Development of a Weather Capability for the Urban Air Mobility Airspace Research Roadmap

Timothy Bonin
Air Traffic Control Systems
MIT Lincoln Laboratory
Lexington, MA
timothy.bonin@ll.mit.edu

James Jones
Air Traffic Control Systems
MIT Lincoln Laboratory
Lexington, MA
james.jones@ll.mit.edu

Gabriele Enea
Air Traffic Control Systems
MIT Lincoln Laboratory
Lexington, MA
gabriele.enea@ll.mit.edu

Ian Levitt
Crew Systems and Aviation Operations Branch
NASA Langley Research Center
Hampton, VA
ian.m.levitt@nasa.gov

Nipa Phojanamongkolkij
Engineering Integration Branch
NASA Langley Research Center
Hampton, VA
nipa.phojanamongkolkij@nasa.gov

Abstract*— Traditionally, the transportation system's resiliency to the impacts of weather is an area where neglected or incorrect assumptions can lead to difficulties later in the research and development lifecycle. To mitigate this, NASA has ongoing efforts to develop a set of research roadmaps for organizing, integrating, and communicating research into new aviation infrastructure and transportation modalities, within which weather is being addressed early on. An effort has been undertaken to add weather assumptions and requirements to an already-existing roadmap for the Urban Air Mobility (UAM) airspace, seeking to integrate weather requirements early in the system design. This effort addresses the way in which state-of-the art and evolving weather science and technology can enable safe and efficient travel with increasing tempo of UAM operations over time. This paper describes the addition of weather as one of 10 capabilities into the UAM Airspace research roadmap, laying out the anticipated weather technology and information requirements needed to facilitate operations at various UAM Maturity Levels. The process developed and exercised by MIT Lincoln Laboratory researchers produced 41 unique requirements to be satisfied by a Weather capability for the UAM ecosystem, with more than 300 dependencies identified across the system. These requirements cover measurement, analysis, modeling, forecasting, decision support, dissemination, and overarching policy, and are provided with an overview of weather challenges for UAM. The requirements were mainly defined based on subject matter expert review of existing UAM Airspace system requirements, and refined based on iterative feedback with various stakeholders including regulators, academia, and industry. Going forward, this roadmap will help researchers and developers align to a common vision in ensuring that weather is appropriately considered in the UAM ecosystem.

Keywords—urban air mobility, weather, research roadmap, requirements

I. Introduction

Advanced Air Mobility (AAM) encompasses a range of innovative and technological changes to aviation (electric aircraft, increasingly automated aircraft, increasingly automated airspace operations, etc.) that are transforming aviation's role in everyday movement of people and goods. The Urban Air Mobility (UAM) concept covers a subset of the AAM concepts, namely those that use electric Vertical Takeoff and Landing (eVTOL) aircraft to provide air-taxi or package delivery services to the public over densely populated cities and the urban periphery, including flying between local, regional, intra-regional, and urban locations. The UAM vision is one in which advanced technologies and new operational procedures enable practical and cost-effective air transport as an integrated mode of movement of people and goods throughout metropolitan areas. To safely support UAM operations at scale in the National Airspace System (NAS), NASA's Air Traffic Management-Exploration (ATM-X) UAM Airspace Subproject has been conducting research that evolves the UAM air traffic management system towards a highly automated and operationally flexible system of the future.

The UAM Maturity Level (UML) scale [1] was developed by NASA to provide insight into UAM operational, technical, and regulatory evolution in the NAS. The UML framework is used herein to help understand the future NAS by stepwise introduction of new operational capabilities. Although the NAS evolves continuously, certain accumulated changes represent a phase change to UAM operations (e.g., demand-capacity balancing, time-based flow management, autonomous operations) enabling a jump to a higher UML. A brief description of the UML scale, including a high-level description

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.
This material is based upon work supported by the National Aeronautics and Space Administration under Air Force Contract No. FA8702-15-D-0001 and IAA contract number 80LARC21T0004. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.
© 2023 Massachusetts Institute of Technology.
Delivered to the U.S. Government with Unlimited Rights, as defined in DFARS Part 252.227-7013 or 7014 (Feb 2014). Notwithstanding any copyright notice, U.S. Government rights in this work are defined by DFARS 252.227-7013 or DFARS 252.227-7014 as detailed above. Use of this work other than as specifically authorized by the U.S. Government may violate any copyrights that exist in this work.

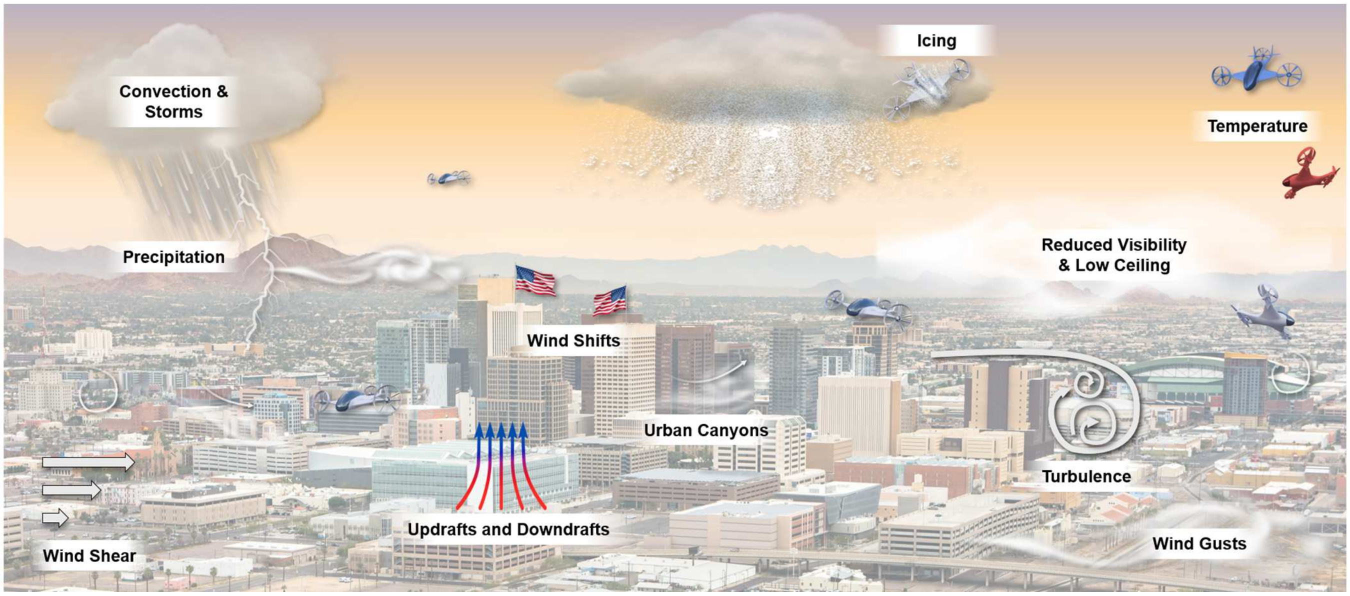

Figure 1: Conceptualization of the plethora of weather conditions anticipated to affect UAM safety and efficiency.

of the operations at UML-1 through UML-4 during which the tempo of operations increases at higher UML, is given in Section II. Readers are referred to [1] for the full descriptions of UML.

The complexity of the UAM airspace progression requires a plan to effectively organize, integrate, and communicate research and development (R&D) in the area. Recently, the concept of a "research roadmap" has emerged as a system engineering approach to the R&D of complex system-of-systems, where interdependencies make it nearly impossible to define requirements for individual elements of the system in isolation. Using this concept, NASA has been developing the UAM Airspace (i.e., traffic management system) research roadmap [2] to establish a complementary framework to study the phase progression from UML-2 to UML-4. This roadmap is a living document and is continually updated based on new information as the Concept of Operations (ConOps) and supporting technology enabling UAM matures. These updates are periodically released the community to encourage collaboration on the research required to enable safe and efficient UAM operations.

To establish this methodology for UAM airspace, the entire UAM system of systems must be considered. To operationalize a concept, the ultimate need to be interoperable with other NAS ecosystems must always be met. The process begins by identifying a discrete set of capabilities which cover the UAM airspace system. These UAM airspace capabilities are derived from several sources, including the global ATM Concept [3], and the FAA's NAS Enterprise Architecture [4]. Each capability is then decomposed into a non-exhaustive list of constituent components. The components are generally functional, and work in combination to deliver the parent capability. While not all elements and components of the UAM airspace system will be directly addressed by NASA R&D, it is important to have a complete view that unifies assumptions and requirements across the system of systems.

Traditionally, the transportation system's resiliency to the impacts of weather is an area where neglected or incorrect assumptions lead to difficulties later in the R&D lifecycle. To mitigate this, NASA is addressing weather early on by assessing weather assumptions and requirements by integrating them with existing UAM research and system design. This will help ensure that the research will accurately address state-of-the art and evolving weather science and technologies, leading to safe and efficient travel with increasing tempo of UAM operations over time.

Numerous weather conditions are anticipated to impact UAM safety and efficiency as shown in Figure 1. Weather conditions that impede conventional aviation, including thunderstorms (convection), icing, and reduced visibility and low ceilings, will remain detrimental to UAM operations [5]. However, new weather challenges also emerge for UAM compared to traditional aviation due to the nature of the new vehicle types and regions of operation. As eVTOLs will be battery powered, their range and endurance are significantly affected by the temperature [5][6]. Hot or cold temperatures reduce the battery capacity and energy may also be used to power heating, ventilation, and cooling (HVAC) systems to improve passenger comfort, with both effects combining to have an expected significant effect on UAM range and recharging requirements.

Both winds and turbulence will be highly impactful to the safety and efficiency of UAM operations. Smaller aircraft, such as those used for UAM, typically have higher sensitivity to winds compared to large commercial jets that most passengers are accustomed to [7]. The complexity of urban and suburban landscapes introduces large roughness elements, such as buildings, that locally alter the flow posing invisible hazards especially to vehicles taking off and landing from vertiports [6], which are identifiable ground or elevated areas (e.g., buildings or facilities) used for the takeoff and landing of eVTOL aircraft. Local updrafts/downdrafts may affect vertical conformance to narrow corridors, as well as wind shifts that may differentially affect the lift of vehicles flying in corridors at different altitudes in opposite directions. Wind gusts and turbulence can also be hazardous for aircraft, particularly those flying at low altitudes, leading to increased battery drain [7] at best and a complete loss of control [8] at worst.

The objective of this paper is to describe how weather was added as one of 10 capabilities to NASA's UAM Airspace research roadmap [2] and identify the weather requirements and their evolution to enable operations at UML-2 through UML-4. The paper is structured as follows: Section II describes the UML scale to lay the framework for interpreting the UAM roadmap. Section III describes the process in which the weather capability was developed, and includes definitions of the various components of the UAM weather ecosystem and how requirements were developed. Section IV provides a summary of the requirements that were developed, which are provided in full in [2]. The tracing of the requirements, including statistics and a discussion of their origin, is given in Section V. Finally, a summary of the whole process and results is given in Section VI.

II. THE UAM MATURITY LEVEL SCALE

The UAM airspace system is expected to move through a series of progressive stages as the technology advances and tempo of operations increases over time. Each stage is defined by a set of capabilities that will be enabled to facilitate operations, with uncertainty in how the stages progress. The stages are defined as UMLs, ranging from UML-1 (pre-operational stage) to UML-6 (ubiquitous mature operations). The UAM roadmap [2] defines the future capabilities and requirements starting with UML-2 only, as UML-1 comes before certified eVTOL aircraft and is outside the scope of airspace research. Similarly, it does not go beyond UML-4 since speculation about airspace operations that far has too much uncertainty to apply rigorous engineering. A brief description of each UML 2-4 is given below for context for the weather requirements creation.

UML-2 represents initial commercial air taxi operations using newly-certified eVTOL aircraft designs under existing airspace and regulations. These operations are expected to take place in carefully chosen early adopter markets where operational challenges can be addressed without significant regulatory accommodations. The traffic density will be low, nominally with tens of UAM aircraft aloft flying between ten or less vertiports but the actual traffic density may vary significantly depending on numerous factors.

UML-3 represents a transitional period, with the introduction of novel regulatory and airspace constructs designed to overcome the capacity constraints of UML-2. This period also comes with the certification or qualification of safety-critical technology onboard and offboard the UAM aircraft, which begins to change the roles of the actors in conflict management functions [3] and which are required to operate in novel ways. Limited scalability and deployment beyond early adopters will be a defining characteristic of UML-3, until regulatory changes allowing integration of key technologies and capabilities allow for higher tempo operations more broadly. The traffic density will be generally be low, nominally with less than a hundred of UAM aircraft aloft in a given metro area with local areas of high density around a few key vertiports.

UML-4 represents a period of integration across the UAM and ATM communities, enabled by regulatory changes to operate differently than the NAS has accommodated previously under IFR and VFR. The UAM Operators will be able to operate under more complex meteorological conditions, supported by automation providing complex safety-critical functions, and with increased digital exchanges including with ATC. At UML-4, UAM is anticipated to become more broadly available in many metropolitan areas outside early adopters. The traffic density will be moderate, nominally with hundreds of UAM aircraft aloft flying between tens of vertiports expected in a given metro area.

III. UAM WEATHER ROADMAP DEVELOPMENT PROCESS

To develop and add a weather capability to the UAM Airspace Research Roadmap, existing ConOps documentation [9], previous literature [3-8], and other elements of the roadmap [2] were reviewed, and assimilated into a set of generalized weather considerations. Based on these considerations, an initial assessment of weather information needs and requirements was conducted in the areas of communications, navigation, surveillance, and operational procedures, guided by the principles of safe and efficient operations. These initial requirements were then refined through an iterative process in which various stakeholders in the UAM community including NASA, FAA, and industry reviewed and provided feedback. The result is a baseline set of weather requirements expected to facilitate UAM at various levels of system maturity, which are feasible and aligned with other ConOps and standardization documents in development. This baseline is meant to serve as a starting point for future research for further refinement and discovery.

A. *Components of the UAM Weather Ecosystem*

As the first step in developing the weather capability, the various components needed to be identified. These components are specific functions, services, and other features that compose a weather capability for UAM. Requirements are then established on each of the components to define what is necessary to support each UML. The weather components and their requirements are largely aligned with how weather information is currently used to support aviation, and with standards that are currently under development (e.g., by ASTM F38 [10]), and are expected to evolve with future research and development.

The logical architecture between the weather components of the UAM ecosystem is shown in Figure 2, which provides context for how the components are related to each other. The components can be categorized as either weather information types (i.e., weather measurements, analyzed weather, weather models, weather forecasts, and decision support, listed in order of increased processing and value) or handling (i.e., dissemination and weather policy).

While the reader is referred to [2] for a comprehensive description of each component, a brief definition for each is as follows:

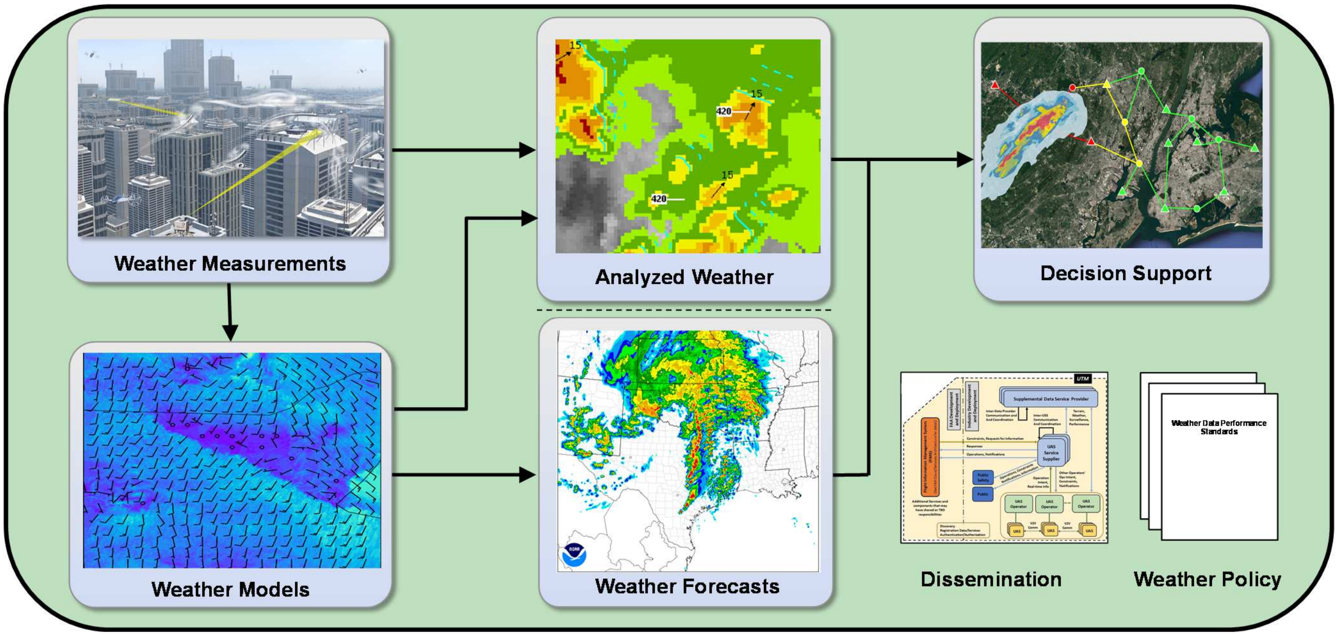

Figure 2: Logical relationship between the weather components and their use in the weather information pipeline. Blue boxes indicate weather information types, while the green box indicates overarching components for handing of the weather data.

- **Weather Measurements** – Measurements of current atmospheric conditions that can be in situ, remotely sensed, or indirectly derived. Each measurement has an associated accuracy and are typically valid at a specific point, line, or volume.
- **Analyzed Weather** – Representation of current atmospheric conditions in full three-dimensions at the surface and aloft. Produced to provide weather information at points between sparse measurements. Analyses have varying degrees of uncertainty, and can be produced using a variety of techniques including interpolation, extrapolation, artificial intelligence, statistical models, or blending with prior forecasts.
- **Weather Models** – Computational models that process weather observations to estimate current conditions and predict future weather conditions. These include full numerical weather prediction and computational fluid dynamics models.
- **Weather Forecasts** – Predictions of conditions into the future, often utilizing measurements, output from weather models, and can include manual intervention by a human forecaster. Includes both nowcasts (short-term forecasts out to two-hours) and longer-term forecasts of meteorological conditions.
- **Decision Support** – Translation of weather conditions, either measured, analyzed, modeled, or forecasted, that incorporate operational constraints to support operational decision-making. These products can be supplied either through automated systems, human analysis, or consulting and may utilize uncertainty to assess risk, intensity range, onset and duration of impacts across the UAM ecosystem.
- **Dissemination** – Data networks that disseminate pertinent weather information across the UAM system at low-latency. The volume of micro-scale weather information is expected to be massive, necessitating new methods to distill and compress this information for real-time dissemination to stakeholders.
- **Weather Policy** – A set of common rules and guidelines to be followed regarding the collection, use, and dissemination of weather data across the UAM ecosystem. These policies include accepted standards developed by the community foundational to the required information and its exchange necessary to facilitate high-tempo UAM operations.

These seven functions, services, and features are understood to compose a weather capability for the UAM ecosystem, and requirements are derived for each one as a function of the time-evolution of the NAS.

B. Development of Requirements

To discover and develop the requirements necessary to facilitate safe and efficient UAM operations at UML-2 through UML-4, both meteorological and aeronautical subject matter experts (SMEs) methodically reviewed the existing version of the roadmap to assess weather impacts and considerations for reach existing requirement. Specifically, the tables of existing requirements were reviewed to systematically document how weather affects the components of each of the nine capabilities below:

- Airspace Management Systems and Services
- Airspace and Procedure Design
- Airspace System Regulations and Policies
- Communication Services and Systems

- Navigation Services and Systems
- Secured Airspace
- Separation Services and Standards
- Surveillance Services and Systems
- Vertiport Operations

The roadmap uniquely identifies each requirement according to a standard labeling scheme, which will be used in the text and tables below. These requirement labels are of the form "(ID# UML-#.Capability)", where "ID#" is a unique numerical identifier used by NASA's Systems Modeling Language (SysML) model [11], "UML-#" indicates which UML the requirement first applies to, and "Capability" is a two-letter acronym identifying in which capability the requirement belongs.

For each existing requirement in the roadmap, the SMEs assessed the associated weather considerations. Many requirements had no weather considerations, and therefore did not lead to the discovery of any weather requirements. For example, it was deemed that the requirement (53 UML-2.SU) "ATC **should** provide surveillance using primary radar services" does not have any noteworthy dependency on requirements related to the UAM weather capability. Overall, 90 of the 246 (37%) existing requirements for the UAM Airspace System were identified as relating to the weather capability, including overarching policy and dissemination. For existing requirements that were listed as To Be Resolved (TBR) [12], the SMEs still assessed weather impacts to the component where possible. In many instances this resulted in identifying additional weather-related TBRs, which will help target future evaluation.

Once the weather considerations were defined across the UAM Airspace System, the SMEs determined if the generalized weather information adequately support other components of the airspace system. Similarly, the weather informational need for each associated existing requirement was systematically identified. Furthermore, specific weather requirements were developed, where appropriate, for each of the several components (measurements, analyzed weather, models, etc.) to identify what is needed to support the other interdependent components. An example of this process is shown in detail for a set of requirements in Table I.

There are four requirements associated with Vertiport Operations Airside Services at UML-4, which originate from the High-Density Automated Vertiport ConOps [13]. Beginning with these vertiport requirements, an example of the weather requirements development process is given in Table I. This table is reduced from the original, wherein there are additional columns for the component, weather policy, dissemination, and rationale notes. In this particular example shown, there were no weather policy or dissemination requirements discovered for Vertiport Airside Services, thus they were omitted in Table I for brevity. Additionally, a rationale column (not shown in Table I) was used to both justify the reasoning as well as add remarks regarding requirements that are TBR.

This process has produced a substantial set of specific requirements that begin to define a weather capability for the UAM ecosystem, and how that capability should evolve to meet the needs of an evolving NAS. This initial iteration has produced requirements largely focused on the specific weather information needed to facilitate various services. This process results in numerous redundant and overlapping requirements, since similar weather data will be required across the UAM Airspace System. Despite the repeated requirements, the traceability to multiple aspect of the roadmap is important as the data will be used for different purposes or require different parameters and this traceability will be useful for lower-level requirements development. To mitigate creating hundreds of requirements for which many have similar wording, overlapping requirements were grouped together to develop more generalized requirements. For example, weather forecasts of different products including wind speed, wind direction, icing, turbulence, temperature, pressure, visibility, precipitation, ceiling, and other weather parameters are required. While an individual service or function may only require a subset of those parameters, the associated weather requirements were grouped together to generate an overarching requirement that forecasts must be produced to include all of those parameters to support UAM more broadly instead of individual services. Generalizing the requirements in this way not only helps with the compactness of the information, but also avoids over-specification.

An example of the generalized weather requirements at UML-4 is given in Table II, along with references to the origin requirement ID(s) that were commonly grouped together. The ID numbers are references to requirements in the UAM Airspace Roadmap [2] for the various services. From Table II, it is clear that numerous functions and services require similar weather information. Many weather requirements are associated with three or more other requirements in other domains of the roadmap, showing the commonality in how weather data is expected to be used throughout the UAM ecosystem.

C. Feedback Solicitation and Refinement

Throughout the process in the creation of this new weather capability, various stakeholders including NASA, regulators (i.e., the FAA), and industry were engaged. This included monthly meetings to discuss progress, as well as targeted reviews of interim drafts of the weather capability description and requirements. This feedback was important to align the roadmap requirements analysis with other standardizations and regulations being developed in parallel. Additionally, input from industry in particular was desired to ensure that weather information and products are anticipated to be available on the associated timelines between UML-2 to UML-4. While there is considerable uncertainty on when high-resolution urban microscale weather information both measured and forecasted will become commercially available, industry review ensured that the timelines and requirements are at least feasible given the collective current understanding and ongoing R&D efforts broadly.

TABLE I. EXAMPLE WEATHER REQUIREMENT DEVELOPMENT PROCESS FOR THE FOUR REQUIREMENTS ASSOCIATED WITH VERTIPORT OPERATIONS AIRSIDE SERVICES AT UML-4.

Requirement	Weather Considerations	General Weather Informational Need	Measurement	Analysis	Weather Models	Forecasts	Decision Support
Vertiport Managers should be responsible for (To Be Resolved, TBR) elements of Conflict Management. (366 UML-4.VS)	Not Applicable (N/A)	N/A	N/A	N/A	N/A	N/A	N/A
Vertiport Managers should assess operational risk and make decisions to mitigate risk in accordance with the Community Based Rules (CBRs). (344 UML-4.VS)	Weather hazards pose an operational risk and impact how operations are conducted and must be considered	Measurements, analysis, and forecasts of conditions should be used to mitigate operational risks with regard to a variety of weather hazards (e.g., adverse winds, reduced visibility, convective weather, icing, etc.). Uncertainty in the weather information will be required to assess risk.	The Supplemental Data Service Provider (SDSP) shall collect and publish weather measurements with uncertainty metrics meeting sensor and data performance standards for weather parameters including, but not limited to, wind speed and direction, precipitation, ceiling, icing, and/or visibility to all subscribers at sufficient density to detect hazards around vertiports.	The SDSP shall publish weather analyses and shall provide uncertainty metrics meeting sensor and data performance standards for weather parameters including, but not limited to, wind speed and direction, precipitation, ceiling, icing, and/or visibility to all subscribers.	The SDSP shall use numerical weather prediction models meeting performance standards for estimating weather parameters including, but not limited to, wind speed and direction at the surface and aloft, turbulence, icing, wind shear, updraft and downdraft intensity, precipitation, ceiling, visibility, pressure, temperature, and dew point.	The SDSP shall publish weather forecast and shall provide uncertainty metrics meeting sensor and data performance standards for weather parameters including, but not limited to, wind speed and direction, precipitation, ceiling, icing, and/or visibility to all subscribers.	The SDSP or Provider of Services to UAM (PSU) should provide decision support capability to advise users of relevant weather risks near vertiports and along routes.
The Vertiport Manager shall monitor aircraft and ground vehicle conformance to trajectories. (345 UML-4.VS)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
The Vertiport Manager shall execute approved off-nominal procedures when an aircraft or ground vehicle trajectory is out of conformance with the expected trajectory. (368 UML-4.VS)	Unexpected winds may lead to out of conformance from the expected 4-D trajectory.	Wind information is needed along path to ensure the 4-D trajectory is accurate to mitigate out of conformance. Additionally, wind information from vehicles could inform why a trajectory is off schedule.	The UAM operator should take meteorological measurements (e.g., temperature, pressure, wind speed, wind direction) on vehicles and transmit the observations periodically for shared use among other operators, SDSPs, and PSUs.	The SDSP shall publish weather analyses and shall provide uncertainty metrics meeting sensor and data performance standards for weather parameters including, but not limited to, wind speed and direction, precipitation, ceiling, icing, and/or visibility to all subscribers.	The SDSP should use computational fluid dynamics models meeting performance standards for estimating weather parameters including, but not limited to, wind speed and direction at the surface and aloft, turbulence, icing, wind shear, updraft and downdraft intensity, precipitation, ceiling, visibility, pressure, temperature, and dew point in regions where conditions are highly complex due to the built environment such as downtown regions.	The SDSP shall publish weather forecasts and shall provide uncertainty metrics meeting sensor and data performance standards for weather parameters including, but not limited to, wind speed and direction, precipitation, ceiling, icing, and/or visibility to all subscribers.	The SDSP or PSU should provide decision support capability to advise users of relevant weather impacts near vertiports and along routes, including trajectories.

TABLE II. GENERALIZED WEATHER REQUIREMENTS AT UML-4 WITH GROUPING OF COMMON REQUIREMENTS AS THE ORIGIN.

Component	Requirement	Origin Requirement ID
Analyzed Weather	The SDSP shall publish analyzed weather meeting performance standards for estimating weather parameters including, but not limited to, wind speed and direction at the surface and aloft, turbulence, icing, wind shear, updraft and downdraft intensity, precipitation, ceiling, visibility, pressure, temperature, and/or dew point to all subscribers.	(342 UML-4.VS), (368 UML-4.VS), (344 UML-4.VS), (341 UML-4.SS), (214 UML-4.SS)
	The SDSP shall publish associated validated uncertainty metrics for analyses of weather parameters using validation methods approved by the FAA to support risk-based decision making.	(342 UML-4.VS), (368 UML-4.VS), (344 UML-4.VS), (341 UML-4.SS), (214 UML-4.SS)
Decision Support	The SDSP or PSU shall incorporate weather information to capacity, availability, and safety of shared airspace resources.	(342 UML-4.VS), (341 UML-4.SS), (214 UML-4.SS)
	The SDSP or PSU shall produce uncertainty metrics on anticipated weather impacts on capacity, availability, and safety of shared airspace resources that is validated.	(342 UML-4.VS), (341 UML-4.SS), (214 UML-4.SS)
	The SDSP or PSU shall provide decision support capability to advise users of relevant weather impacts near vertiports and along routes.	(342 UML-4.VS), (368 UML-4.VS), (344 UML-4.VS), (161 UML-4.CS), (337 UML-4.CS), (336 UML-4.CS)
Dissemination	The UAM operator shall obtain weather information from a source approved by the FAA, including SDSPs and PSUs, to comply with regulations, for additional situational awareness, and to support high tempo operations.	(160 UML-4.AR), (341 UML-4.SS), (214 UML-4.SS)
	The SDSP and PSU shall alert UAM operators of hazardous weather conditions when they are detected.	(342 UML-4.VS)
	The UAM operator shall report hazardous weather conditions when they are detected or encountered for shared use among other operators, SDSPs, and PSUs.	(342 UML-4.VS)
Weather Forecasts	The SDSP shall publish forecasts meeting performance standards for weather parameters including, but not limited to, wind speed and direction at the surface and aloft, turbulence, icing, wind shear, updraft and downdraft intensity, precipitation, ceiling, visibility, pressure, temperature, and dew point to all subscribers.	(342 UML-4.VS), (368 UML-4.VS), (344 UML-4.VS), (214 UML-4.SS), (161 UML-4.CS), (337 UML-4.CS), (336 UML-4.CS)
	The SDSP shall publish associated validated uncertainty metrics for forecasts of weather parameters using validation methods approved by the FAA to all subscribers.	(342 UML-4.VS), (368 UML-4.VS), (344 UML-4.VS), (214 UML-4.SS)
Weather Measurements	The SDSP shall collect and publish weather measurements meeting sensor and data performance standards for weather parameters including, but not limited to, wind speed and direction at the surface and aloft, turbulence, icing, wind shear, updraft and downdraft intensity, precipitation, ceiling, visibility, pressure, temperature, and dew point to all subscribers at sufficient density to support high tempo UML-4 operations.	(342 UML-4.VS), (368 UML-4.VS), (344 UML-4.VS), (214 UML-4.SS), (161 UML-4.CS), (337 UML-4.CS), (336 UML-4.CS)
	The SDSP shall publish associated validated uncertainty metrics be included with each weather measurement in compliance with CBRs to all subscribers.	(342 UML-4.VS), (368 UML-4.VS), (344 UML-4.VS), (214 UML-4.SS)
	The UAM operator should take meteorological measurements (e.g., temperature, pressure, wind speed, wind direction) on vehicles and transmit the observations periodically for shared use among other operators, SDSPs, and PSUs.	(368 UML-4.VS), (341 UML-4.SS)
Weather Models	The SDSP shall use numerical weather prediction models meeting performance standards for estimating weather parameters including, but not limited to, wind speed and direction at the surface and aloft, turbulence, icing, wind shear, updraft and downdraft intensity, precipitation, ceiling, visibility, pressure, temperature, and dew point.	(344 UML-4.VS), (214 UML-4.SS), (161 UML-4.CS), (337 UML-4.CS), (336 UML-4.CS)
	The SDSP shall use computational fluid dynamics models meeting performance standards for estimating weather parameters including, but not limited to, wind speed and direction at the surface and aloft, turbulence, icing, wind shear, updraft and downdraft intensity, precipitation, ceiling, visibility, pressure, temperature, and dew point in regions where conditions are highly complex due to the built environment such as downtown regions.	(342 UML-4.VS), (368 UML-4.VS), (161 UML-4.CS), (337 UML-4.CS), (336 UML-4.CS)
Weather Policy	The UAM community shall include weather and microclimate information in establishing and approving airspace constructs to minimize susceptibility to weather hazards.	(159 UML-4.AD)
	The FAA should make public the Final Operational Capability (FOC) process for qualifying weather SDSPs.	(148 UML-4.AR)
	The UAM community should collaborate on developing mature weather SDSP standards for measurements, models, and forecasts, including uncertainty metrics and operational safety in various weather conditions. The updated standard should also incorporate changes to adjust for other standards development e.g., cyber standards, CBRs, and ensuring compatibility with FOC qualification process.	(143 UML-4.AR)

In addition to the aforementioned review from targeted stakeholders identified by NASA and the MIT Lincoln Laboratory team that added this weather capability, a period of public comment from a wider audience was also solicited. For this, a draft v1.2 of the UAM Airspace Research Roadmap was posted publicly online along with a form in which anyone could provide feedback on specific sections, including a draft of the weather capability. As this draft was posted online, NASA hosted an open session highlighting the work done to add the weather section and opening up to public questions, which the session was recorded and is available online [14]. The open forum led to several suggestions for revisions into the weather capability that were incorporated into an updated and final draft of the UAM weather capability.

IV. THE UAM WEATHER RESEARCH REQUIREMENTS

Overall, there were 41 consolidated weather requirements developed from this effort. While the reader is referred to [2] for a comprehensive listing of the requirements and a description of the weather capability, a high-level summary of the requirements is presented here. Each requirement is written using either a **will**, **shall**, or **should** statement. **Will** is used to indicate a statement of fact and are binding in that an expectation of certainty is established. **Shall** indicates a requirement that has been demonstrated through research system implementation to be a potential minimum requirement. **Should** indicates a desired goal at the boundary of existing research and is non-binding, but can be revised to **shall** as research matures.

As UML-2 consists of initial commercial air taxi operations using newly certified eVTOL aircraft designs under existing airspace operations, requirements were largely developed from current regulations, specifically:

- FAA's Code of Federal Regulations: Part 91 and 135
- FAA Order 8900.1, Volume 3, Chapter 26: Aviation Weather Regulatory Requirements

For requirements stemming from these sources, **will** statements are used as certainty is established as the regulations already exist. Additional requirements at UML-2 were also added for early available supplemental weather information to be utilized, given that current aviation products are anticipated to be insufficient to resolve features pertinent to UAM. These additional requirements are written using **should** statements, as products are not expected to be fully mature during UML-2.

Progressing to UML-3 (Transition and Growth), requirements are written incorporating new actors in the UAM ecosystem, including Provider of Services to UAM (PSUs) and weather Supplemental Data Service Providers (SDSPs) also referred to as Weather Information Providers (WIPs) or Meteorological Service Providers (MSPs). These new actors are anticipated to be certified to serve UAM by UML-3 and be the primary source for high-resolution weather information, either via an SDSP directly or with data routed through a PSU. At UML-3, weather information requirements begin to incorporate performance-based standards that are currently under development using **shall** terminology. However, requirements for uncertainty of weather parameters uses **should** terminology, as estimating uncertainty of weather conditions accurately and reliably will be at the boundary of existing research. As UAM ecosystem matures to a UML-4 (New Predetermined Separator) state, many of the requirements for SDSPs and PSUs to provide weather information are similar to UML-3, however requirements regarding providing uncertainty information become **shall** statements as it is anticipated technology will enable reliable estimates of uncertainty in conditions by UML-4. Furthermore, the higher density and tempo of operations at UML-4 will necessitate robust uncertainty metrics to better assess the range of conditions possible that may affect the capacity of airspace, spacing of aircraft, and other safety and efficiency of UAM.

In addition to requirements for PSUs and SDSPs at UML-3 and UML-4, there are other requirements that have been developed for fleet managers, the FAA, and the UAM community at large. Specifically, **shall** statements are used to specify that fleet managers are required to obtain meteorological information from sources approved by the FAA and report hazardous weather conditions when they are encountered. Additionally, it is desired that fleet managers **should** take meteorological measurements onboard and transmit the data for shared use, which will benefit all actors within the UAM ecosystem. For the FAA, requirements were developed so that the Initial and Final Operating Capability process for qualifying SDSPs be established for UML-3 and UML-4 respectively. Additionally, overarching requirements were added stating that the UAM community (a joint body of regulatory authorities and industry representatives) **should** develop standards and infrastructure to support operations at advancing UMLs.

While numerous weather requirements were discovered in this process, there are a few areas where the interconnection between weather and other capabilities of the UAM airspace system were noted but no specific requirements could be developed at the time. These were noted in the process in the tables generated as TBR, and it is expected additional new requirements will be developed associated with these in the future. One example is that space weather (solar flares and other activity) may impact the availability and accuracy of satellite-based GPS. At this time, more research is required to identify how space weather information will be used as part of the UAM airspace ecosystem, especially since solar flares that are likely to be problematic are extremely rare, thus no requirement can be identified at the time leaving it as a TBR.

V. Requirements Tracing

As a result of the process described in Sect. III, a set of 27 tables, similar to Table I, were generated in total including three tables for each of the nine capabilities at UML 2, 3, and 4. These tables were produced by the SMEs to discover the weather requirements and their tracing to other areas of the UAM airspace system. These were delivered to NASA as part of supporting documentation of the new weather capability, and were incorporated into NASA's SysML model [11] for the UAM Airspace. This tracing provides NASA researchers and engineers the ability to more readily identify what specific weather requirements need to be leveraged or revised as the research into the UAM Airspace is conducted and the related technology matures in the lab and in the field.

Examples of these relationships and tracings are shown in Figure 3. Columns, grouped by capabilities as shown as folder icons, are associated with the unique IDs of requirements in [2]. Rows are weather requirement's unique IDs. Arrows in the intersecting cells indicate the "deriveReqt" relationships, which is to say that the requirement in the row is derived from the requirement in the column. For instance, requirement 295 UML-2.WX is derived from 45 UML-2.CS. The numbers in the gray rows and columns are the total row and column counts of these relationships, respectively. As an example, 45 UML-2.CS has three weather requirements derived from it. Not shown in the figure, there are also traces between the weather capability requirements that represent the evolution of requirements from lower UML to higher UML.

During the weather requirements development, a total of 339 traces were identified. Figure 4 shows the trace distribution broken down by association to other capabilities of the airspace. While there is tracing from weather to most UAM airspace capabilities, there is no traceability between weather (10. WX) requirements to navigation services and systems (05. NS) or secured airspace (06. SA) at this time. This is logical, as there are few weather impacts expected on either of these two capabilities. As noted previously, there may be some impacts

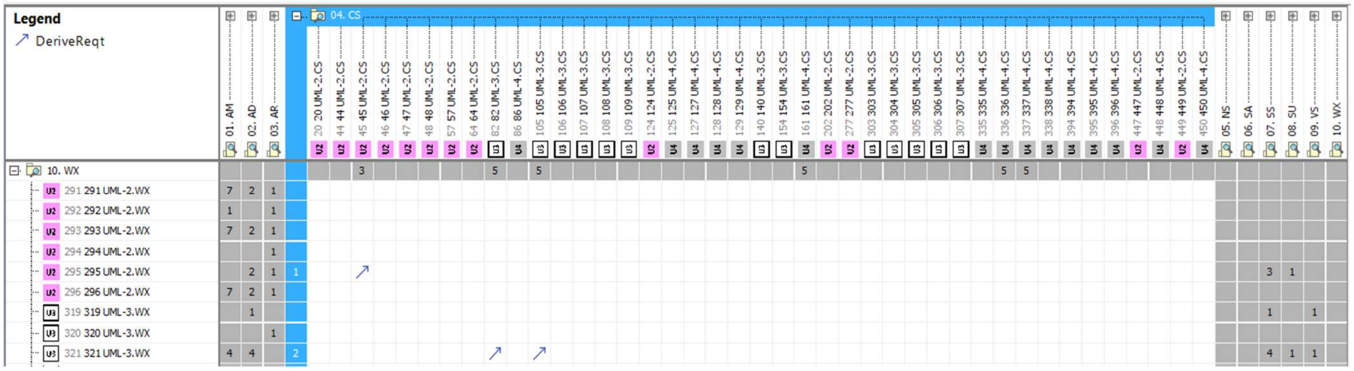

Figure 3: Sample traces between the weather requirements and other airspace capability requirements.

from space weather on GPS and navigation, these impacts are expected to be very rare and there is more research that must be conducted to understand the problem prior to creation of a requirement. Similarly, the dissemination of weather information is anticipated to follow requirements established as part of the secured airspace (06. SA), however there is no new additional weather data or specific requirement that has been discovered from various elements of the secured airspace.

As shown in Figure 4, the top three capabilities from which weather requirements were discovered and derived are airspace management systems and services (01.AM), separation services and standards (07. SS), and airspace and procedure design (02. AD). This is due to the large number of weather impacts anticipated on each of these capabilities, resulting in dependencies from them on a weather capability that provides adequate information to support each. Specifically, airspace management systems (01. AM) have a significant reliance on weather including ceiling and visibility, winds at the surface and aloft, icing, and thunderstorms that impact the availability and capacity of shared airspace resources. These necessitate a variety of weather products including measurements, analyses, modeling, forecasts, and decision support that are disseminated efficiently with supporting policies in place. Similarly, enacting separation services and standards will require high-density weather information particularly at higher UMLs, where the tempo of operations will be increased. Ceiling and visibility conditions will likely determine the community-based rules (CBRs) or regulations in effect. Winds, especially updrafts/downdrafts and wind shifts, will affect the separation

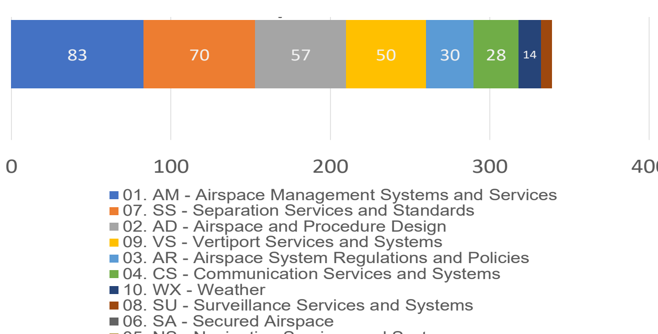

Figure 4: Trace distribution broken down by association to other airspace capabilities.

of aircraft both vertically and horizontally. These prompt the need for high-resolution weather information at a variety of timescales for both tactical and strategic decision making. The establishment of airspace and procedure design (02. AD) will depend on weather and climatological conditions, especially as airspace construct should be established where increased predictability is necessary.

Table III shows the top three weather requirements with the most traces, broken down by UML-2, 3, and 4. These general weather requirements were associated with the greatest number of non-Weather requirements across the entire UAM Airspace system, thus can be interpreted as being highly important weather requirements at each UML and potentially deserving of elevated priority for further R&D. Of course, R&D priorities are complex and must also take into account the potential safety and efficiency ramifications.

With all traces in the SysML model, it is possible to perform other deep-dive analyses such as which requirements are the driver/critical to airspace management for UAM operations by determining the requirements with the highest number of traces, or change impact analysis if any requirement is proposed for change. Additionally, the dependency can be closely reviewed to understand how a requirement was developed and assess how individual changes within the UAM Airspace System, which are expected as the R&D process matures, percolate throughout the rest of the system.

One example of this analysis for the single weather requirement associated with the most other system capability requirements is shown in Figure 5. Within this example, it shows how the weather capability requirement will provide adequate information enabling other UAM capabilities to operate while incorporating weather assumptions. In this particular example, the SDSP is required to published forecasts that meet performance standards for weather parameters to all subscribers to support the 18 other associated system capability requirements at UML-3. The requirement is general enough to encompass all of the specific information needed to support each of the other capabilities, which may have different weather informational needs. These forecasts are intended to be published and consumed by the other systems identified.

TABLE III. TOP THREE WEATHER REQUIREMENTS BY UML.

UML-2	UML-3	UML-4
1. The Fleet Manager should use supplementary weather measurements for enhanced situational awareness and flight planning and to increase safety and efficiency. (412 UML-2.WX)	1. The SDSP shall publish forecasts that meets performance standards for weather parameters to all subscribers. (411 UML-3.WX)	1. The SDSP shall collect and publish weather measurements that meets sensor and data performance standards for weather parameters to all subscribers at sufficient density to support high tempo UML-4 operations. (351 UML-4.WX)
2. The Fleet Manager should use supplementary high-resolution forecasts for enhanced situational awareness and flight planning and to increase safety and efficiency. (410 UML-2.WX)	2. The SDSP shall publish analyzed weather that meets performance standards for estimating weather parameters to all subscribers. (405 UML-3.WX)	2. The SDSP shall publish associated validated uncertainty metrics for analyses of weather parameters using validation methods approved by the FAA to support risk-based decision making. (407 UML-4.WX)
3. The Fleet Manager should use operational weather models (i.e., from the National Weather Service) and supplementary high-resolution models to support situational awareness and flight planning. (295 UML-2.WX)	3. The SDSP shall use numerical weather prediction models that meet performance standards for estimating weather parameters. (327 UML-3.WX)	3. The SDSP shall use computational fluid dynamics models that meet performance standards for estimating weather parameters in regions where conditions are highly complex due to the built environment such as downtown regions. (349 UML-4.WX)

VI. SUMMARY

NASA has been developing a research roadmap [2] to guide the direction of future R&D to design the UAM Airspace and how it evolves as technology matures at various UMLs. This roadmap lays out the various capabilities that need to be developed to facilitate safe and efficient UAM operations. While an initial draft of this roadmap was published in 2021, NASA recognized that other capabilities needed to be added, including one for weather given that transportation systems resiliency to weather is an area where neglected or incorrect assumptions often lead to difficulties later in the R&D cycle where it is costlier to address.

A team of aviation weather SMEs from MIT Lincoln Laboratory, in coordination with NASA and other representatives from government and industry, developed a weather capability that defines the required weather information, including its dissemination and overarching policies. This new weather component lays out, at a high-level, the technology and systems needed to facilitate safe and efficient UAM operations at UMLs 2, 3, and 4. By systematically reviewing and assessing weather considerations for all other capabilities of the future UAM Airspace System, weather requirements were discovered and similar specific ones were consolidated together and generalized for this high-level roadmap. This approach led to clean traceability and linkages between the weather requirements to other specific capabilities in the UAM Airspace System.

Figure 5: Example tracing of the weather requirement derived from the most other system capability requirements.

While an initial assessment of the future UAM weather capability has been established based on our collective current understanding of UAM, the UAM Airspace Research Roadmap [2] is a living document and is expected to be refined in the future as the R&D lifecycle progresses. Changes throughout the system are anticipated as UAM matures, leading to a more accurate understanding of the ConOps. These changes may affect several of the capabilities and requirements of the system. With the traceability to weather requirements matrixed, it will be easy to identify weather requirements that need to be reviewed as other capabilities are updated. Furthermore, changes to the weather capability itself may need to be made based on the advancement of weather technologies (e.g., sensing, modeling, forecasting, use of artificial intelligence) on timelines that may not be aligned with our current best estimate, as well as the evolution of the UAM community's needs.

ACKNOWLEDGMENTS

The authors thank the reviewers of drafts of the weather component of the UAM Airspace System, who provided valuable feedback and comments that helped refine the description and requirements of the capability and ensure its in line with other standards and policy in development. While we appreciate the feedback from the numerous reviewers, we especially thank Nancy Mendonca and Don Berchoff for their comprehensive reviews and providing iterative feedback as the weather capability was finalized.

REFERENCES

[1] Goodrich, K., Theodore, C., "Description of the NASA Urban Air Mobility Maturity Level (UML) Scale," AIAA 2021-1627. AIAA Scitech 2021 Forum. January 2021.

[2] Levitt, I., Phojanamongkolkij, N., Horn, A., and Witzberger, K., "UAM Airspace Research Roadmap, Revision 2.0," NASA TM-2023-0002647, March 2023. (To appear)

[3] International Civil Aviation Organization (ICAO), "Global Air Traffic Management Operational Concept," Doc 9854 AN/458, Montreal, Canada, 2005.

[4] Federal Aviation Administration, "NAS Enterprise Architecture Infrastructure Roadmaps v16.0," https://www.faa.gov/sites/faa.gov/files/NAS-Infrastructure-Roadmaps-v16.0.pptx, Accessed March 2023.

[5] Reiche, C., Cohen, A.P. and Fernando, C., 2021. An initial assessment of the potential weather barriers of urban air mobility. IEEE Transactions on Intelligent Transportation Systems, 22(9), pp.6018-6027.

[6] Chao, H., Maheshwari, A., DeLaurentis, D. and Crossley, W., 2021. Weather impact assessment for urban aerial trips in metropolitan areas. In *AIAA AVIATION 2021 FORUM* (p. 3176).

[7] Steiner, M., 2019. Urban air mobility: Opportunities for the weather community. *Bulletin of the American Meteorological Society*, *100*(11), pp.2131-2133.

[8] Galway, D., Etele, J. and Fusina, G., 2008, August. Modeling of the urban gust environment with application to autonomous flight. In AIAA Atmospheric Flight Mechanics Conference and Exhibit (p. 6565).

[9] Bradford, S., 2020. Urban Air Mobility (UAM) Concept of Operations (ConOps) v1.0. *Federal Aviation Administration.* https://nari.arc.nasa.gov/sites/default/files/attachments/UAM_ConOps_v1.0.pdf, Accessed March 2023.

[10] ASTM Standard WK73142 (in development), 2023, "New Specification for Weather Supplemental Data Service Provider (SDSP) Performance," ASTM International, West Conshohocken, PA, 2003, https://www.astm.org/workitem-wk73142.

[11] Weilkiens, T., 2011. Systems engineering with SysML/UML: modeling, analysis, design. Elsevier.

[12] National Aeronautics and Space Administration, "NASA Systems Engineering Handbook", NASA/SP-2016-6105 Rev 2, Appendix C. 2016

[13] Northeast UAS Airspace Integration Research Alliance (NUAIR), High-Density Automated Vertiport Concepts of Operations, NASA Technical Reports Server (NTRS), Washington, D.C., May 2021.

[14] NASA Ames Aeronautics. NASA AAM – Airspace Working Group: UAM Airspace Research Roadmap – Deep Dirve and Q&A. (July 19, 2022). Accessed: Mar. 23, 2023. [Online Video]. Available: https://www.youtube.com/watch?v=nR0Pa4RpgFU.