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UAM Airspace Research Roadmap

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1. Introduction

Advanced Air Mobility (AAM) encompasses a range of innovative aviation technologies (small drones, electric aircraft, automated air traffic management, etc.) that are transforming aviation's role in everyday life, including the movement of goods and people. The concept of Urban Air Mobility (UAM) is composed of certain AAM concepts that provide commercial services to the public over densely populated cities and the urban periphery, including flying between local, regional, intra-regional, and urban locations using revolutionary new electric Vertical Takeoff and Landing (eVTOL) aircraft that are only just now becoming possible. The improvement of UAM envisages a future in which advanced technologies and new operational procedures enable practical, cost-effective air transport as an integrated mode of movement of people and goods in metropolitan areas.

In order to safely support these revolutionary vehicle operations at scale in the National Airspace System (NAS), NASA's Air Traffic Management-Exploration (ATM-X) UAM Airspace Subproject is conducting research that evolves UAM airspace towards a highly automated and operationally flexible system of the future. The scope of NASA's research into the UAM airspace system is defined to encompass the airspace itself and the system of systems that comprise the UAM operations within. This is understood to include the conduct of UAM operations in relationship to other NAS operations, the supporting technologies and information exchanges, and the architecture of the associated systems and services.

The UAM Maturity Level (UML) scale [3] developed by NASA provides insight into UAM operational, technical, and regulatory progression in the National Airspace System (NAS). The UML scale is a useful framework for understanding and evaluating the evolution of the NAS as it pertains to UAM, where the UMLs themselves are periods of change that build up to significant "step-functions" in operational capabilities. While the existing definition of the UML scale provides an extensive and well-defined treatment of the progression of UAM from a vehicle operations perspective, it is limited in its treatment of the UAM airspace system. As such this paper begins to establish a framework, termed the UAM airspace system research roadmap, to help NASA meet the goal of *evolving the UAM airspace towards UML-4.*

The complexity of UAM airspace evolution requires a plan to effectively organize, integrate, and communicate NASA's research and development. The UAM airspace system research roadmap, or just roadmap, is a system engineering approach to manage what is known, what is developed, and what is planned for in NASA's UAM airspace research & development lifecycle. It accomplishes this by first decomposing the UAM airspace system of systems into discrete research *elements* and their constituent *components*. This decomposition allows for an integrated approach to the development, verification, and validation of assumptions, requirements, constraints, and airspace system architectures that will be developed by NASA.

Once UAM operations are introduced to the NAS, and as the demand levels for UAM operations grows, there will be a significant increase in the need for integrated Research, Development, Test, & Evaluation (RDT&E) [9]. During this time the lifecycle of NASA's UAM airspace research will unfold, providing significant input into the safety, technology, and operational research necessary to meet the emerging need for updated regulatory and airspace frameworks in the NAS. The RDT&E conducted during this critical phase of NAS evolution will drive the AAM community's investment in the promise of the envisaged future.

2 UAM Airspace System Definition

NASA has pioneered the paradigm of an Extensible Traffic Management (xTM) system, defined as a federated and automated service-based Air Traffic Management (ATM) System [11]. The UAM airspace system follows this xTM paradigm, alongside other examples such as small Unmanned Aircraft System

(UAS) Traffic Management (UTM) [15, 17] and Upper Class E Traffic Management (ETM) [16]. Other applications are expected to follow.

A federated enterprise architecture is one which operates collaboratively, where governance is divided between a central authority and constituent units, balancing organizational autonomy with enterprise needs [8]. The role of the central authority is to ensure the well-being of the enterprise, while constituent units have the flexibility to pursue autonomous strategies and independent processes. The UAM airspace system architecture will be federated, with central authority derived largely from the Air Navigation Service Provider (ANSP) (and possibly other entities), and with a distributed constituency of UAM Operators who operate safely and with increasing flexibility as the system evolves.

The UAM Operators will exercise this independence and flexibility through use of an array of services that are either self-provided or from a third-party, such as the Provider of Services to UAM (PSU), the Vertiport Operator, or a Supplemental Data and Services Provider (SDSP, see note below). The systems and services that support the UAM Operator in complying with regulatory and community-based requirements will evolve towards being highly automated [3].

There are several human and system entities and actors in the UAM airspace system of systems. The roadmap applies the following definitions:

Pilot in Command (PIC): The human operating the UAM Vehicle. Used on its own, the PIC always refers to a human onboard the UAM Vehicle. A Remote PIC (RPIC) is a human piloting the UAM Vehicle remotely.

UAM Vehicle: The system that is providing inner-loop control of the aircraft, and supporting sensors, navigation systems, communication systems, and avionics.

> *Note: In general the UAM vehicle may have various pilot configurations, including remotely piloted and autonomous. This version of the roadmap does not treat vehicle automation levels, but future development should include a complete treatment of the vehicle pilot configurations*.

UAM Operator: The entity responsible for the overall management of a UAM operation, which may represent the organization that is executing the operation. The UAM Operator may also be the PIC e.g., of an owner-operated eVTOL. This is consistent with the definition of *operate* from 14 CFR § 1.1 General Definitions, which states

> Operate*, with respect to aircraft, means use, cause to use or authorize to use aircraft, for the purpose…of air navigation including the piloting of aircraft, with or without the right of legal control (as owner, lessee, or otherwise)*

Vertiport Operator: The entity responsible for the safe and efficient management of the vertiport resources. The Vertiport Operator may have authority over the UAM Operator’s ability to land and depart.

Provider of Services to UAM (PSU): An entity responsible for providing specific and secure services to the UAM Operator that are required for operating in the airspace, with authority derived from the ANSP.

Supplemental Data and Service Provider (SDSP): An entity providing certain services, other than the PSU.

> *Note: While the term “Supplemental Data and Services Provider” is used here to align with the underlying literature, as of the writing of this document there are known changes under development. Future iterations will update terminology in this area.*

3 UAM Airspace System Evolution

The UAM airspace system will follow an evolutionary, albeit radical, path from the current NAS to a NAS with integrated UAM operations accommodating a federated system of UAM Operators, PSUs, and Vertiport Operators to safely manage the airspace at scale. While any prediction of how the airspace system may evolve will be uncertain, some reasonable path must be perceived so that the research can be conducted efficiently. The progression of the NAS through the UMLs from an airspace system perspective is summarized below. This progression is largely drawn from the FAA NextGen UAM Concept of Operations v1.0 [1] and is complementary to existing UML definitions [3]. Other longer-term ConOps, e.g. the NASA Community ConOps [2], are also used to help guide later stages of the evolution.

3.1 UML-1: Pre-Operational

UML-1 represents the (current) pre-operational phase that precedes the first operational approval of commercial UAM eVTOL operations in the NAS. These will be largely experimental operations in the NAS, although there may be a period of non-experimental flights in the NAS (e.g. under part 91) using eVTOL that are certified while commercial operations are not yet approved.

Existing infrastructure will be used to demonstrate UAM operations, and to collect field data that will advance UAM operations to the next stage. Traffic densities will be low, and interactions with existing ATC will be known and controlled through the appropriate safety management system (SMS) processes. These operations will primarily take place under Visual Meteorological Conditions (VMC), and as piloted operations under Visual Flight Rules (VFR) or Instrument Flight Rules (IFR).

3.2 UML-2: Initial

UML-2 represents initial commercial operations under existing regulations which utilize existing airspace constructs. These operations are expected to take place in carefully chosen early adopter markets where operational challenges can be eased with non-regulatory accommodations where possible. These operations will likely rely on commercial pilot certification and ratings, operating under VFR or IFR with Part 91 and Part 135 approvals. UAM operations will be designed to minimize interactions with existing ATM operations, with operational tempo expected to be on the order of 3-15 operations per vertiport per hour, and simultaneous operations in the tens (10-50) per metropolitan area [3]. Existing and new infrastructure will be leveraged by the UAM Operator, initially with low-complexity route networks. Vertiports are expected to be shared among UAM Operators in some cases, and in others private vertiports may be employed by a single UAM Operator.

Assistive technology will be leveraged by the PIC and the UAM Operator to safely increase operational tempo without increasing ATC workload to the extent possible, and the operational design will be to enable safe and efficient scaling of the operations. Technology maturation will be on a path towards, among other things, assisting humans in the safe and strategic management of airspace resources being utilized by UAM operations. Information exchanges may be established that permit cooperative behaviors that lead to overall system benefit.

Eventually, the need to increase operational tempo will be limited by the capacity of existing NAS constraints. More significant regulatory changes will be required to further increase operational flexibility while maintaining safety. The same is true for increased UAM Vehicle autonomy, and a holistic approach to maturing regulations to permit both operational flexibility and alternate pilot configurations on the UAM Vehicle would be ideal.

3.3 UML-3: Proliferation

UML-3 represents the proliferation of novel regulatory and airspace constructs (e.g., cooperative UAM corridors) and the supporting systems and services, designed to overcome the capacity constraints of UML-2. The UAM Operators will seek operational credit for systems and services that have matured in an assistive capacity during UML-2, and which will reduce the ATC workload otherwise required to maintain the increase in operational tempo. It is expected that the vertiports may service 20-30 operations per hour, with up to 100 simultaneous airborne UAM operations in a metropolitan area.

In order to accommodate this new operational flexibility and responsibility for the UAM Operator, regulatory changes will need to be made. This may include the establishment of new airspace constructs (e.g., UAM Corridors), Letters of Agreement (LOA), and waivers to existing rules. Airspace systems and services will support complex strategic conflict management and provide early safety-critical functionality to assure separation provision between all UAM and non-UAM operations, including under updated VMC and IMC regulatory framework. This will permit greater complexity in the route and vertiport networks, potentially incorporating novel airspace constructs. Within this period, the UTM ecosystem will be mature and interoperate with the UAM airspace system.

This increased operational flexibility also comes at a time of increased automation on the vehicle, supporting concepts such as Simplified Vehicle Operations (SVO) and Remote Pilot in Control (RPIC) [3]. The relationship between increased autonomy levels for the vehicle and increased responsibility of the UAM Operator is important.

The solutions put in place for UML-3 will be tailored to many of the specific regional conditions and operational use cases that proliferate across the NAS. Individual SMS processes and technologies will be employed for operational approval. These pathfinder use cases will eventually lead to a national strategy for integrating UAM operations in a streamlined manner to meet the growing national market demand.

3.4 UML-4: Integration

UML-4 represents the integration of UAM operations into the NAS under more complex meteorological conditions, with the support of more complex safety-critical systems, and with increased digital exchanges including with the ANSP. The airspace constructs that will have emerged are used routinely in conjunction with third party systems and services to ensure safe, efficient, and equitable access to the airspace for the UAM Operator. It is expected that the vertiports may service 40-60 operations per hour, with hundreds (100-500) of simultaneous airborne UAM operations in a metropolitan area. The route and vertiport networks will be highly complex and responsive to accurate weather and traffic predictions.

The UAM Operator is responsible for cooperatively managing conflicts within the parameters of the airspace constructs and ultimate form of regulatory accommodations. They are supported by mature rules and requirements, some of which are achieved by consensus in industry and approved by the FAA. Performance standards will enable heterogeneous operations and vehicle types while allowing operational flexibility and adaptation, supported by increasingly autonomous technologies both airborne and terrestrial.

4 Roadmap Process

The roadmap is defined to meet the need for tracing and maturing system engineering artifacts which cover multiple complex dimensions in scope and time. The breadth and complexity of the research that underpins these artifacts requires organization, a common language, and a unifying approach. The first step in meeting this need is accomplished by decomposing the UAM airspace system into constituent components, and then tracking key requirements and assumptions for that component across the UML progression. This structure allows the system engineer to easily index a topic of interest and study one focused aspect of the UAM airspace system. The decomposition is described in further detail in the next section. Based on that decomposition, a process for tracking progress along the roadmap is given in section 6.

There are major parts of UAM research that do not fall strictly within the domain of the airspace system and are not captured, including aspects of the vehicle, vertiport, and community. Integration and interoperability with those significant areas of research are critical, and a coordinated effort is required. It is worth noting in particular that the level of autonomy and piloting configurations for the UAM vehicle have not been assessed in this airspace research roadmap, and forming an integrated understanding is an important next step.

Having established a roadmap process, NASA research activities will be the primary driver for updates and iterations. For example, the ATM-X UAM Airspace Subproject, in partnership with the AAM National Campaign and other subprojects, will execute the X4 simulation over the period of roughly a year. Throughout that time, the X4 effort will be a source of changes for the roadmap and upon completion the roadmap will be updated to reflect the validation that such a broad and collaborative activity provides. A similar process is expected throughout the lifecycle of NASA's UAM airspace research, absorbing the results and maturing the view of UAM Airspace evolution to UML-4.

Finally, the roadmap is a living document, and it is expected that iterations will be ongoing with periodic versions released to encourage internal and external collaboration. The roadmap will follow a development lifecycle that will culminate in a mature set of assumptions, requirements, constraints, and architecture for UAM airspace systems and services. These system engineering artifacts will be validated by technology and other deliverables researched and developed by NASA, which will also be easily tracked via the roadmap.

5 Roadmap Decomposition

To begin the roadmap process as described above, this paper will decompose the UAM airspace system into a non-exhaustive list of operational research *elements*. This initial list of research elements is derived from existing examples in the NAS [10], and subject matter experts working in both ATM and xTM. They focus largely on systems and services, including services like communication, navigation, and surveillance, as well as services traditionally provided by the Air Navigation Service Provider (e.g., separation and flow management). The research elements also encompass features of the UAM airspace system whose definition and performance impacts the systems and services, such as procedures and policies.

Information was synthesized from numerous activities, reports, and analyses to arrive at the identified list of operational research elements below. The list of research elements is expected to change and expand during the lifecycle of the roadmap.

- Airspace Management Systems and Services Architecture
- Airspace and Procedure Design
- Airspace System Regulations and Policies
- Communication Services and Systems
- Navigation Services and Systems
- Separation Services and Standards
- Surveillance Services and Systems

In the subsections that follow, each research element is further decomposed into constituent *components*, which are briefly defined and described to provide enough structure for analysis and documentation.

Following the component description of each research element, a table of requirements is provided per component, and for each UML. These requirements will be updated, added, and deleted based on NASA research and development, and as part of the roadmap's iteration and revision cycles.

The requirements, assumptions, and constraints are written using the following conventions respectively:

- **shall** is used to indicate a binding requirement, and will be verified
- **will** is used to indicate a statement of fact, or an assumption taken for granted, and are binding in that an expectation of certainty is established
- *should* is used to indicate a desired goal at the boundary of existing research, is non-binding, and is used to guide evaluation activities. As the research matures, these can be revised to become requirements.

Requirements, assumptions, and constraints are generally written in the form [Actor or Entity] **shall/will/***should* [perform an action]. In the tables that follow these are only written for UML-2 and above, since requirements on pre-operational phase do not guide NASA's UAM airspace research efforts.

Finally, To Be Resolved (**TBR**) will used to indicate best estimates, a lack of known requirements, assumptions, or constraints, or simply areas where further roadmap development is needed. As with requirements, **TBRs** will be updated, added, and resolved during roadmap iterations. In many cases, **TBRs** will graduate to requirements. Wherever possible, the **TBRs** will be documented with a rationale and action plan for resolution.

5.1 Airspace Management Systems and Services Architecture

The Airspace Management Systems and Services Architecture research element applies to that part of the UAM airspace system that provides the UAM Operator with the ability to access and exchange information, provides services to the UAM Operator to meet all or part of an FAA regulation [1], and enables interoperability amongst distributed actors and systems in the federated system architecture. This element of the UAM airspace system includes the interface to the ANSP and relies on a common infrastructure and protocols within the UAM ecosystem. Examples of services that fall under the element include approving deconflicted operational plans, discovery of actors and services relevant to the UAM Operator.

- *Provider of Services to UAM (PSU)*: A PSU is an entity that provides services to the UAM Operator to help them meet UAM operational requirements that enable safe, efficient, and secure use of the airspace [1]. Multiple PSUs employed by different operators will be part of a network and subject to interoperability requirements. The PSU is the trusted source for some of the traditional ANSP services, such as distribution of notifications, confirmation of flight intent, and confirmation of authorized access to airspace.
- *Supplemental Data and Services Provider (SDSP)*: UAM Operators and PSUs use Supplemental Data Service Providers (SDSPs) to access supporting data including, but not limited to, terrain, obstacle, aerodrome availability, and weather. SDSPs may be accessed via the PSU network or directly by UAM operators. [1]
- *Discovery Services*: The process of automatically detecting relevant information and services on the PSU Network. Systems and services search seamlessly across a range of content providing relevant information for the UAM Operator to conduct the desired mission, for example the other UAM Operators and their PSUs with flights scheduled near the same time and location. Discovery services provide a centralized architectural element, which enables the distribution of other systems and services in the federated architecture.
- *FAA-Industry Data Exchange Protocol (FIDXP)*: The FAA-Industry Data Exchange Protocol (FIDXP) is an interface for data exchange between FAA systems and UAM participants. The FIDXP provides an interface for the NAS Data Exchange to request UAM operational data on demand and send FAA information to the PSU network for distribution to UAM operators, PICs, UAM Vehicle, and public interest stakeholders [1]. FIDXP is managed by the FAA and is a part of the UAM ecosystem. FAA NAS data sources are available to UAM operations via FAA-industry exchange protocols. This allows for authorized data flow between the UAM community and FAA operational systems. This interface between the FAA and UAM stakeholders is a gateway such that external entities do not have direct access to FAA systems and data. FAA data sources available via the FAA-industry data exchange include, but are not limited to, flight data, restrictions, charted routes, active Special Activity Airspaces (SAAs)
- *UAS Service Supplier (USS)*: A USS is an entity that assists small UAS Operators with meeting UTM operational requirements that enable safe and efficient use of airspace. A USS (1) acts as a communications bridge between federated UTM actors to support Operators’ abilities to meet the regulatory and operational requirements for UAS operations, (2) provides the Operator with information about planned operations in and around a volume of airspace so that Operators can ascertain the ability to safely and efficiently conduct the mission, and (3) archives operations data in historical databases for analytics, regulatory, and Operator

accountability purposes. In general, these key functions allow for a network of USSs to provide cooperative management of low altitude operations without direct FAA involvement. [15]

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Discovery Services	Discovery services *should* enable UAM Operators, through their PSU, to discover and identify other PSUs with active operations in the area and time of interest	**TBR:** How Discovery services will be architected in UML-3 and beyond cannot be determined until UML-2 is better understood.	**TBR:** How Discovery services will be architected in UML-3 and beyond cannot be determined until UML-2 is better understood.
FIDXP	**TBR**	The FIDXP **shall** provide a means for authentication and authorization of the PSU. The FIDXP **shall** provide a means for the UAM Operator to obtain authorization from ATC to operate in the airspace. Typically, this will be achieved through the PSU. The FIDXP **shall** provide a means to distribute NAS data sources. The FIDXP **shall** provide access by the FAA to active, pending, and past UAM Operations. The FIDXP **shall** provide a means for the PSU to notify the FAA of non-conforming and contingency UAM Operations. The FIDXP **shall** provide a means for the FAA to make updates and distribute airspace constraints to the PSU in real time. Some examples of airspace constraints include corridor availability, dynamic constraints like TFRs, hazards, and other potential safety directives.	**TBR**: Those FIDXP requirements that would be in UML-4, but not in UML-3, have not been developed.

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
USS	**TBR:** It is not clear whether sUAS will interact with UAM traffic at all under existing regulatory structure of UML-2.	The PSU **shall** obtain UTM operations information via the USS network The USS **shall** obtain UAM operations information via the PSU network The USS **shall** coordinate with PSUs to facilitate operations crossing a UAM corridor	**TBR:** Those USS requirements that would be in UML-4, but not in UML-3, have not been developed
PSU	The UAM Operator *should* utilize unqualified PSU capabilities that provide advisory information which enables increased operational tempo without overburdening ATC. The PSU and PSU Network *should* possess key characteristics such as interoperability, scalability, and security. The PSU *should* submit operational plans and modifications to the PSU Network. The PSU *should* be capable of detecting strategic conflicts in accordance with anticipated CBRs. The PSU *should* be capable of providing a resolution to the UAM Operator when a strategic conflict is detected. The PSU *should* identify demand-capacity information for the UAM Operator. The PSU *should* monitor operational conformance to the confirmed UAM Operational Intent.	The UAM Operator *should* take operational credit for certain PSU services. The FAA should certify or qualify such PSU services. The PSU *should* share position reports with other PSUs that are operating in the intended area. The PSU **shall** monitor operational conformance to the confirmed UAM Operational Intent. The PSU **shall** detect strategic conflicts in accordance with established CBRs. The PSU **shall** provide a resolution to the UAM Operator when a strategic conflict is detected. The PSU **shall** alert the PSU Network of non-conforming and contingent UAM operations. The PSU *should* provide FAA operational data and advisories, weather, and other supplemental data to UAM Operators. The PSU *should* support cooperative decision making amongst the UAM Operators and their PSUs.	The PSU *should* allocate airspace resources to maintain capacity, in cooperation with UAM Operators and their PSUs and in accordance with established CBRs. The PSU *should* use weather constraints to make decisions in accordance with established CBRs. The PSU *should* provide safety-critical services to the UAM Operator, including conflict management

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
SDSP	The UAM Operator *should* use low-fidelity weather information, terrain and obstacle information, and airspace structure information where required by CBR or to increase safety and efficiency. Vertiport Operators (or FBOs) *should* provide services to the UAM Operator to manage surface constraints, for example landing reservation times. UAM Operators, PSUs, Vertiport Operators, ANSP, and other UAM Community stakeholders *should* use standardized data sources for weather, terrain and obstacle, and airspace structure information	The ANSP *should* approve services to provide high-fidelity weather information, terrain and obstacle information, and airspace structure information for use by the UAM Operator and the PSU. The ANSP *should* approve information derived from NAS data sources to be used by services to the UAM Operator and the PSU. The ANSP *should* approve monitoring services to be used by the UAM Operator and PSU for such systems as communication, navigation, and surveillance systems	**TBR**: The role of the SDSP, and indeed whether SDSP is the correct system architecture, need to be better understood at UML-3.

5.2 Airspace and Procedure Design

The Airspace and Procedure Design operational research element includes the design and definition of airspace constructs within the NAS that support the UAM operational environment, with associated performance requirements and operational procedures that reduce operational complexity where possible and provide structure where needed. Multiple components are identified to decompose the element into discrete areas of research and operational evolution.

- *Airspace Management*: Processes and procedures applied by actors in the system, including ATC, that ensure safe, efficient, equitable, and scalable access to the airspace for the UAM Operators. Examples of airspace management include processes for establishing or activating corridors, establishing capacity constraints, and establishing arrival/departure configurations at the vertiport.
- *Airspace Construct*: Identification and definition of new or novel airspace structures in controlled and uncontrolled airspace that are utilized by UAM Operators to execute their UAM mission. Airspace constructs for UAM are central to the introduction of UAM into the NAS, providing ATC with the ability to manage new traffic flows within their airspace with minimal impact on their workload and eventually providing the UAM Operator with some relief from existing regulatory constraints. In the latter case, the airspace constructs are expected to rely on safety-critical systems and infrastructure both on- and off-board the UAM vehicle.

- *Approach and Departure Procedures*: Identification and definition of pre-planned and published procedures providing ingress and egress to the surface. Approach and departure procedures are expected to be impacted by multiple environmental conditions, including weather and predicted demand.
- *En-route Procedures*: Identification, definition, and usage of nominal pre-planned and published procedures providing access to controlled and uncontrolled airspace for the conduct of airborne UAM flight. En-route procedures are expected to be impacted by multiple environmental conditions, including weather and predicted demand. Associated performance requirements also affect how these procedures are defined and used.
- *Contingency Procedures*: Identification, definition, and usage of off-nominal pre-planned procedures for managing contingent operations. Contingency scenarios divert from the operations intended plan but are circumstances that are expected to occur with some degree of frequency and if left unmitigated may impact operational safety [6]. Contingency procedures may be invoked at any point during the flight from liftoff to touchdown. These procedures are expected to impact ATC and the UAM airspace system with as minimal disruption as possible while ensuring safety. Examples of contingency procedures include go-arounds, lost-link, and passenger emergency. Note: Scenarios that induce Contingency scenarios are not the same as Off-Nominal scenarios, which are addressed in the **Safety** operational research component.

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Airspace Management	The UAM Operator **shall** obtain all airspace management services from ATC where applicable. The Vertiport Operator *should* establish or configure arrival and departure configurations and constraints at the vertiport	The ANSP *should* establish and configure the new airspace constructs (e.g. activating corridors). The ANSP *should* define capacity constraints on the new and existing airspace constructs. The Vertiport Operator *should* establish and configure arrival and departure configurations and constraints at the vertiport	The PSU *should* make cooperative decisions with other PSUs in order to equitably allocate existing capacity to the UAM Operator demand for airspace resources

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Airspace Construct	The UAM Operator *should* use existing helicopter routes and low-density VFR patterns to enable initial commercial missions. The UAM Operator *should* use internally defined constructs, such as regular flight paths in Class G airspace, to increase the safety and efficiency of the UAM operations. The UAM Operators and ATC *should* use Letters of Agreement (LOA) to establish regular flight paths in Class G airspace, where beneficial	The ANSP *should* approve airspace constructs that allow the UAM Operator to execute missions at increased tempo. The ANSP *should* approve airspace constructs that provide structure where necessary but allow for flexibility where possible. The UAM Operator **shall** utilize the PSU to support cooperative flight planning and to adhere to regulations or CBRs established for the airspace constructs	The UAM Operator *should* make use of scalable airspace constructs regularly, supporting medium-tempo operations. **TBR**: The characteristics of airspace constructs utilized by UAM operations, especially in relation to ATM and UTM traffic, depend on the regulatory approach taken and the associated airspace constructs in UML-3. More needs to be understood about UML-3 in order to resolve this issue
Approach & Departure Procedures	The UAM Operator *should* operate with approach and departure procedures that do not present a hazard to existing ATM operations	The ANSP *should* approve the use of approach and departure procedures with reduced separation minima and associated performance requirements	**TBR**
En Route Procedures	The UAM Operator *should* use internally defined constructs for the en route portion of flight, such as regular flight paths in Class G airspace	The ANSP *should* approve the use of en route procedures with reduced separation minima and associated performance requirements	**TBR**
Contingency Procedures	**TBR**: Contingency procedures requirements need development. ATC and PIC will be involved in contingencies, and UAM Operator will be involved in contingency planning	**TBR**: Contingency procedures requirements need development. Within the airspace constructs, UAM Operator and PIC will resolve the contingency. Outside of the airspace constructs, ATC and PIC will resolve the contingency. UAM Operator will be involved in contingency planning	**TBR**

5.3 Airspace System Regulations and Policies

The Airspace System Regulations and Policy operational research element includes regulations, certifications, processes, and other policies which apply to the airspace in which UAM aircraft operate. The UAM operations will be enabled at times through maximizing existing regulatory framework for operational flexibility, and at times require more significant regulatory or policy change. Policy changes such as Letters of Agreement (LOAs) [OpSpec] and waivers are included here, as well as changes to the Code of Federal Regulations [4] through rulemaking.

- *Cooperative Operating Practices (COP) / Community Based Rules (CBR)*: proposed rule-making procedure that would augment existing regulations and emphasize industry input. CBRs are collaboratively developed by industry stakeholders based on FAA guidelines, and some level of FAA approval is required to complete the process.
- *FAA Regulations (FAR) / Code of Federal Regulation (CFR)*: The FAA Regulations (FAR) are found under the Code of Federal Regulations (CFR), Title 14 Aeronautics and Space [5]. Title 14 is decomposed into Volumes, Chapters, and then Parts. The most relevant Parts are Part 91 and Part 135, but UAM operations are impacted and impact more than that. Operational approval to the UAM Operator will be provided by an approved Operations Specification [OpSpec] under Part 121 or Part 135. Letters of Agreement (LOA) are developed under Part 91.
- *Policies and Guidance*: Official guidance or acceptable practices on how to find compliance with a specific CFR. Examples of Policies and Guidance include the Aeronautical Information Manual (AIM), specific LOAs, and Operation Specifications developed by the UAM Operator and approved by the ANSP.
- *Safety Management System (SMS) / Safety Risk Management (SRM)*: Safety Management System (SMS) is the formal, top-down, organization-wide approach to managing safety risk and assuring the effectiveness of safety risk controls. It includes systematic procedures, practices, and policies for the management of safety risk. SMS is becoming a standard throughout the aviation industry worldwide, and is widely recognized across both public and private sectors as the next step in the evolution of safety in aviation. The SMS is established for the FAA by Order 8000.369C[7]. The Safety Risk Management (SRM) process is the key tool used by the FAA to meet their SMS mission. SRM is required to apply to all investments that have an impact on the National Airspace System, and is part of Acquisition Management System (AMS) policy [4]. Whenever there is a change to the NAS, the SRM process is invoked. For more information see [12]
- *System Certification and Qualification*: The UAM airspace system will include a range of system components that are used in part to provide services to the UAM Operator. Depending on the level of criticality of the systems and associated services, the systems will require various levels of certification and qualification by the ANSP and other organizations. It is expected that SMS will be applied wherever system certification and qualification are required.

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
COP / CBR	**TBR**: The regulatory nature of CBRs are not understood.	**TBR**	**TBR**
FAR/CFR	The UAM Operator **will** design operations within existing regulations	**TBR**: The regulatory changes necessary for new airspace constructs need to be better understood	**TBR**: The regulatory changes necessary for integrated airspace constructs, and for delegation of the entire conflict management function, need to be better understood
System Certification & Qualification	**TBR**: The UAM Operator will not rely on ANSP qualified systems, except for those required by the airworthiness certification for Part 135 and Part 91 operations. Industry standards will be developed during UML-2, to be used as means of compliance in UML-3	**TBR**: How the ANSP will certify or qualify technologies and services for use by the UAM Operator needs to be better understood. How industry standards will be used as methods of compliance in the qualification process for third-party services and systems also needs to be better understood	**TBR**
SMS/SRM	UAM Operators, PSUs, Vertiport Operators, ANSP, and other UAM Community stakeholders *should* collect operational data to feed the safety and certification processes that will be needed to take operational credit for services and new airspace constructs	UAM Operators, PSUs, Vertiport Operators, and other industry stakeholders, **shall** employ robust SMS processes	UAM Operators, PSUs, Vertiport Operators, and other industry stakeholders, **shall** employ state of the art SMS processes using mature system models
Policy and Guidance	Regulatory changes such as LOA, waivers, and exemptions **will** be used to advance through UML-2, eventually giving way to mature regulations	**TBR**: Policy and guidance will follow from FAR/CFR and CBRs, which are not well understood	**TBR**

5.4 Communication Services and Systems

The Communications Services and Systems operational research element includes the usage of verbal and/or digital exchange between the actors/entities which are required to enable the safe, efficient, and scalable execution of operations as defined by regulations and policies. Communications includes discrete control instructions, advisories, clearances, data exchange models, etc. Communications may be conveyed by a combination of terrestrial, airborne, and satellite means. The Communications element is decomposed into components by exhaustive enumeration of data services (e.g., Voice, Telemetry, Command and Control, etc) that may be provided between actors (e.g., fleet operator, aircraft, PSU Network, etc.), eventually tracing to lower-level performance requirements on the link technologies that support them. The performance requirements for each data service may vary depending on where UAM aircraft are operating (e.g., en route versus vertiport proximity), and the additional RF interference and propagation challenges posed by the urban environment may warrant wireless link technologies that provide reliable CNS services locally at each urban vertiport.

- *Voice Services*: For piloted UAM aircraft, voice communications between the pilots, UAM operators, and possibly vertiport operators may be required to ensure safety of operations during the early phases of UAM where on-board automation will be relatively immature. As aircraft automation improves, on-board pilots would utilize voice communications during off-nominal events only. For remotely piloted aircraft, voice communications between the RPIC and passengers would be available in the event of a passenger emergency or distress
- *Telemetry Services*: Aircraft will periodically provide telemetry data describing its position and overall operating status to the UAM operator and subsequently to the PSU Network via the PSU supporting the operation.
- *Command Services*: A UAM operator may update the flight plan of any aircraft at any given time using the command data service. This service may also be used to provide approach authorization and guidance as the aircraft approaches its destination vertiport.
- *Contingency Communications*: During off-nominal conditions, the UAM operator may want access to additional information about the current state of his or her aircraft that is not included in the nominal telemetry data service. This additional information may include in-cabin or external video feeds, detailed battery status, raw sensor data, and additional telemetry from the on-board avionics suite. This information may be requested by the RPIC or an automated diagnostics algorithm provided by the aircraft manufacturer.
- *Vehicle-to-Vehicle Services*: Direct communications links between aircraft may be used to carry multiple data types include voice and cooperative separation data. These links may also be used to relay other data services such as telemetry and command data during lost link events.
- *Pre-/Post-Flight Wireless Services*: Before takeoff, UAM aircraft will require wireless data links to report their status, receive flight plans, and receive airspace and weather data. Additional services may include pre-flight briefings between passengers and RPICs and over-the-air software and firmware updates. After each flight, aircraft may upload vehicle performance data to the UAM operator for prognostics and maintenance purposes.

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Voice Services	The PIC and ATC **shall** be able to communicate by voice. The UAM Operator and the PIC *should* be able to communicate by voice.	**TBR**: Requirements on the role of voice services in UML-3 need to be developed	The UAM Operator *should* use voice communications to the passengers. Proximate PICs *should* use voice communications between them.
Telemetry Services	The UAM Operator *should* receive position and status from the vehicle and share with the PSU Network as required. The Vertiport Operator *should* receive position and status from the vehicle and share with the PSU Network as required	The UAM Operator **shall** receive position and status from the vehicle and share with the PSU Network as required. The Vertiport Operator *should* receive position and status from the vehicle and share with the PSU Network as required	The UAM Operator *should* receive enhanced telemetry from the vehicle and share with the PSU Network within proximity of the vertiport. **TBR**: Specifics of what enhanced telemetry includes need to be better defined, to include both higher performance telemetry, as well as inclusion of new information
Command Services	**TBR**: How command services are developed and matured during UML-2 needs to be better understood	The UAM Operator and the PIC *should* be able to communicate flight path updates for flights under active command	The PIC and the Vertiport Operator *should* be able to communicate authorization and approach information
Contingency Communications	**TBR**	**TBR**	The UAM Operator and the Remote PIC *should* have access to enhanced telemetry, sensor data, and video feeds for real-time diagnostics and command
Vehicle to Vehicle Services	The UAM Vehicle *should* have a means for cooperative Vehicle to Vehicle communications, suitable for advisory information	The UAM Vehicle *should* have a means for cooperative Vehicle to Vehicle communications	UAM Vehicles **shall** exchange information, including position and other data, to aid in collision avoidance and separation assurance

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Pre-/Post-Flight Wireless Services	The UAM Operator *should* be able to obtain performance information from the UAM Vehicle	The UAM Operator *should* be able to upload and download flight plan information to and from the UAM Vehicle. The PIC *should* be able to report the readiness of the UAM Vehicle	The Remote PIC should have the means to obtain pre-flight briefings

5.5 Navigation Services and Systems

The Navigation Services and Systems operational research element includes technologies, processes and infrastructure necessary to plan, record, and enable control of the movement of a vehicle from one place to another by providing accurate, reliable and seamless position determination capability and time synchronization.

- Ground-based positioning services (e.g. ILS, DME/VOR, RF beacons, etc.): These services utilize beacons, timing sources, or other information sources located on the ground to provide positioning, timing, and guidance data to UAM aircraft. These services may be especially useful during operations near urban areas where satellite-based services may be degraded or unavailable.
- Satellite-based positioning services (e.g. GPS, Galileo, Satellites, etc.): These sources provide position and timing data to UAM aircraft over a wide area and at higher altitudes, making them ideal for en route positioning services. Furthermore, these systems may be augmented by secondary services (e.g., GBAS, SBAS, WAAS) to improve various performance metrics such as accuracy and integrity.

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Ground-based Positioning Services	**TBR**	**TBR**	The UAM Vehicle *should* employ ground-based PNT services for urban vertiports. The UAM Vehicle *should* employ ground-based landing assist services for urban vertiports

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Satellite-based Positioning Services	The UAM Vehicle **shall** use at least one satellite-based PNT service (e.g. GPS).	The UAM Vehicle *should* employ real-time accuracy and integrity verification of external PNT source(s).	The UAM Vehicle *should* use multiple PNT services to support operations in GPS-denied environments

5.6 Separation Services and Standards

The Separation Services and Standards operational research element includes technologies, standards, and services providing functions that limit, to an acceptable level, the risk of collision between aircraft and hazards. A hazard is anything from which an aircraft will be separated, which includes other aircraft, terrain, weather, wake turbulence, incompatible airspace activity, etc. Separation minima are the minimum displacements between an aircraft and a hazard that maintain the risk of collision at an acceptable level of safety. Any situation involving aircraft and hazards in which the applicable separation minima may be compromised is referred to as a conflict [14].

Parts of the function of conflict management, as defined by the ICAO Global Air Traffic Management Operational Concept [14] (see section 2.7), will be allocated to the UAM operators, including PIC and aircraft capabilities, and may include support from the PSUs [1]. These self-provided and third-party services are directly reliant on the roles & responsibilities of the actors and entities in the UAM airspace system of systems, as well as the separation minima that are agreed and approved via rigorous application of SMS.

- *Strategic Conflict Management Services*: Strategic conflict management is the first layer of conflict management and is achieved through the airspace organization and management, demand and capacity balancing and traffic synchronization services. Properly applied, strategic conflict management services reduce the need to apply services from the second layer – separation provision – to an appropriate level.
- *Separation Provision Services*: Separation provision is the second layer of conflict management and is an iterative tactical process of keeping aircraft away from hazards by at least the appropriate separation minima [14]. Separation consists of conflict detection, resolution, and monitoring.
- *Collision Avoidance Systems*: Collision avoidance is the third layer of conflict management and must activate when the separation mode has been compromised. Collision avoidance is not part of separation provision, and collision avoidance systems are not included in determining the calculated level of safety required for separation provision. Collision avoidance systems will, however, be considered as part of ATM safety management. The collision avoidance functions and the applicable separation mode, although independent, must be compatible. [14]
- *Roles & Responsibilities*: Separation provision is assured through an approved set of rules, procedures and conditions of application associated with separation minima. These are dependent upon the roles of the system actors, with clearly defined responsibilities. For

example, depending on the operational context and how the UAM airspace evolves, the separator may vary between ATC, PIC, UAM Operator, Vertiport Operator or PSU.

- *Separation Minima*: Separation minima are the minimum displacements between an aircraft and a hazard that maintain the risk of collision at an acceptable level of safety. The separation mode is an approved set of rules, procedures and conditions of application associated with the separation minima. The separation mode will take into account the safety level required, the nature of the activity and hazard, the qualifications and roles of the actors, and other conditions of application such as weather conditions and traffic density.

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Strategic Conflict Management	The UAM Operator *should* use strategic scheduling services to plan operations that have minimal impact on UAM and ATM traffic	The UAM Operator **shall** use strategic scheduling services to plan operations in accordance with established CBRs. These services should be cooperative in nature and include pre-departure scheduling, and strategic conflict detection and resolution.	The UAM Operator **shall** use strategic scheduling services to plan operations in accordance with established CBRs. These services should include pre-departure scheduling, and strategic conflict detection and resolution
Separation Provision	The UAM Operator and PIC *should* use advisory separation provision services to keep UAM vehicle away from other UAM and ATM traffic whenever possible. The PIC **shall** provide Remain Well-Clear by "see and avoid" under VFR The PIC *should* provide Remain Well-Clear by "see and avoid" enhanced by automation such as advisory DAA.	The UAM Operator and PIC *should* use assistive separation provision services in accordance with established CBRs to keep UAM vehicle away from other UAM and ATM traffic by at least the appropriate separation minima. Examples of separation provision services include DAA, and conformance monitoring by multiple human and system actors (PSU, UAM Operator, PIC). The PIC *should* provide Remain Well-Clear from UAM, IFR, and VFR traffic by using "see and avoid" and systems and services such as assistive DAA The UAM Operator *should* rely on separation provision services during the execution of approach and departure procedures.	The UAM Operator and PIC *should* use collaborative and responsible separation provision services in accordance with established CBRs to keep UAM vehicle away from other UAM and ATM traffic by at least the appropriate separation minima. Services will be highly automated The PIC *should* provide Remain Well-Clear from UAM, IFR, and VFR traffic by using "see and avoid" under VFR and enhanced by highly automated systems and services such as cooperative and responsible DAA.

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Collision Avoidance	**TBR**	TBR	The PIC **shall** use collision avoidance automation to extend operations into IMC
Roles & Responsibilities	ATC or PIC **shall** be the designated separator for all interactions, according to existing IFR and VFR as appropriate. ATC **shall** assure separation between UAM and UTM traffic by way of segregation of traffic	The UAM Operator and/or the PIC *should* be the designated separator from other UAM traffic.	The UAM Operator or the PIC **shall** be the designated separator from other UAM traffic. ATC *should* be the designated separator between UAM traffic and IFR traffic.
Separation Minima	The UAM Operator *should* meet performance requirements that would support performance-based standards in the future, which are driven in part by proven (certified) aircraft performance	The UAM Operator *should* satisfy performance requirements in order to participate in new airspace constructs. The UAM Operator *should* use performance data to receive operational credit for conflict management services	The UAM Operator *should* meet variable performance-based separation standards, in accordance with established CBRs and other regulations

5.7 Surveillance Services and Systems

The Surveillance Services and Systems operational research element includes technologies and procedures that assist in providing awareness of the contents of the airspace. This includes the validation of self-reported aircraft position data, cooperative separation services (i.e. tactical deconfliction), and non-cooperative surveillance to detect sUAS, GA aircraft, UAM aircraft as necessary, birds, hi-rise construction cranes, and any other objects in the airspace that may present a collision risk.

- Non-Cooperative: This includes the use of on-board DAA sensors and ground-based surveillance assets (e.g., radar, cameras, radiometric tracking, etc.) to detect physical objects in the airspace and to validate the self-reported position of UAM aircraft.
- Cooperative: This primarily includes the passing of intent data between aircraft for tactical deconfliction (e.g., ADS-B).

UMLs → Components ↓	UML-2: Initial	UML-3: Proliferation	UML-4: Integration
Non-Cooperative	The ANSP *should* provide surveillance using existing radar sources	The ANSP *should* approve surveillance services using radar sources installed at vertiports. The UAM Operator and the PSU *should* use approved surveillance services at vertiports	The ANSP *should* approve the use of radiometric tracking and verification of vehicle position reports. The ANSP *should* approve the use of DAA information for hazard surveillance services
Cooperative	UAM Vehicles **shall** carry ATC-mandated transponders in accordance with existing regulations. UAM Operators *should* use telemetry directly from the vehicle. The PIC *should* use vehicle-to-vehicle surveillance for advisory purposes	UAM Operators **shall** obtain telemetry directly from the vehicle, and report that information to the PSU	The UAM Operator and the PIC **shall** use vehicle-to-vehicle surveillance for cooperative separation assurance

6 Roadmap Progression

The airspace roadmap decomposition is illustrated in the figure below (Figure 1). Crossing the component structure below with the UMLs as in the tables above yields a matrix of combinations of components and UMLs which can be individually assessed for maturity. This approach will be used to enable periodic assessments that track the progression of NASA's UAM Airspace research towards UML-4.

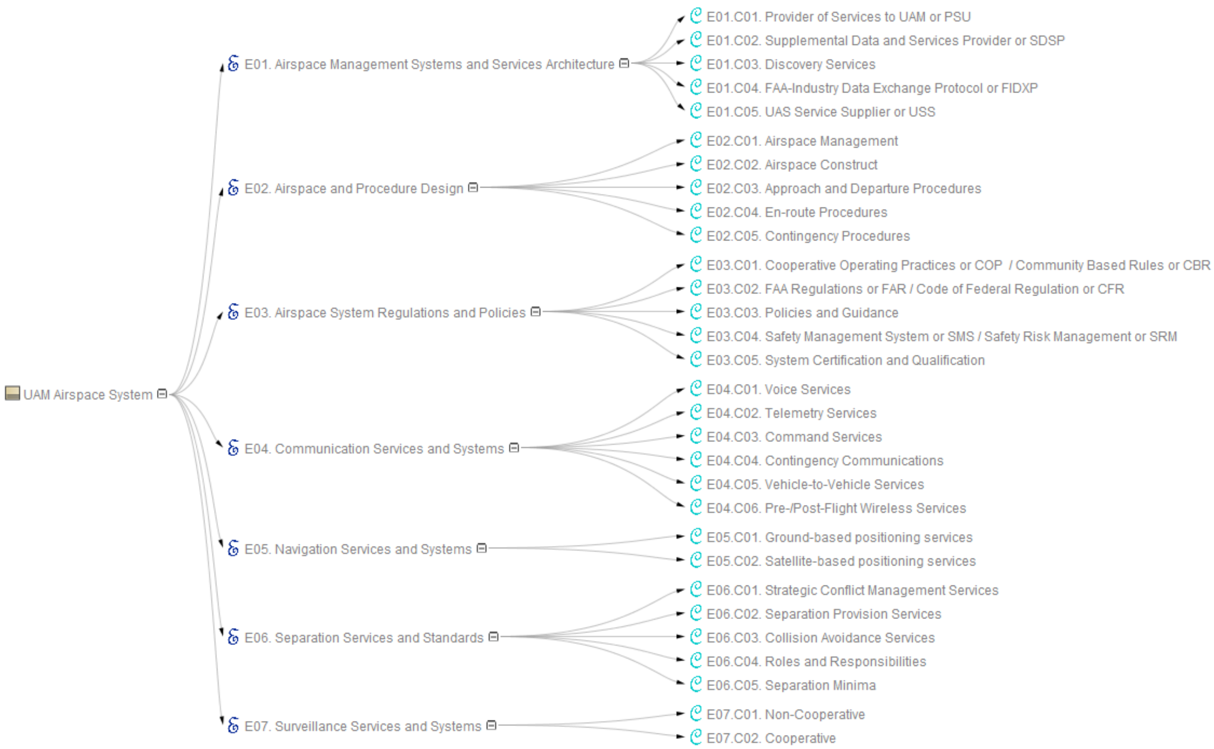

Figure 1: Airspace Research Element and Component Tree Decomposition

There are a variety of as-yet defined approaches to measuring and tracking progress of airspace research along the roadmap, and a simple approach is taken here to illustrate the technique. This simple maturity assessment of the requirements will be based on a certainty metric applied to the requirements, defined to measure the certainty around each requirement in the tables above. Such a certainty metric can be defined in many ways, but it should always have the property that certainty around the requirements increases as research progresses. A simple approach is taken by assigning a value to each requirement based on a heuristic sense of certainty associated with its "flavor":

- **will** has a value of 4
- **shall** has a value of 3
- *should* has a value of 2
- **TBR** with comment has a value of 1
- **TBR** without comment has a value of 0

With this simple definition, requirements that are more certain generally have a higher value in the roadmap. Naturally this schema does not capture the fact that not all requirements of the same flavor (**will**/**shall**/*should*/**TBR**) pose the same level of certainty, for example some may be based on broad organizational research efforts, while others may be best guesses. Future versions will refine how to take appropriate credit for major efforts such as requirements development (internal or external), validation, and satisfaction (e.g. by experimentation).

For each component, and at each UML, a composite index is defined simply as the sum of the certainties over all requirements in the component-UML combination (i.e. each cell in the tables above). Note that this scoring will increase wherever higher numbers of requirements have been identified, which is appropriate as the number of requirements is also a simple indication of the volume of research and insights to draw from. However, this too is inexact in that there may be a variety of reasons for increased or decreased numbers of requirements in a certain research component.

This index is displayed as a heatmap view in the figure below, where a darker color indicates more knowledge about a component at that UML in terms of both the number and certainty of requirements. Lighter colors are indicative of research gaps that need to be addressed.

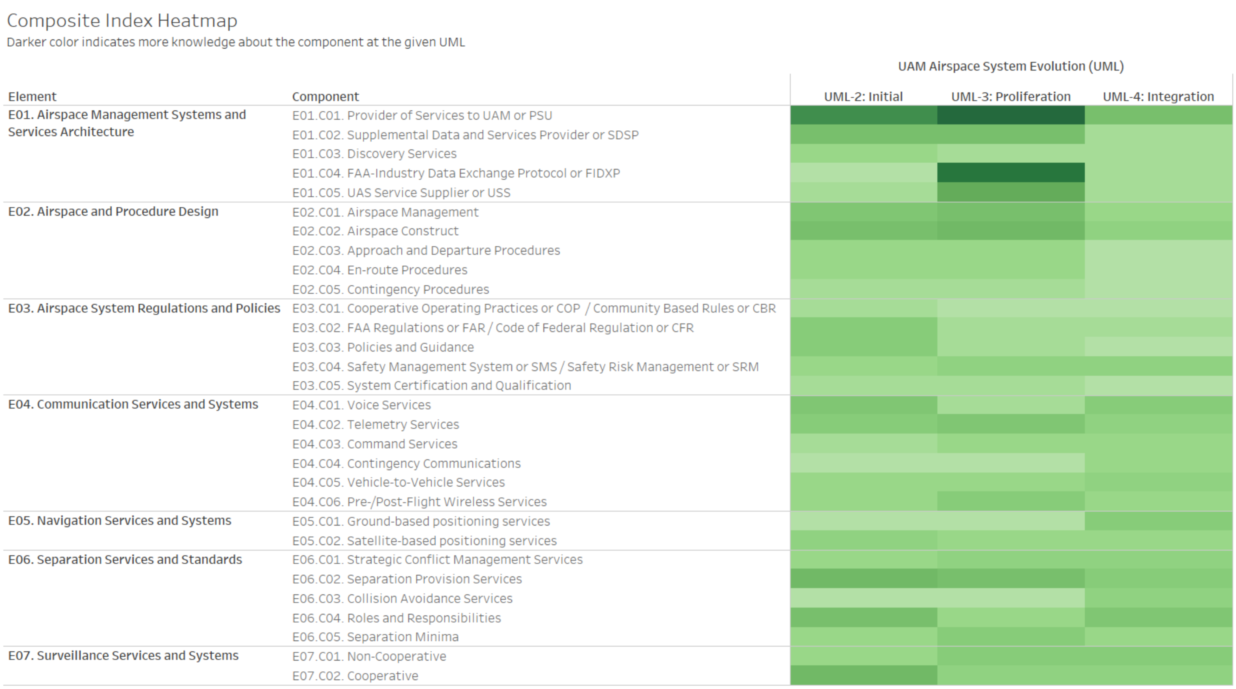

Figure 2: Notional Roadmap Progression Heatmap

It is important to reiterate that the chosen representation is preliminary and for illustrative purposes. The schema should be revised for most effective usage. However, this simple model does already match intuition in several areas. For example, the darkest cells are around PSU and FIDXP services in the UML-3 timeframe, and some of the lightest areas are around airspace design and procedures, and airspace policies and guidance in UML-4. It is expected that as the requirements evolve and mature, and as more refined metrics for success are identified, roadmap views such as the heatmap will be increasingly valuable tools for NASA and the community.

7 Conclusions and Next Steps

The UAM Airspace research roadmap defined here is expected to be an important tool for the execution of NASA's research over the next ten years, with the goal of evolving UAM airspace to UML-4. It provides a basis for prioritizing and coordinating research efforts, and for integrating results that build towards NASA's research goals. The roadmap also has the potential to serve as a focal point for ongoing and continuous deliberation, as has been the case during its development. It naturally attracts questions and feedback that are beneficial to overall understanding, which is key to NASA's leadership in defining the airspace of the future.

This initial version of the roadmap is a starting point and next steps are being identified, in large part based on feedback received. Internal and external input will be the fuel that drives further development and refinement of the process. Time will be spent early on to ensure that the form and purpose of the roadmap is coordinated with the stakeholders it may impact. Next steps will include building out additional research elements around Safety, Environmental, and Security issues, as well as synthesizing information from major research efforts such as X4 and potentially standards development activities.

Finally, views of the roadmap such as the heatmap above will be refined and the underlying roadmap model will become more comprehensive. For instance, requirements may be subjectively rated for maturity to enhance identification of research gaps, or the components may be traced to other lower-level requirements and source documentation.

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14. ABSTRACT
The UAM Airspace research roadmap defined herein is expected to be an important tool for the execution of NASA's research over the next ten years, with the goal of evolving UAM airspace to UML-4. It provides a basis for prioritizing and coordinating research efforts, and for integrating results that build towards NASA's research goals. The roadmap also has the potential to serve as a focal point for ongoing and continuous deliberation, as has been the case during its development. It naturally attracts questions and feedback that are beneficial to overall understanding, which is key to NASA's leadership in defining the airspace of the future.

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