple-UAS Operations*

The idea of deploying swarms of sUAS was prominent 10-15 years ago, to the point that "swarm" became a buzzword with an accompanying loss of precision in its meaning. The clamor over swarm deployments waned with concerted efforts of FAA to enforce requirements for COAs and special airworthiness certificates for operations outside special-use airspace. Regardless, science applications for the simultaneous deployment of multiple UAS abound. In 2011, CU received FAA authorization to conduct multi-UA operations with a pen & ink change to an existing COA. To ensure UA separation to prevent mid-air collisions, one requirement is that each UAS have a dedicated GCS, PIC, and VO. CU has operated safely with these constraints; however the burden of replication of equipment and personnel severely constrains applications. Easing or eliminating the replication requirements will expand opportunities for novel missions.

References

1. U.S. Code 40102 Title 49. Available online at http://www.gpo.gov/fdsys/pkg/USCODE-2011-title49/pdf/USCODE-2011-title49-subtitleVII.pdf (accessed 1/31/2017).
2. Maciej Stachura, Jack Elston, Brian Argrow, Eric W. Frew, and Cory Dixon, "Certification Strategy for Small Unmanned Aircraft Performing Nomadic Missions in the U.S. National Airspace System," **Handbook of Unmanned Aerial Vehicles**, Editors: K. Valavanis, George J. Vachtsevanos, Springer, pp. 2177-2198 (2013).
3. Memorandum of Agreement Concerning the Operation of Department of Defense Unmanned Aircraft Systems in the National Airspace System. Available online at http://www.usaasa.tradoc.army.mil/docs/br_Airspace/DoDFAA_MOA_OpsinNAS_16Sep2013.pdf (accessed 1/31/2017).
4. FAA Flight Standards Service, **Pilot's Handbook of Aeronautical Knowledge 2016**, United States Department of Transportation, Federal Aviation Administration, Airman Testing Standards Branch, AFS-630.
5. Murphy, R. and Argrow, B., "UAS in the National Airspace System: Research Directions," *Unmanned Systems*, **27**, No. 6, pp. 23-28 (2009).
6. Merlin, P.W., **Ikhana Unmanned Aircraft System: Western States Fire Mission**, National Aeronautics and Space Administration (2009).
7. Sensing Hazards with Operational Unmanned Technology (SHOUT). Available online at https://uas.noaa.gov/shout/. Accessed 1/31/2017.
8. Public Law 112-95. Available online at https://www.congress.gov/112/plaws/publ95/PLAW-112publ95.pdf. Accessed 1/31/2017.
9. FAA, "Interpretation of the Special Rule for Model Aircraft," U.S. Federal Register, 25 July 2014. Available online at https://www.federalregister.gov/documents/2014/07/25/2014-17528/interpretation-of-the-special-rule-for-model-aircraft (accessed 1/31/2017).
10. Focus Area Pathfinder Program. Available online at: https://www.faa.gov/uas/programs_partnerships/focus_area_pathfinder/. Accessed 1/31/2017.
11. Maslanik, J.A., "Investigations of Spatial and Temporal Variability of Ocean and Ice Conditions in and Near the Marginal Ice Zone: The "Marginal Ice Zone Observations and Processes Experiment" (MIZOPEX) Final Campaign Summary," Ed. by Robert Stafford, DOE ARM Climate Research Facility. DOE/SC-ARM-15-046 (2016).
12. Ballinger, M. and Bossert, D., "FAA Certification Process for a Small Unmanned Aircraft System: One Success Story," AIAA Infotech@Aerospace 2007 Conference and Exhibit, Rohnert Park, CA, May 2007.

13. National Research Council, “Autonomy Research For Civil Aviation: Toward a New Era of Flight,” The National Academies Press, ISBN 978-0-309-30614-0 (2014).
14. “FAA gives green light to drones monitoring.” Available online at: fireshttp://www.hoodrivernews.com/news/2014/jul/30/faa-gives-green-light-drones-monitoring-fires/. Accessed 1/31/2017.

12 Appendix 5: White Paper UAS Platforms

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1.0 Executive summary

Many atmospheric science investigations that typically use manned aircraft can be classified as dull, dirty, or dangerous. UAS platforms are uniquely suited for these types of missions. Numerous small UAS and several large UAS have been used successfully by government agencies and academia for scientific research. No single class or type of UAS can satisfy all anticipated mission scenarios. This whitepaper provides an overview of the different classes of UAS and their capabilities along with some recommendations for implementation of this technology for scientific pursuits.

2.0 Outline of the topic

1. UAS Classifications
2. Past UAS activities / platforms used for Atmospheric Research
3. Available UAS and their performance specifications
4. Notes regarding trade-offs between altitude, endurance and payload
5. Data handling and telemetry

2.1 UAS Classification

UAS can be categorized in a variety of ways based on vehicle attributes including the type of aircraft (fixed wing or rotorcraft), flight altitude (high, medium, low), weight, speed, etc. In general, larger aircraft use larger engines that confer higher altitude, longer endurance and more payload capacity than smaller vehicles. Cost of maintenance and operations and consequently research budgets also scales with size.

Different organizations (NATO, DoD, NASA, State Regulatory Authority) each have defined groups or classes of UAS. Most of these classifications are based on weight and altitude or speed. While classification group nomenclature differs among these organizations, some specific weight limits are commonly used. The typical weight limits for different classes of vehicles are 25 kg (55 lbs), 150 kg (330 lbs), and 600 kg (1320 lbs).

The Federal Aviation Administration (FAA) has initially provided regulations (14 CFR Part 107) for "small UAS" operations for vehicles under 55 pounds [1]. Additional restrictions include maximum speed of 87 knots and maximum altitude of 400 feet. The 55-pound weight limit has been historically used to define model aircraft in the U.S.

Based on FAA interaction with other organizations concerning integration of UAS in the National Airspace System, we could expect future FAA regulations to consider vehicle classes with weights from 55 to 330 pounds, 330 to 1320 pounds, and greater than 1320 pounds. Again this would historically relate directly to current ultralight, light sport aircraft, and normal/utility and transport category aircraft and rotorcraft respectively.

DoD subdivides vehicles weighing more than 1320 pounds into two groups based maximum altitude [2]. FAA may eventually add additional classes based on a 12,500pound weight. This would enable promulgation of airworthiness and operational standards for normal (<12,500 lbs) and transport (>12,500 lbs) category aircraft and rotorcraft to UAS. A representative classification matrix is shown below in Table 1. The NASA classification matrix, shown in Table 2, includes both weight the airspeed limitations for three categories of UAS [3]. In addition, NASA specifies requirements for the UAS Pilot and Observer.

Table 1. Representative UAS Classification

Weight kg	Normal Operating Altitude, ft	Mission Radius km	Typical Endurance, hrs	Representative Platforms
< 2	< 400	5	< 1	Black Widow, Raven
2 - 25	< 3000	25	2 - 8	Aerosonde, Scan Eagle, Puma
25 - 150	< 5000	50	4 - 12	Manta B
150 - 600	< 10,000	200-500	8 - 14	SIERRA, Viking 400, TigerShark
>600	<18,000	1000	>20	Ikhana (Predator B)
>600	>18,000	5000	>24	Global Hawk

Table 2. NASA UAS Classification Matrix

Category	I	II	III
Weight	≤ 55 lb (25 kg)	55-330 lb (25-150 kg)	> 330 lb (150 kg)
Airspeed (kt)	≤ 70	≤ 200	> 200
Type	Model or sUAS	sUAS	UAS

2.2 Past UAS activities / platforms used for Atmospheric Research

UAS have been utilized in many science missions, going all the way back to 1993. Some of these missions have targeted imagery (fire, vegetation) and surface measurements, but many have been applied to atmospheric research, both physical (dynamics, weather, etc.) and chemical (e.g., composition). The timeline in Figure 1 shows early NASA UAS missions. The information in Table 3 provides more information about a selection of atmospheric research activities.

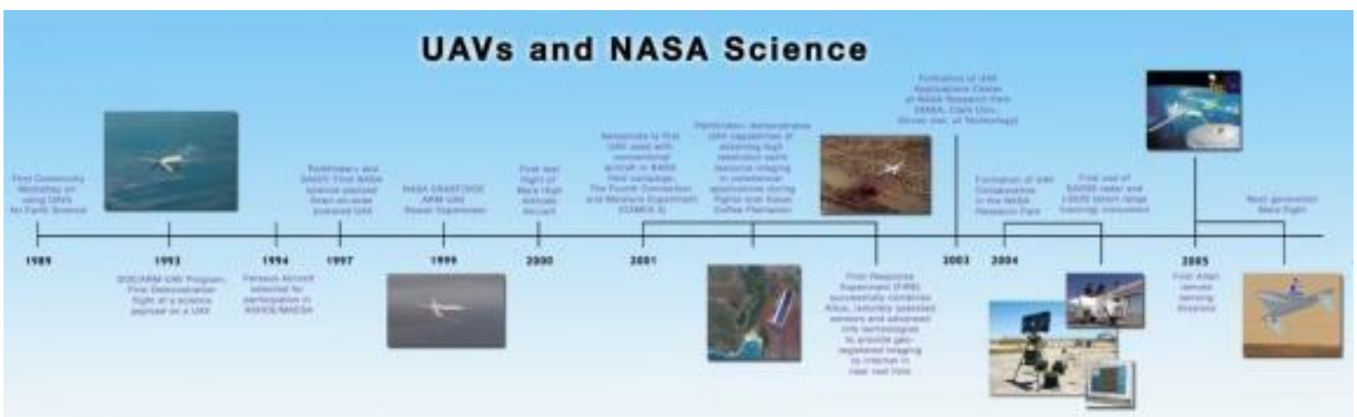
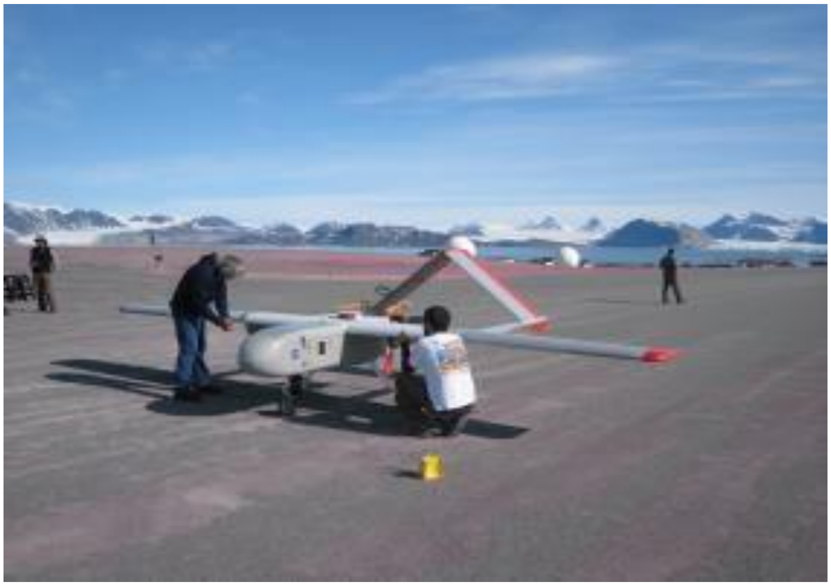


***Figure 1**. Early UAV timeline*

Table 3. Representative UAS Missions

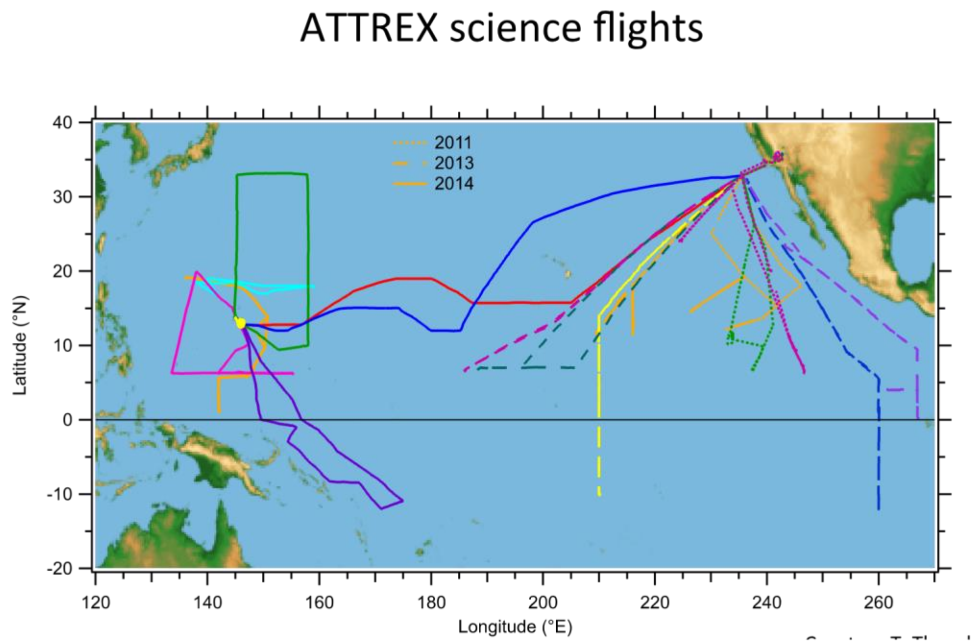
Mission	Agency	PI	Date	UAS
Altus Cumulus Experiment (ACE)	NASA / Marshall	Blakeslee	2000	Altus
ARM-UAV	DOE	Gore	2002	Gnat
Aerosonde Hurricane mission	NOAA	Cione	2005	Aerosonde
Maldives (vertical stack)	Scripps	Ramanathan	2008	Mantas (3)
GloPac	NASA / NOAA		2010	Global Hawk
GRIP	NASA / NOAA		2010	Global Hawk
Western States Fire	NASA	Ambrosia	2007-2009	Altair, Ikhana
CASIE	NASA	Maslanik	2009	SIERRA
MIZOPEX	NASA / NOAA	Maslanik	2013	SIERRA, Scan Eagle, DataHawk
SO_2 sampling	NASA / JPL	Pieri	2014	DragonEye
ATTREX	NASA	Jensen	2011 -2014	Global Hawk
HS3	NASA		2012-2014	Global Hawk
SHOUT	NOAA	Hood	2015-2016	Global Hawk

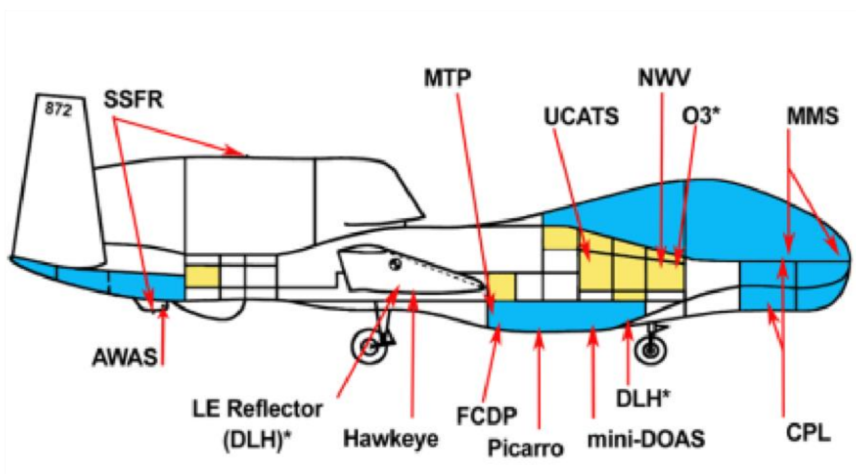
*Multiple Manta UAS participated in the **Maldives AUAV Campaign** (MAC) to observe Aerosol-Cloud-Radiation-Climate Interactions (Scripps, 2006)*

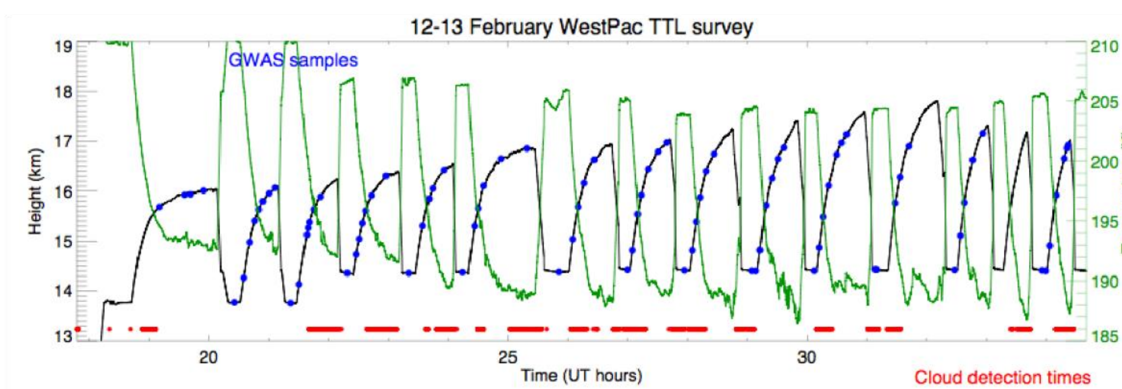


SIERRA UAS during ***Characterization of Arctic Sea Ice Experiment (CASIE)*** *with LIDAR and C-band SAR (NASA, 2009)*

Global Hawk flew from Wallops Flight Facility for the Sensing Hazards with Operational Unmanned Technology (SHOUT) mission to track Atlantic Hurricanes (NOAA, 2015 and 2016)







The Airborne Tropical TRopopause Experiment sampled profiles over the Pacific (2013, 2014, NASA)

2.3 Available UAS and their performance specifications

Most of the commercially available "drones" are multi-rotor aircraft designed for short distance and short duration flight. For the most part, they fall into the FAA "small UAS" (sUAS) category, are limited in payload weight and altitude, and are often restricted to flight within line-of-sight of the operator. US government agencies that have been involved in using UAS for science experiments either own their own aircraft or contract with vendors for flight activities. For the most part, government agencies own and operate only a few of their own UAS. Table 4 shows a representative list of agency-owned UAS. Table 5 shows some of their performance specifications. Table 6 lists some of the UAS available from industry that may be useful for science.

Table 4 Representative Agency UAS aircraft

Agency	UAS owned and operated
NASA	SIERRA, VIKING400, DragonEye, Ikhana, Global Hawk
JPL	3DR Solo, 3DR X-8, DJI S1000, QAV 400, Infinity-6
DOE	Arctic Shark (variant of TigerShark); CU Datahawk
NOAA	Scan Eagle
NRL	Ion Tiger – 48 hours, 5 lb
Univ. Alaska Fairbanks	Scan Eagle
Univ. Colorado	CU Datahawk, Tempest UAS

Table 5. Agency UAS Specifications

Name	Max Altitude, ft	Max flight duration, hr	Max payload, lb
Tempest	400	1.5	7
DragonEye	1000	1	1
IonTiger	1000	48	5
ScanEagle	19,500	24	EOIR sensors included
SIERRA	12,000	10	100
Viking 400	25,000	11	100
TigerShark	15,000	10	100
Ikhana (Predator B)	45,000	20	2000
Global Hawk	65,000	26	1800

Table 6 Commercial UAS suitable for atmospheric science

Vendor	Aircraft name	Notes
DJI	Matrice 600, S-900, S-1000	EPA plume sampling
3DR	IRIS, X-8	Quadcopter with aerial camera
Swift Engineering	020	Vertical take-off, level flight
Lockheed Martin /MLB	VBAT	Long endurance
Boeing / InSitu	ScanEagle	Very long endurance, swappable payload
AAI Corp / Textron	Shadow 200 TAUS	FAA Experimental Airworthiness Certificate, multiple payload capability
Griffin Aerospace	Outlaw Sea Hunter	Operated at Alaska test range
Vanilla Aircraft	VA001	Very long endurance, heavy fuel

2.4 Trade-offs

UAS are frequently advertised by their payload capability, flight duration, or maximum altitude. It is important to note that an aircraft can often not achieve maximum performance of all these parameters at one time. A trade-off between payload weight and flight duration may be made to exchange fuel, and hence flight time, for payload carrying capacity, for example.

Payload is proportional to vehicle gross weight as shown in the following Figure 2.

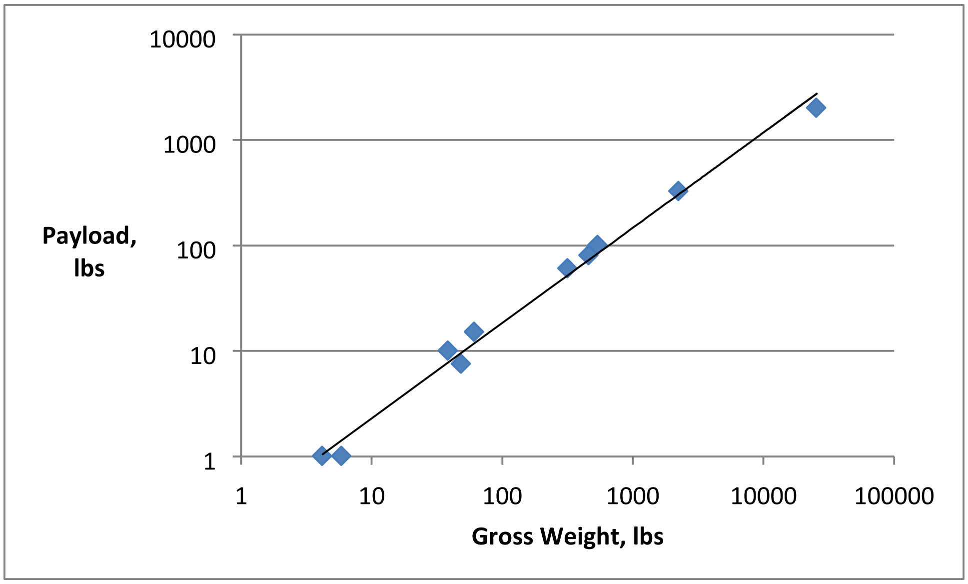


Figure 2. *Payload weight for representative UAVs listed in Table 1.*

Another trade-off is between cost (or complexity) and payload capacity. Figure 3. shows the payload capacity for several small and mid-size UAS. Very large UAS, like Global Hawk and Ikhana can carry up to 2000 lbs payload, but these are large, expensive aircraft. System cost can be difficult to compare directly due to system complexity, various payload options, and even the number of air vehicles and ground stations comprising a complete system. Figure 4 shows typical single vehicle cost and payload capacity ranges for current DoD UAS groups Note the logarithmic scale.

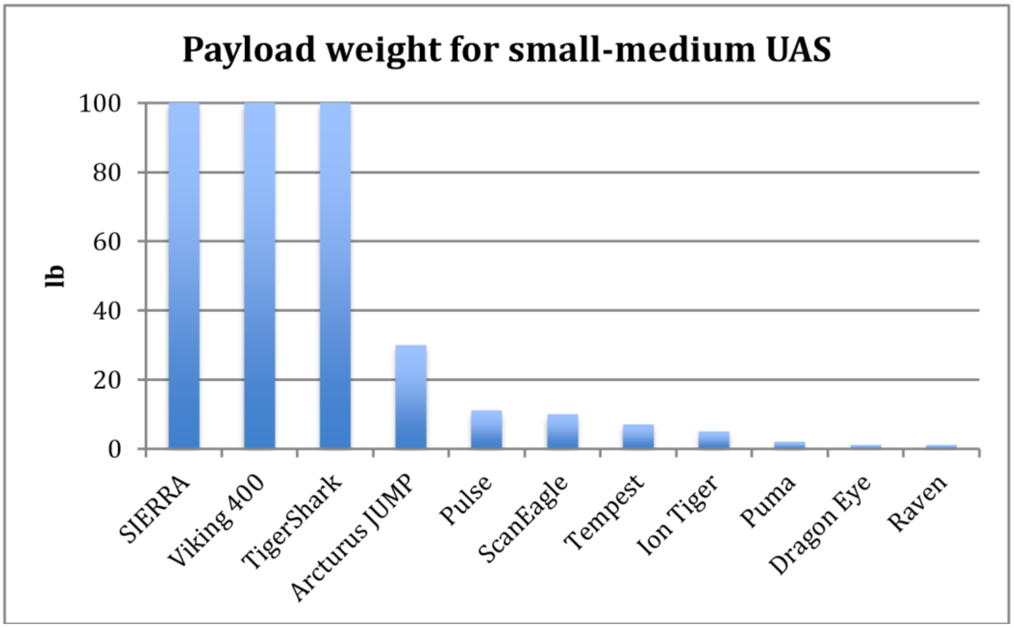


Figure 3. *Payload weight (lb) for some small and mid-size UAS*

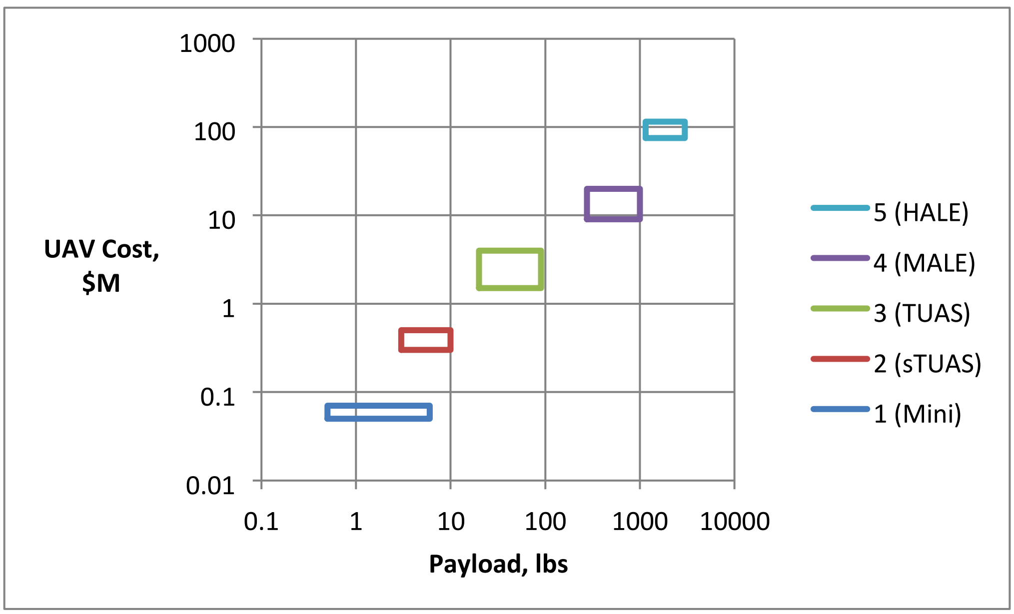


Figure 4. *Vehicle Cost and payload capacity ranges for DoD UAV Groups (compiled from various public domain sources).*

2.5 Data Handling and Telemetry

An important consideration when selecting aircraft for science observations is the degree to which the payload is either independent or dependent on aircraft power and communications. For sUAS it is often the case that the payload is entirely independent from the power and communications in order to conserve battery power and telemetry bandwidth. Aircraft position and navigation data is then downloaded from the aircraft or ground station after the flight to support data processing and interpretation. Larger aircraft will often provide power and either line of site telemetry or SATCOM connectivity via the autopilot or an independent radio or modem. Realtime data from the payload enables controllers to ensure that the instrument is operating as expected and collecting data. Ideally information on the aircraft and payloads are displayed into a geographic information system of some kind which enables integration of other data sets that can aid in interpretation of the data as well as assisting controllers in ensuring that flight plans can be updated as conditions change. As an example, the NASA Mission Tools Suite (www.mts.nasa.gov) is a common operating picture used for all NASA science aircraft enabling mission participants to track aircraft position on a moving maps display, view data quick-looks, and overlay thousands of different satellite and ground data sets.

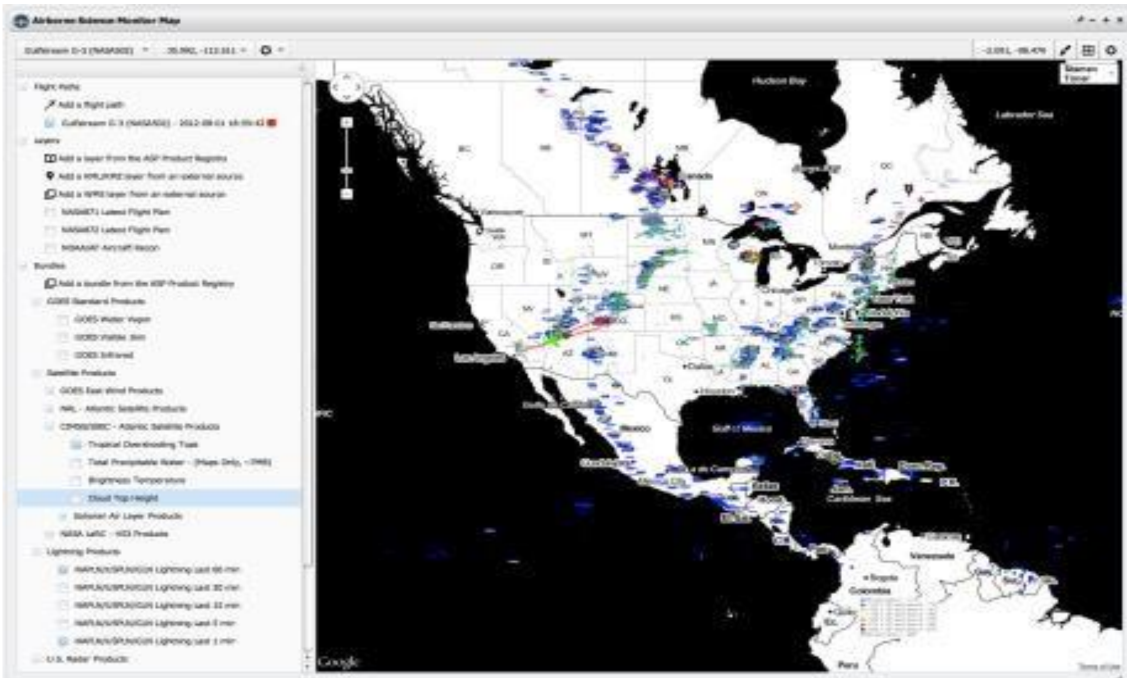


Figure 5*. A Screenshot of the NASA Airborne Science Program Mission Tools Suite that enables realtime tracking of aircraft position as well as information on payload status and data quicklooks*.

3.0 Perspective

Offer perspective on the topic area (why important, key challenges, major opportunities, limitations and/or constraints on progress, etc.)

Opportunities for UAS to perform atmospheric research abound because they can fly where manned aircraft cannot or do not, for safety reasons. In principle, they can fly very long duration, thus sampling atmospheric parameters over a diurnal cycle, for example. They can fly very high, if desired, or loiter in a region of interest.

A major gap in capabilities can be seen, however in Figures 6 and 7, which show payload weight, altitude and flight duration for the platforms listed in Table 5. There are very few UAS currently available in the flight regime between relatively small (10 lb payload) and very large (1500 lb payload). The TigerShark, SIERRA and Viking 400 are versatile and can carry approximately 100 lb of payload but none offer long duration or high altitude. Miniaturization of payload components can sometime lead to increased flight duration, but does not typically allow for increased altitude. The challenge to development of more diverse types of aircraft is primarily the lack of a commercial market in this size range.

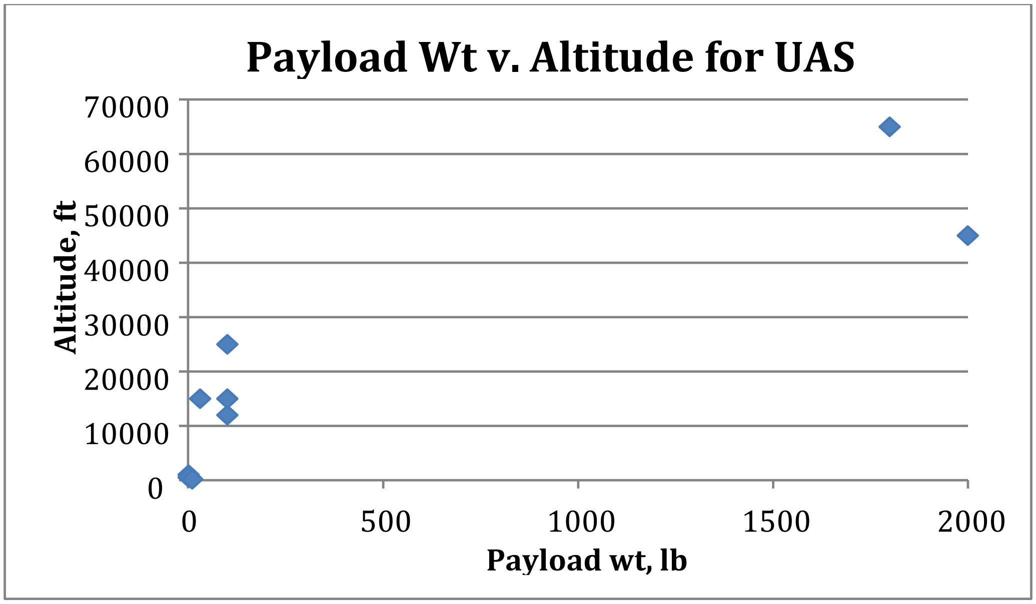


Figure 6. *Payload / altitude regime of current UAS*

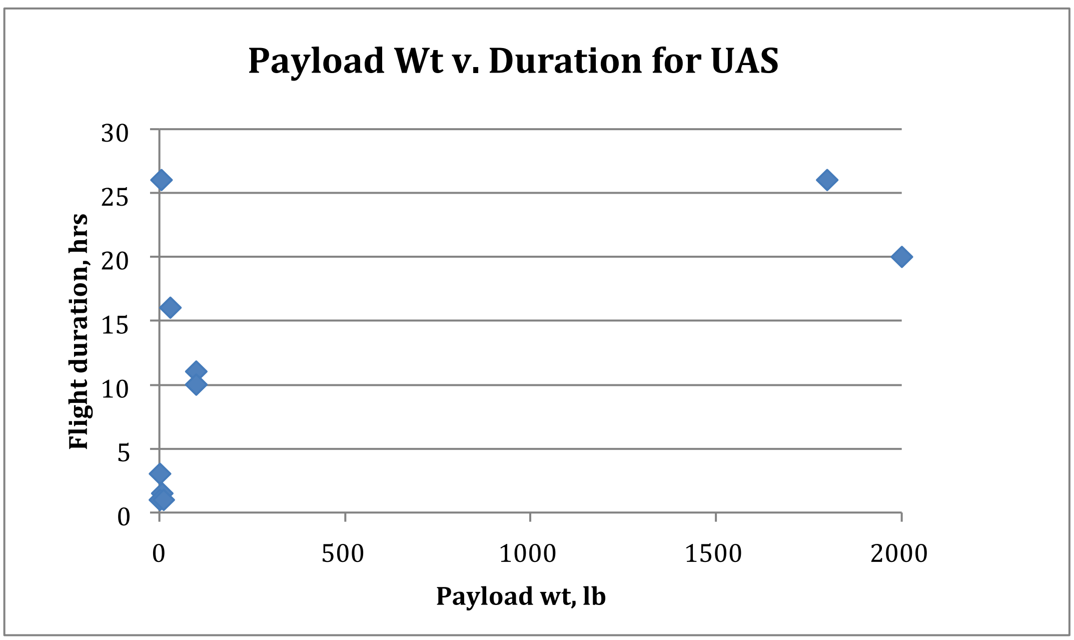


Figure 7. *Payload / flight duration regime of current UAS*

4.0 Discussion Topics

List of discussion topics for the workshop:

- Are there desired/required airframe capabilities (e.g. weight limits, flight duration, etc.) that are needed by the community?
- Compromises in terms of altitude, duration and payload
- What data handling and telemetry are needed by the community to support science goals?
- Are there specific hindrances to use of UAS system and mitigating measures that can be identified?

5.0 References:

[1] FAA Circular 107-2.
<https://www.faa.gov/documentlibrary/media/advisory_circular/ac_107-2.pdf>

[2] Department of Defense. "Unmanned Aircraft System Airspace Integration Plan" [3] NASA Interim Directive (NID): Unmanned Aircraft System (UAS) Policy Update; http://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=7900&s=3B [4] https://phys.org/news/2016-12-nrl-flight-uav-custom-hydrogen.html

13 Appendix 6: White paper Unmanned Aerial Systems for Atmospheric Research, Instrumentation Issues for Atmospheric Measurements

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This white paper is not intended to be a comprehensive review, but instead a living document to provide discussion of potential research needs and technology drivers. The authors thank the many contributors for their input and insight into the issues related to the problem at hand.

Statement of the Problem

The availability of high-quality atmospheric measurements over extended spatial and temporal domains provide unquestionable value to meteorological studies. In recent reports from the National Research Council and instrumentation workshops, (e.g., NRC, 2009; Hoff, et al. 2012) it was stated that observing systems capable of providing detailed profiles of temperature, moisture and winds within the atmospheric boundary layer (ABL) are needed to monitor the lower atmosphere and help determine the potential for severe weather development. Despite the need for such data, these measurements are not necessarily easy to acquire, especially in the ABL. One typically relies on remote sensing instruments (radars, lidars, sodars and radiometers) or in-situ probes carried by balloons or manned aircraft. An alternative to these traditional approaches is the acquisition of atmospheric data through the use of highly capable unmanned aircraft systems (UAS) and the subset of small-unmanned aircraft systems (SUAS) working in coordination with weather radar systems and other observing stations and platforms. Eventually, these systems will be ubiquitous among meteorologists and atmospheric scientists. However, many open questions remain because these methods have not been thoroughly developed and evaluated.

In regards to onboard instrumentation for atmospheric sensing, the instrumentation system consisting of the sensors, data acquisition system and storage/telemetry is the most critical element. It's the purpose of the system after all! Without proper operation of the instrumentation system, the SUAS as a measurement platform will be ineffective and deficient. Therefore, it's important to consider how the sensor system interacts with all aspects of the UAS, including issues such as platform integration and sensor placement, data acquisition and storage and telemetry/communications. In addition, as both SUAS autopilots and sensor systems become more advanced, measurements will eventually drive the autonomous path planning algorithms in the autopilot, requiring integration between these systems as well.

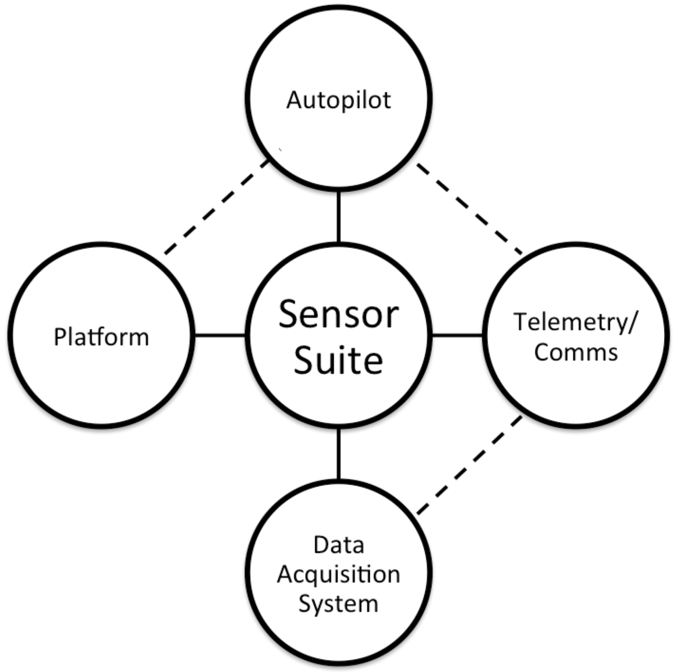


Figure 1. Functional relationship between sensor suite and other UAS components.

Background

UAS have demonstrated the capability of atmospheric profiling, providing temperature, humidity and wind measurements that are important to characterize the vertical structure of the lower troposphere. Greater insight can be gained by expanding capabilities; however, the behavior with height of the virtual potential temperature can be used to identify the regions of thermal stratification and the degree of atmospheric stability. The vertical gradient of the wind vector leads to wind shear, which can produce turbulence and thus turbulent fluxes in the atmospheric boundary layer. There is currently a gap between tower-based measurements and airborne (manned) systems, and this gap occurs at critical levels in the boundary layer. Remote sensing systems, such as radar, sodar and Lidar fill part of this gap but still do not provide the detailed information required to initialize and/or validate models and for a complete understanding of the formation of complex weather systems.

In recent reports from the National Research Council and instrumentation workshops, (e.g., NRC, 2009; Hoff, et al. 2012) it was stated that observing systems capable of providing detailed profiles of temperature, moisture and winds within the atmospheric boundary layer are desperately needed to monitor the lower atmosphere and help determine the potential for severe weather development and monitor the kinematic and thermodynamic state of the atmosphere. Ancillary data from sources such as radar, ground based meteorological stations, atmospheric soundings from weather balloons and models can be used in the analysis as part of any overall analysis.

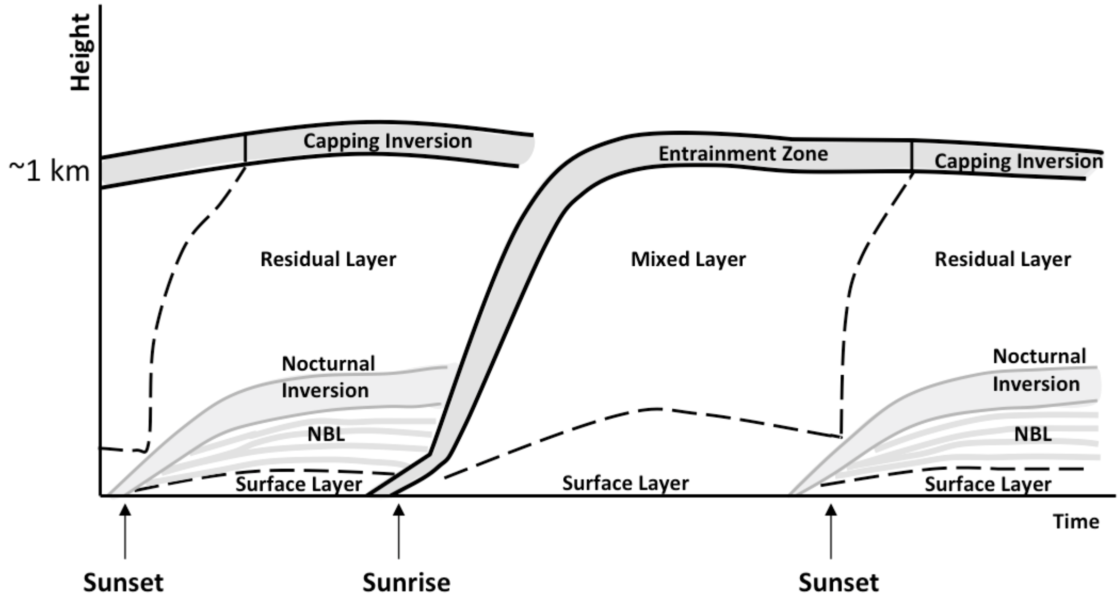


Figure 2*. Region of the troposphere most amenable to UAS measurements. The measurement needs in this region drive the instrumentation requirements. Balloon borne measurements tend to traverse this region quickly, manned aircraft typically fly above this region, and instrumented towers only reach the lowest part of the atmospheric boundary layer.*

In the long term, integration of atmospheric instrumentation may be ubiquitous for all SUAS platforms, such as those used for package delivery and inspection. Measurement of certain meteorological parameters, particularly temperature along with horizontal and vertical wind speed, can provide sufficient data onboard for improved path planning. Not only can this be used to avoid areas of poor weather but also for increased endurance through energy harvesting. As these systems become more common, the potential arises to mine this data for improved modeling and forecasting. As such, how can this data be utilized in the future?

For regular and robust use of UAS as an atmospheric measurement system, many questions need to be addressed regarding instrumentation issues. These include: 1. How should the instrumentation be integrated with the platform, viz. how do platform dependent features (fixed wing vs. rotary wing, tractor vs. pusher, gas vs. electric, etc.) impact sensor performance and placement? 2. What sampling rates are needed for different sensors? 3. How should sensor data be stored and/or transmitted? 4. How can sensor data be used in real-time to guide the UAS to the next measurement location?

For a preliminary assessment of instrumentation issues related to a specific UAS implementation, the vast array of options can generally be reduced to providing answers to the following two questions:

1. What measurements can be obtained from systems already onboard?
   - *This includes autopilot related systems such as the IMU and GPS, which will typically provide direct measurement of latitude and longitude, altitude, and pressure as well as derived quantities such as wind speed.*
2. What sensors need to be added?
   - *What system and vehicle modifications, if any, need to be made to accommodate the additional sensors?*
   - *How will the data be stored or relayed?*

Even providing cursory answers to these questions can typically provide enough guidance for initial sensor and data acquisition system selection.

Figure 3. *Representative unmanned aircraft ranging from the small (MTOW <55 lbs) to large.*

Technology Capabilities

There are a range of possibilities for utilizing unmanned aircraft for atmospheric measurements, ranging from small hand launched commercially available quadrotors to deploying systems from manned aircraft via dropsonde tubes to high altitude long endurance (HALE) unmanned aircraft. While the scale of the systems range to much larger and proven systems such as NASA's Ikhana, the discussion will be split between SUAS and "all other" UAS based on FAA definitions of a MTOW of <55 lbs.

A breakdown of UAS weight categories is provided in the appendices. This is a military delineation and not necessarily representative of weight categories seen in UAS used for scientific applications (it leaves out micro-UAS, for example, whose categorization and regulation is still undetermined at the time of this writing). Regardless, it serves as a familiar benchmark. It is worth noting that in regards to instrumentation, large UAS (Group 3 and above) derive their instrumentation systems from manned aircraft while SUAS (Groups 1 and 2) have more in common with radiosondes and other balloon borne platforms. As such, the differences in these instrumentation system requirements and design philosophies will be driven by their historical antecedents.

Large Unmanned Aircraft Systems

While the primary benefit of SUAS is their cost and availability, the restriction to smaller sizes limits their capabilities, specifically size, weight, endurance, and altitude. At this larger scale, the majority of unmanned aircraft used for atmospheric research have been military aircraft repurposed or retrofitted for a scientific mission. These typically provide a capability significantly greater in endurance and altitude than similarly sized manned aircraft, such as the WC-130 and Gulfstream IV for NOAA hurricane research, which are limited to service ceilings of 33,000 ft and 45,000 ft respectively. This is significantly less than the desired altitude of 60,000 ft to 70,000 ft achievable by the Global Hawk to track and model the movement of hurricanes, or that of the Ikhana. Capabilities of large unmanned aircraft in Group 3 or larger will provide payload capabilities similar to the current array of manned aircraft, including large sensor arrays and dropsondes such as AVAPS and the Coyote. Capabilities of such systems for long duration observing are immense and provide a unique resource for environmental assessment and aid in improving forecasting. An example of the instrumentation layout for the SHOUT program is shown in Figure 4. The unprecedented observational capabilities come with a high price tag and the operational cost has to weigh against the scientific benefit for any single platform.

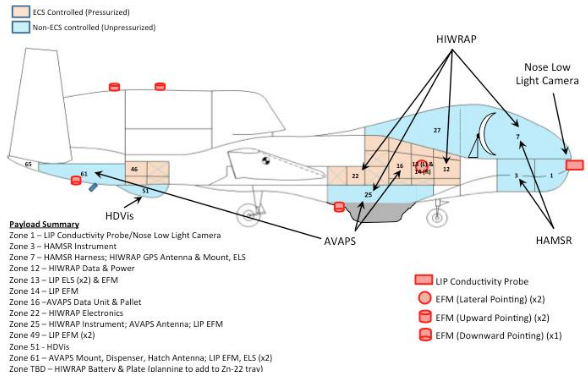


Figure 4. *Payload layout for NOAA Sensing Hazards with Operational Unmanned Technology.*

Small Unmanned Aircraft Systems

There are several ongoing efforts in developing SUAS technology to collect weather data, but overall the achievements have been limited due to targeted investigations of specific environments, such as severe weather, arctic measurements or environmental monitoring. As the Federal Aviation Administration (FAA) works toward developing a set of rules and guidelines that will help regulate everyday SUAS operations, companies, universities and national laboratories have been working on effective systems for full implementation. While not discussed herein, the development of small inexpensive autopilots and airspace traffic management systems are required for integration into the National Airspace (NAS). Technologies such as light-weight and inexpensive Automatic Dependent Surveillance-Broadcast (ADS-B) technology to allow SUAS and manned aircraft to detect and avoid each other is necessary for this integration to take place. As this takes place, there will be overlap and integration between some of the sensor suites and navigation systems, perhaps beneficial to both. These efforts have been the primary focus of most SUAS technology research. In regards to research pertaining to meteorological advancements, several groups have been working toward solutions both on the sensor and UAS level.

Figure 5. *Size comparison of the NCAR dropsonde and driftsonde systems (Hock and Franklin, 1999).*

Most of the technology developed for SUAS is derived from their radiosonde predecessors, including current dropsondes and balloonsondes counterparts. NCAR originally developed the dropwindsondes in order to analyze the effect of tropical oceans on Northern Hemisphere weather and climate, including the NCAR GPS dropsonde known as the Airborne Vertical Atmospheric Profiling System (AVAPS). Early systems such as these demonstrated increased measurement resolution, and the dropwindsonde represented major advances in both accuracy and resolution for atmospheric measurements over data-sparse oceanic areas of the globe. This provided wind accuracies of 0.5 m/s with a vertical resolution of approximately 5 m (Hock and Franklin, 1999). The dropwindsonde has four main components: the pressure, temperature, humidity (PTH) sensor module, a microprocessor, and GPS as well as a 400-MHz transmitter. The sensor specifications are shown below in Table

1. AVAPS is used to study hurricanes for improved forecasting. AVAPS is 16 inches in length, 2.75 inches in diameter and weighs 0.86 pounds. On board is a microprocessor that digitalizes the raw data received from the temperature, humidity and pressure sensors and then transmits the data readings back to a ground control station (GCS) using a radio transmitter. Due to the size of the dropsondes, they must be manually flown and deployed over the desired area of study with no control capabilities. These dropsondes are not retrievable and must be designed to be disposable, with each dropsonde typically costing approximately $500. Similarly, the *Miniature In-situ Sounding Technology* (MIST) driftsonde reduced size and weight while maintaining or improving system measurement performance. It updated PTH data at 2 Hz and wind data at 4 Hz.

	Operating range	**Accuracy**	**Resolution**	**Time constant**
Pressure	20–1060 mb	0.5 mb	0.1 mb	< 0.01 s
Temperature	–90° to 40°C	0.2°C	0.1°C	2.5 s at 20°C 3.7 s at –40°C
Humidity	0%–100%	2%	0.1%	0.1 s at 20°C 10 s at –40°C
Wind	0–150 m s^{-1}	0.5 m s^{-1}	0.1 m s^{-1}	

***Table 1.** Dropwindsonde sensor specifications (Hock and Franklin, 1999).*

UA	Wind	Humidity	Temperature	Pressure
Manta	9 hole probe	Vaisala HMP45C	Vaisala HMP45C	All Sensors barometric sensor
Scan Eagle	9 hole probe	Vaisala HMP45C	Vaisala HMP45C	All Sensors barometric sensor
Aerosonde	Proprietary Algorithm	Vaisala RS90	Vaisala RS90	Vaisala RS90
RMPSS	GPS / INS	Humidity sensitive capacitor	Thermal Resistor	MEMS
Tempest	Aeroprobe 5 hole probe	Vaisala RS92	Vaisala RS92	Proprietary autopilot sensor
M^{2}AV	5 hole probe	Custom	Thermocouple	Sensortechnics
Aerolemma-3	None	CSI HMP-50	CSI HMP-50	CSI CS100
SmartSONDE	GPS / Infrared	Sensiron SHT75	Sensiron SHT 75 / VTI SCP1000	VTI SCP1000
Powersonde	None	NSSL Radiosonde	NSSL Radiosonde	NSSL Radiosonde
Kali	None	Honeywell HIH-3605-B	National Semiconductor LM50 C	Motorola MPX 2100
DataHawk	GPS / Infrared	Honeywell capacitive polymer	TI ADS1118	MS5611-01BA03
SUMO	GPS / Infrared / IMU	Sensiron SHT75	Sensiron SHT 75 / PT1000	VTI SCP1000

***Table 2**. Instrumentation used on previous SUAS platforms (Elston et al.).*

Table 2 summarizes early SUAS efforts using primarily custom sensor suites. Of early note, the small unmanned meteorological observer (SUMO) was demonstrated in multiple campaigns to measure temperature, humidity, wind speed and direction up to 3500 m AGL (Reuder et al., 1988), successfully operating in polar conditions with wind speeds up to 15 m/s. The collection of wind data was only possible during autonomous flight mode above 200 m since it derived wind directly from the autopilot system. Over the project timeline, the SUMO was improved with a faster temperature sensor to reduce the measuring time from 5 to 1 s and also adopted a five-hole probe system for improved wind measurements. The system was successfully adapted into other variants, such as the OU SMARTSONDE, with examples shown below.

More recently, several commercial systems have been developed to off-the-shelf capabilities. International Met Systems (iMet) has developed small, compact sensors designed to collect humidity, temperature, pressure, latitude, longitude and altitude data. This small, 15 gram, 100 mm by 30 mm sensor carries 16 mb of internal flash memory that stores incoming data and can later be access via micro USB port. Various institutions have been beta testing the sensors and although they are capable of accurate and precise data collection, the iMet reliability remains uncertain at this time. Other current drawbacks are the inability to access the data in real-time unless attached to a 3DR Solo quad-copter, and the price per sensor is approximately $500. Similarly, iMet has released the iMet-XF with a larger array of sensor suite options. Windsond is a small, standalone atmospheric sensor used for balloon systems produced by Sparv Embedded and comes pre-calibrated. As with the iMet, the Windsond collects humidity, temperature, pressure, latitude, longitude and altitude data. In addition to this, the sensor is capable of collecting not only wind speed but wind direction. The sensors reside within a small cup that is attached to a balloon.

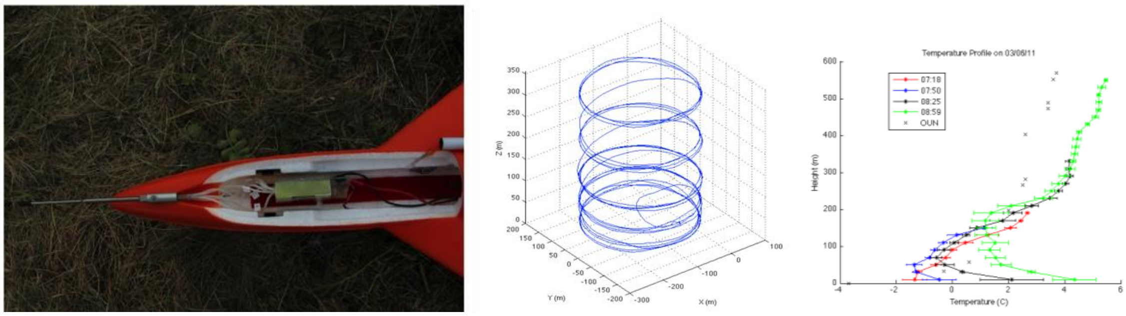


Figure 6. *SUMO (left) and UAS data from using the OU SMARTSONDE corresponding to transition of the lower boundary layer (Chilson et al.).*

Rain Dynamics has developed a prototype compact 5-hole air data probe system designed to measure 3D wind components, humidity, temperature, pressure, latitude, longitude and altitude data. This sensor uses a miniature, high-performance dual antenna GPS aided INS paired with an air data probe to measure the 3D wind vectors. The two separate GPS receivers enable accurate true heading measurements without reliance on vehicle dynamics or magnetic sensors. In an early prototype of this sensor, low cost INS systems were found to produce erroneous heading measurements especially during turns, which introduced significant errors in the wind solution. Figure 8 shows wind speed and direction data from this sensor installed on the Applied Aeronautics Albatross UAV with wind speeds up to 16 ms^{-1}. The wind direction was steady at 250 degrees despite the many turns to keep the aircraft within line of sight. Data acquisition is at 5 Hz (~ 10 m resolution) but higher data rates are being explored.

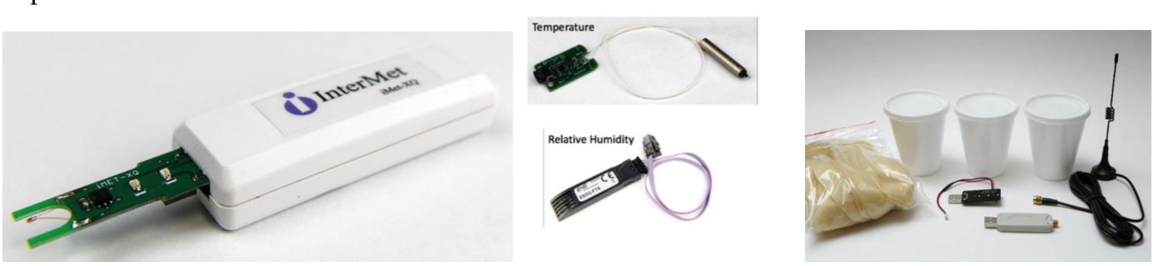


Figure 7. *iMet XQ (left), iMet XF sensors (center) and Windsond (right) systems.*

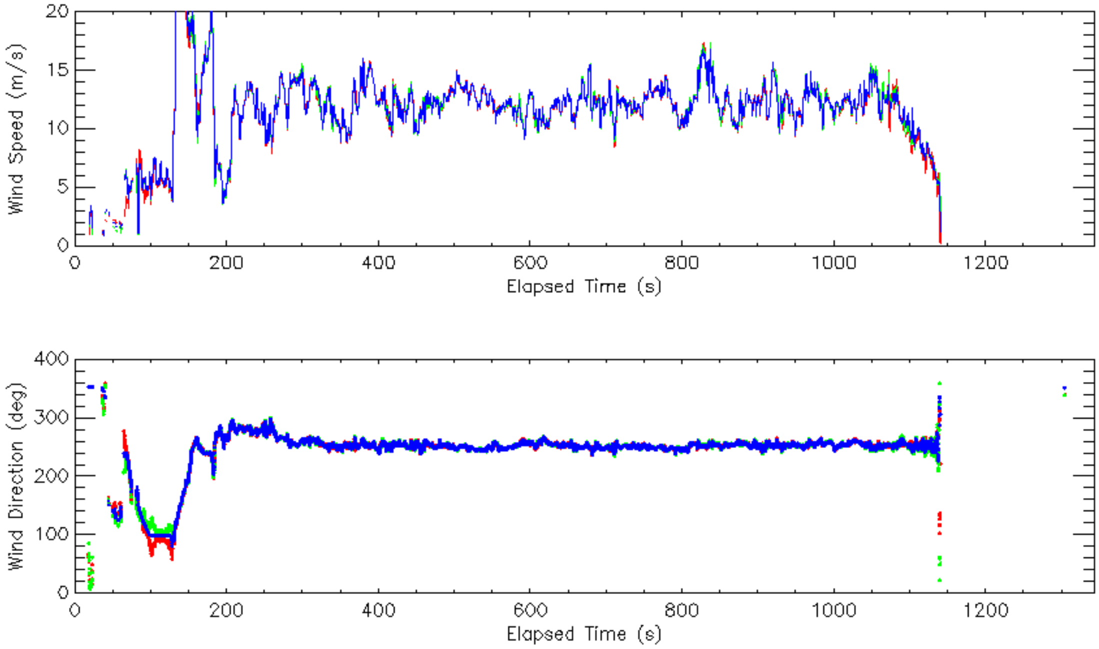


Figure 8. *Wind speed (top) and wind direction (bottom) from the Rain Dynamics wind sensing system. In the first three minutes of the time series the sensor is acquiring a GPS lock and these data are rejected.*

Measurement and Integration Needs

Measurement needs range from standard meteorological measurements to quantities for advanced forecast modeling and are dependent upon the UAS mission and capabilities. Detailed discussion of meteorological measurements and instrumentation can be found elsewhere (e.g., see Harrison and the WMO's *Guide to Meteorological Instruments and Methods of Observatio*). While standard instrumentation such as PTH will most likely be integrated into every sensor platform, additional measurements may include both direct derived quantities as well operating environment including altitude and temperature. SWAP and cost is the primary consideration here. Gas measurements include greenhouse gases including carbon dioxide (CO_2), methane (CH_4) and tropospheric ozone (O_3). CO is identified as an important indirect greenhouse gas (IPCC).

Identified direct and indirect quantities include, but are not limited to the following:

- PTH (wet and dry bulb, RH)
- Wind vector (2-D, 3-D); steady, gusts (e.g., with 5-hole probe)
- Turbulence (e.g., with hot-wire)
- Latent and sensible heat flux
- Eddy covariance
- Gas concentrations
    - CO_2
    - CH_4
    - O_2/O_3
    - N_2O
    - SO_2
- Liquid water content
- Cloud hydrometeor size and concentration (cloud and precipitation)
- Frost point
- Solar irradiance
- EO/IR, NIR, UV imagers

- Navigation and control sensors
    - IMU (attitude, rate)
    - GPS
    - Altitude
    - Air-speed (Pitot)

Integration issues include ensuring proper sensor aspiration and shielding, particularly with temperature and humidity sensors. Many probes will be mounted on data booms that may extend beyond the aircraft structure. Primary consideration for the design of any boom is safety and integrity of the airframe. Installers must also ensure that large booms do not impact the vehicle stability. Secondary but important considerations from the standpoint of data quality include good data acquisition. Ease of installation and maintenance is also important, particularly for systems that may need to be accessed during field operations for installation, operation, or removal.

Figure 9. *Sample gas sensing system with integrated environmental sensors including CO_2 & CH_4.*

Instrumentation resolution and response time play a role into how the sensor suite can be utilized as a measurement tool. For SUAS, radio and balloon borne instruments serve as the most relevant benchmark. For "typical radiosondes," the vertical resolution of the thermodynamic data is usually 5 to 10 m depending on the interval at which the data acquisition system samples the signals from the radiosonde and the time response of the sensor. However, the wind data resolutions are much lower with ranges from approximately 50 to 200 m, depending on the type of sounding system used. The data-averaging interval for radiosondes in the tropospheric portion of a sounding (e.g., lowest 3000 m) is 1 to 2 minutes. This may be higher in the upper part of a sounding. For all UAS, sensor response and resolution must be evaluated as part of the requirements process on the front end and as part of the measurement tool's capability in regards to accuracy on the back end. While steady state measurements will typically not be impacted, accurate measurement of transient events such as severe storms, gust fronts, or environmental scenarios can be impacted. NOAA has provided a guideline for sensor range and accuracy as a starting point shown in Table 3.

Desired Sensor Ranges and Accuracies	
Temperature	-30 – 40 C, +/- 0.2 C
Relative Humidity	0 – 100 %, +/- 5.0%
Pressure	+/- 1.0 hPa
Wind Speed	0 – 45 m/s, +/- 0.5 m/s
Wind Direction	+/- 5 Degrees Azimuth
Sensor Response Time	< 5 s (Preferably < 1 s)

Table 3. *Proposed meteorological sensor specifications.*

An example of plume detection is shown in Figure 10, which represents a case with high spatial and temporal gradients that push the limits of sensor response time. As the UAS traverses the plume (or in the case of a stationary UAS and transient event, vice-versa), the measurement accuracy will depend upon both the sensor response and flight characteristics. While a few seconds delay in peak detection time is short enough to shift the data to refine the location of the detected plume, a greater issue may be the time it takes for the sensor to return to atmospheric background levels.

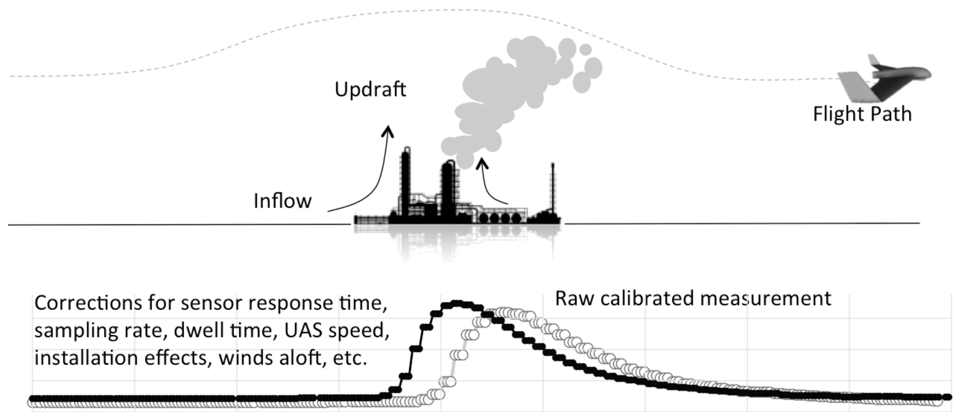


Figure 10*. Sample data correction of an in situ gas measurement correcting for sensor, integration, and flight path issues.*

The uncertainties of the selected sensor suite must be fully characterized using a thorough calibration and validation process to properly collect meaningful observations. Calibration of the sensors is first typically performed against reference measurements, such as in a thermal altitude chamber specific to the instrument at hand. Other measurement checks may include comprehensive instrument characterization and consistency cross checks across sensors of the same type and different sensor designs to verify the response. Further steps should then involve validation of the sensors in flight conditions. This may utilize towers as a potential validation source or other airborne instrumentation. Sensor response may be biased by installation, particularly on SUAS where induced flows and thermal sources may be present. These should be considered as part of the calibration and validation process.

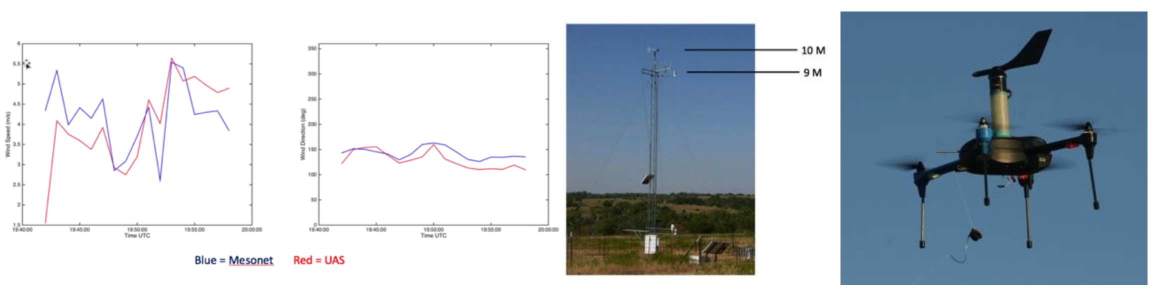
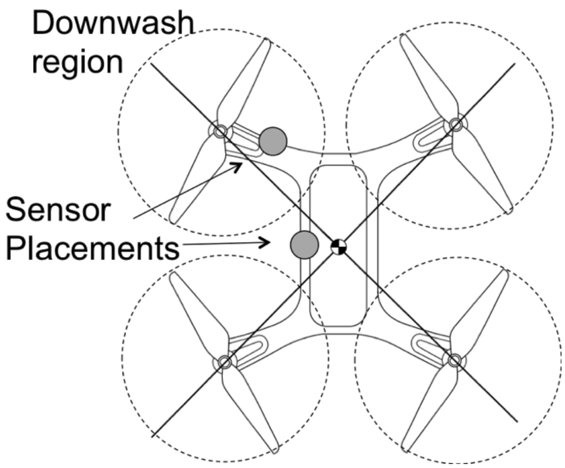


Figure 11. *Comparisons between onboard and field sensors from Univ. of Oklahoma (Chilson et al.) and Oklahoma State University.*



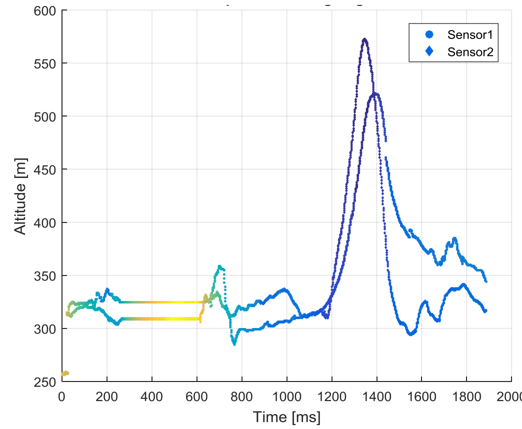


Figure 12. *Illustration of potential sensor placement issues on a SUAS that may result in measurement variation due to integration.*

Open Questions and Needs

As a starting point, we provide the following questions for discussion.

- Is there a need/desire to establish a list of approved or suggested sensors and a corresponding sensor database?
- Should there be development of guidelines for sensor placement and operation?
- How can existing onboard systems (such as IMU, GPS) be leveraged to obtain needed meteorological information (such as wind direction and speed)?
- Is there a need to establish calibration/validation, data acquisition, data quality, and analysis protocols and recommendations?
- How should data acquisition requirements be addressed as part of the sensor suite?
- What accuracy and sensitivity ranges are required? Time response?
- What is the trade-off between instrument development viz., cost, data quality, and risk? (e.g., a low cost IMU introducing significant errors in wind estimation.)

References and Selected Bibliography

de Boer, G., S. Palo, B. Argrow, G. LoDolce, J. Mack, R.-S. Gao, H. Telg, C. Trussel, J. Fromm, C.N. Long, G. Bland, J. Maslanik, B. Schmid, and T. Hock: The Pilatus Unmanned Aircraft System for Lower Atmospheric Research, *Atmos. Meas. Tech*., 9, 1845-1857, doi:10.5194/amt-9-1845-2016.

Brock, F. V., K. C. Crawford, R. L. Elliott, G. W. Cuperus, S. J. Stadler, H. L. Johnson, and M. D. Eilts, The Oklahoma Mesonet: A technical overview. *J. Atmos. Oceanic Technol.*, **12,** 5–19, 1995.

Chilson, C., R. Huck, C. Fiebrich, D. Cornish, T. Wawrzyniak, S. Mazuera, A. Dixon, E. Burns, and B. Greene, Calibration and Validation of Weather Sensors for Rotary-Wing UAS: The Devil is in the Details, *97th American Meteorological Society Annual Meeting*, Seattle, WA, 2017.

Cione, J.C., K. Twining, M. Silah, A. Brescia, E. A. Kalina, A. Farber, C. Troudt, A. Ghanooni, B. B. Baker, E. J. Dumas Jr., T. Hock, J. A. Smith, J. French, C. W. Fairall, G. deBoer, and G. Bland, NOAA's operational end game for the Coyote Unmanned Aircraft System, *97th American Meteorological Society Annual Meeting*, Seattle, WA, 2017.

Coffey, J.C., R. Hood, T. Jacobs, G. Wick, R. Moorhead, and J. Walker, NOAA Atmospheric, Marine and Polar Monitoring UASs (including Rapid Response), AIAA Aviation, Washington DC, June 13-17, 2016.

Elston, J., T. Nichols, B. Argrow, E. W. Frew, D. Lawrence, J. Cassano, M. Nigro, G. de Boer, A. Houston A. Schueth, C. Weiss, N. Wildmann and P. Chilson, "Multi-sUAS Evaluation of Techniques for Measurement of Atmospheric Properties (MET MAP)," *ISARRA*, Norman, OK, 2015.

Frew, E. W., J. Elston, B. Argrow, A. L. Houston, and E. N. Rasmussen, Unmanned Aircraft Systems for Sampling Severe Local Storms and Related Phenomena. *IEEE Robotics and Automation Magazine*, **19,** 85-95, 2012.

Harrison, R. Giles, *Meteorological Measurements and Instrumentation*, Wiley, 2015.

Hock, T. F. and Franklin, J. L., The NCAR GPS dropwindsonde. *Bull. Amer. Meteor. Soc*., **80**, 407–420, 1999.

Hoff, R.M., R.M. Hardesty, F. Carr, T. Weckwerth, S. Koch, A. Benedetti, S. Crewell, D. Cimini, D. Turner, W. Feltz, B. Demoz, V. Wulfmeyer, D. Sisterson, T. Ackerman, F. Fabry, and K. Knupp, 2012: Thermodynamic Profiling Technologies Workshop report to the National Science Foundation and the National Weather Service. *NCAR Technical Note NCAR/TN-488+STR*, 80 pp, 2012.

Houston, A. L., B. Argrow, J. Elston, J. Lahowetz, E. W. Frew, and P. C. Kennedy, The Collaborative Colorado-Nebraska Unmanned Aircraft System Experiment. *Bull. Amer. Meteor. Soc*.**, 93**, 39-54, 2012.

IPCC, *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp, 2001.

Laurence III, R., Nichols, T., Elston, J., and Argrow, B., "Validation of Supercell Wind and Thermodynamic Measurements from the Tempest UAS and a Mobile Mesonet," Proceedings of the AUVSI Unmanned Systems 2014 Conference, Orlando, FL, May, 2014.

NRC, *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks.* Washington, DC: The National Academies Press, 2009.

Reuder, J.; Jonassen, M.; Ólafsson, H., The small unmanned meteorological observer sumo: Recent developments and applications of a micro-uas for atmospheric boundary layer research. *Acta Geophys. 60*, 1454–1473., 2012.

World Meteorological Organization, WMO-No.-8. *Guide to meteorological instruments and methods of observation.* Geneva, Switzerland: Secretariat of the World Meteorological Organization, 2008.

https://uas.noaa.gov/shout/

http://www.webmet.com/met_monitoring/toc.html

UAS Categories

Standard UAS categorization is provided below as a guideline for size estimates. As a representative payload capability, a typical platform will be able to carry anywhere from 10-30% of its GTOW in payload based upon historical benchmarks.

Group 1: Typically hand-launched, self-contained, portable systems. Mostly electric.

Group 2: Small to medium in size. They usually operate from unimproved areas and may be launched via catapult or runway and recovered via runway or net.

Group 3: Operate at medium altitudes with medium to long range and endurance. They usually operate from unimproved areas and may not require an improved runway.

Group 4: Relatively large UAS that operate at medium to high altitudes and have extended range and endurance. They normally require improved areas for launch and recovery and ground support for BLOS communications and SATCOM.

Group 5: Include the largest systems, operate at medium to high altitudes, and have the greatest range, endurance, and airspeed capabilities. They require improved areas for launch and recovery, BLOS communications and perform broad area surveillance.

UAS Groups	Maximum Weight (lbs) (MGTOW)	Normal Operating Altitude (ft)	Typical Speed (kts)	Representative UAS
Group 1	0 – 20	<1200 AGL	100	Sumo, Raven, Puma, Tempest
Group 2	21 – 55	<3500 AGL	< 250	ScanEagle, Albatross
Group 3	< 1320	< FL 180	< 250	Shadow, Mugin
Group 4	>1320	< FL 180	Any Airspeed	Predator/Ikhana
Group 5	>1320	> FL 180	Any Airspeed	Global Hawk, BAMS

Table 4: UAS Group Descriptions Typical Operating Ranges

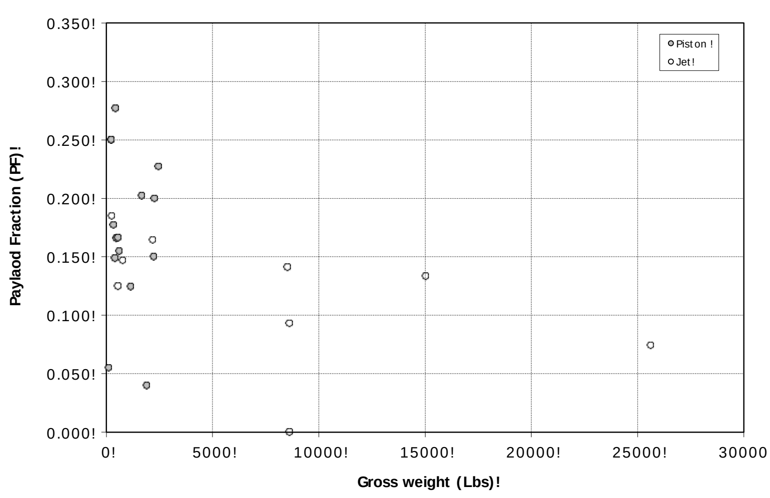


Figure 13. *Payload fraction as a function of gross weight based for a range of GTOW.*