Contract Number: GS00Q14OADU130 Delivery Order: 80GRC019D0017, Deliverable 5

Reliable, Secure, and Scalable Communications, Navigation, and Surveillance (CNS) Options for Urban Air Mobility (UAM)

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12 August 2020

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The material is based upon work supported by the National Aeronautics and Space Administration under Contract Number GS00Q14OADU130.

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EXECUTIVE SUMMARY

Charter

This report documents the results of the task entitled "Investigation of Reliable, Secure, and Scalable CNS Options for Urban Air Mobility for the UAM Coordination and Assessment Team (UCAT)." The results from this study "inform NASA about technical approaches to providing reliable and secure communications, navigation, and surveillance (CNS) services to support urban air mobility (UAM) operations at UAM maturity level (UML) 4." These results inform the UAM community about operational challenges in CNS, recommends technologies to support UML-4, identifies the gaps to fulfill before achieving UML-4 operability and makes recommendations for overcoming those obstacles.

Concept of Operations

UAM will provide intra-urban transportation like terrestrial ride sharing services in vehicles carrying up to five people. In flight, UAM will share the airspace with conventional piloted aircraft and, in the low altitude, "urban airspace," with emerging small unmanned aircraft systems (sUAS) package-carrying vehicles. The UAM vehicles at UML-4 will have defined and limited landing and takeoff spots, as opposed to ad hoc, land anywhere operations that are forecast for UML-6.[1] We assume that UAM vehicles will have vertical take-off and landing (VTOL) capabilities, enabling landing at, and departing from, an urban vertiport approximately the size of a parking garage rooftop. We also assume:

- UML-4 is ten to fifteen years in the future.
- The UAM vehicles will be electrically powered.
- The UAM vehicles will fly at low altitudes, under 5000 feet above ground level (AGL).
- The UAM vehicles may have pilots on board, may be autonomously piloted, or may have a range of autonomous functions, and the UAM fleet may be mixed among these options.

The urban environment imposes constraints on low-altitude CNS. Buildings, bridges, towers, and structures block signals that are intended to communicate with airborne vehicles, block global navigation satellite system (GNSS) signals those vehicles might use to navigate, and prevent traditional radar surveillance of traffic. In addition, very high frequency (VHF) voice communications and automatic dependent surveillance – broadcast (ADS-B) over 1090 MHz are already at capacity at high density airports and would be overwhelmed by hundreds of new vehicles. The operational impacts of these constraints can be stated:

1. Air Traffic Control (ATC) is unable to track low altitude aircraft with radar, and thus cannot provide separation and navigation services; therefore, another means of separation and navigation is required.
2. ATC cannot communicate with a high number of low altitude urban aircraft using VHF voice or identify aircraft with ADS-B on 1090 MHz, which violates the entry conditions and provision of ATC services in Class B and C airspace; therefore, alternate airspace rules need to be applied.
3. The expected density in the urban core, and at vertiports, requires less than the minimum radar minimum standard separation of three miles; therefore, new separation rules are needed.

These limitations create a requirement for UAM flight functions in the urban environment to be satisfied with non-traditional means. We assume a UAS Traffic Management (UTM) ecosystem will provide the flight rule and authorization environment, and that some form of autonomous flight rules will be used for

[1] UML-4 is expected to happen in the early 2030s and is defined by medium density and complexity of operations. Vehicles may be equipped with simplified vehicle operations using collaborative and responsible automated systems and will be capable of operating in low-visibility environments. There will be hundreds of simultaneous flights, operating from high-capacity UAM ports.

separation and navigation. Instead of a centralized, ground-based system, the UAM operations will be vehicle-based, self-navigating and self-separating, and use cooperative surveillance. Air Traffic Management (ATM) services will be inspired by, and will be, the logical progression of UTM.

CNS Functions and Recommended Technologies

The study surveyed available, near term, and future CNS technologies and assessed their ability to fulfill UAM CNS functional requirements in terms of capacity, availability/reliability, precision, update rate, range, all-weather, and several stress-test use cases. Size, weight, power, and cost were also decision factors. Signal constraints prevent many technologies used in the national airspace system (NAS) currently from fulfilling UAM needs. Communication functions included: vehicle position and health reporting to ground owner/operator[2], flight plan filing and flight plan changes between aircraft and ground owner/operator, vehicle video downlink to ground owner/operator, passenger emergency communications, and weather uplink.

In no particular order, the recommended technologies for ***all*** UAM communication functions are:

- VHF Data Link (VDL) Mode 3
- 5G via satellite integration
- Commercial low Earth orbit (LEO) satellites
- C Band[3]
- 5G Cellular

GNSS navigation is widely available but unreliable in the urban environment, thus requiring supplementation. Numerous technologies exist as suitable supplements. Multiple-sensor fusion for positioning is being tested by avionics and UAM manufacturers; this is a likely solution and industry standards organizations should embrace writing guidelines toward performance-based navigation certification. In Table 1, a check mark indicates that the identified technology is recommended for en route, approach, or landing navigation in the lateral or vertical dimension. Greater precision is required for approach than en route; and even greater precision for landing.

Table 1. Navigation Functions and Recommended Technologies

NAVIGATION TECHNOLOGIES	EN ROUTE LATERAL	EN ROUTE VERTICAL	APPROACH LATERAL	APPROACH VERTICAL	LANDING LATERAL	LANDING VERTICAL
GNSS + PNT augmentation	✔	✔	✔	✔	✔	✔
GNSS + LAAS (GBAS)	✔	✔	✔	✔	✔	✔
GNSS + WAAS	✔	✔	✔	✔	✔	✔
GNSS + LEO	✔	✔	✔	✔		
GNSS + RF mapping	✔		✔			
GNSS + SAR/ISAR mapping	✔					
GNSS (only)	✔					

[2] *Owner/operator in the sense of dispatch operational control in a commercial entity like an airline. Remote piloting is untenable in a dense urban environment.*
[3] *Refers to the C band spectrum being considered by FAA for allocation to UAS for command and control (C2).*

NAVIGATION TECHNOLOGIES	EN ROUTE LATERAL	EN ROUTE VERTICAL	APPROACH LATERAL	APPROACH VERTICAL	LANDING LATERAL	LANDING VERTICAL
GNSS + INS /IRS (FOG /MEMS)	✔					
GNSS + RF Beacon			✔	✔	✔	
GNSS+LIDAR				✔	✔	✔
GNSS + K band radar					✔	✔
GNSS + FMCW in GHz					✔	✔
GNSS + Machine vision (optical)					✔	
Radio/Radar Altimeter		✔		✔		✔
Barometric Pressure Altitude		✔				
Barometric Pressure with References		✔				

PNT = positioning, navigation and timing; LAAS = local area augmentation system; WAAS = wide area augmentation system; GBAS = ground-based augmentation system; RF = radio frequency; SAR = synthetic aperture radar ISAR = inverse SAR; INS = inertial navigation system; IRS = inertial reference system; FOG = fiber optic gyro; MEMS = microelectromechanical system; LIDAR = light detection and ranging; FMCW = frequency modulated continuous wave

Surveillance consists of cooperative and non-cooperative techniques for air and ground. UAM vehicles will separate cooperatively, using broadcast position and intent. They will also need a non-cooperative sensing system to avoid collisions with aircraft and obstacles; this non-cooperative sensing may do dual duty as a landing sensor. Ground cooperative surveillance provides data for dynamic density management and safety. Ground-based non-cooperative surveillance will become desirable to ensure public safety and security.

Table 2. Surveillance Functions and Recommended Technologies

SURVEILLANCE FUNCTION	RECOMMENDED TECHNOLOGIES
Air and Ground Cooperative Surveillance	• Universal Access Transceiver (UAT)-2 on 1104 MHz • Mode C Multilateration • Airborne Collision Avoidance System (ACAS-X) • 5G (passive listen)
Airborne Non-Cooperative Surveillance	• K-band RADAR • RF Detection • LIDAR • Infrared (IR) Sensing • Sensor fusion
Ground-Based Non- Cooperative Surveillance	• Advanced Doppler Range Gating Radar • Infrared (IR) Sensing • Bistatic Radar • Acoustic Detection

For brevity, only recommended technologies are shown here. Specification requirements appear in Appendix A; technology descriptors in Appendix B, and advantages and disadvantages in Chapter 2.

In the course of this study, technology and process gaps were discovered and this report makes numerous recommendations to promote the achievement of a viable UAM ecosystem. These appear throughout the report and are consolidated in Chapter 5. The most urgent and strongest recommendations are summarized below.

Recommendations

Core CNS Findings and Recommendations

Cooperative surveillance for vehicle-to-vehicle separation is a must-have function for UAM, and UAT2 (on proposed 1104 MHz) is a highly superior alternative to satisfy that function, due to ab initio message set design and because it is ATC compliant but filterable.

Using 5G for UAM communication functions requires infrastructure changes at the carrier and cell tower level in prioritization and antenna pointing, and without these required changes, 5G is not a suitable alternative.

Multiple sensors and sensor fusion are likely manufacturer solutions for the navigation and detection sensing problems, but to perfect these solutions requires the definition of UAM operating altitudes, which should include low altitude airspace above 400 feet AGL, as well as definition of approach phases or procedures for urban vertiports.

Certification Standards and Guidelines

Industry-wide standards for common elements share the cost across a market segment and are effective for reducing barriers to entry in new industries. Industry standards groups should work to define common navigation and detection sensor package standards on a performance-based basis, to lower the cost of entry, provide standardization, and encourage the U.S. market. The recommended communications technologies are the worst in lacking standards and guidelines, and should be started as soon as possible, as spectrum demand is increasing.

The Second Universal Access Transceiver (UAT2) frequency of 1104 MHz offers an opportunity to develop a broadcast/receive capability for use by the UAM community that could support multiple equipment functions, including multiple communications, active and passive surveillance, and fulfillment of ATC ADS-B requirements given ATC modifications, thus saving weight and power consumption background. Agreement on use of this frequency for UAM should be attained and work begun on message sets.

Work defining access and procedures is needed to support UAS and UAM interoperability in the same airspace, particularly at vertiports.

A design assurance level (DAL) l for the U.S. UAM market needs to be established in order for the industry to move forward, to propose designs meeting a recommended reliability setting.

Better understanding of the effect of urban multipath and signal blocking is needed through realistic testing. This may also support commercial-off-the-shelf (COTS) components testing to determine their suitability for various air-ground functions, and is necessary to progress to Minimum Operational Performance Standards (MOPS) level standards.

Integration Recommendations

The UAM ecosystem requires greater definition of the operating environment, concept of operations, and flight rules to move forward, as vehicle manufacturers are building advanced vehicles for revenue operations in the NAS as it exists now. These early vehicles will create a legacy fleet that will restrain operational progress for decades to come, by constraining flight rules and technologies to accommodate mixed fleets and requiring large commitments of human resources in each market to keep the urban airspace system functioning well. Given the five to seven year development time from definition to commercial availability of advanced avionics, the existing airspace system will be a factor in operations for years to come. The legacy vehicles and procedures will delay and inhibit the successful implementation of UML-4, so ecosystem development must be pursued as soon as possible.

The need for precise position awareness and corresponding flight management is greater than exists in aviation today and will be a certification challenge for the manufacturers and regulators. The timely definition of the UAM airspace design and a concept of operations are critical to meeting this challenge.

At UML-4, some of the UAM vehicles designed and built specifically for UML-4 operations will be equipped as needed. Older, or legacy, vehicles that are not equipped for UML-4 type operations will need to be accommodated through procedural workarounds. Standards are inadequate for managing mixed fleet configurations of the industry and should not be used as substitutes in attempt to do so. Knowing which vehicles are equipped to the UML-4 performance standards, along with vehicles that are not, is tantamount. In practice, a trusted agent — an air authority service provider — is a superior method for dealing with mixed fleet equipage and differing aircraft capabilities in a performance-based airspace.

Interoperability Recommendations

UAM and sUAS will operate in the same environment, potentially with different communications signals; the vast numbers of urban drones may require their own communications solution. Navigation suites may be very similar. Cooperative surveillance, however, must be compatible for interoperation.

The high number of sUAS operations will create its own avionics market, which may seek approval at a lower standard of reliability, to keep costs lower. In the area of cooperative surveillance however, performance requirements between sUAS and UAM will be the same, to allow interoperation in the urban airspace. Any difference in navigation precision between sUAS and UAM must be accounted for in separation technologies, algorithms, software, and procedures, just as maneuverability and speed are taken into account.

Existing methods of establishing airspace authorization for sUAS, Remote Identification (RID) and Low Altitude Authorization and Notification Capability (LAANC), will need to mature and evolve to accommodate UML-4 traffic density demands.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Charter

The charter of this task is to "conduct and document a study that informs NASA about various technical approaches to providing reliable and secure communications, navigation, and surveillance (CNS) services to support urban air mobility (UAM) operations at UAM maturity level (UML) 4, with special considerations for early test and deployment at UML-2 and 3, as well as extensibility considerations to UML-6. The UAM community will use the results and recommendations of this study to improve understanding of the current state-of-the-art, aid in efforts to prioritize UAM challenges, identify technology gaps, and better inform decision makers.

1.2 Process

Our study team is composed of experts in CNS and aeronautics. Our study incorporates systems engineering approaches to analyze the requirements in areas of CNS, identifying alternative technologies meeting the requirements for CNS, analyzing the alternates for their relative merit in the UAM operation, and recommending the most promising technologies for further research. Communication elements of the study include data service requirements, air/air and ground/air wireless links, and ground-based network architecture for the urban environment. Navigation elements involve navigational requirements, navigational technologies, denied navigation, and augmented navigation for precision and integrity. Finally, surveillance elements include UAM aircraft detection and tracking, non-UAM aircraft detection, and non-aircraft detection. Upon reaching a recommended set of technologies, we examined integration and interoperability, consisting of: avionics guidelines and standards, avionics architecture, exploiting CNS functional commonality, efficient use of spectrum, shared airspace CNS operations, and small unmanned aircraft system (sUAS)-UAM CNS interoperability. We identified gaps in technology, procedures, standards, and certification guidelines and conclude with recommendations to solve gaps.

We followed a method of research that included subject matter expert interviews, study of relevant technologies, and discussion and analysis within the operational construct for each of the named task elements. We interviewed over 100 people, most of them in industry, from these areas:

- UAM and UAS Traffic Management (UTM) researchers
- Federal Aviation Administration (FAA) Spectrum and UAS CNS users
- Artificial intelligence and autonomous navigation developers
- Communications experts including Satcom, automobile, wireless
- Nationwide wireless law enforcement network, FirstNet
- UAM start-ups
- UAS researchers and developers
- Spectrum multipath experts
- Avionics manufacturers
- Standards groups' representatives (precursors and supplements to FAA standards)
- Airline chief pilots and maintenance chiefs
- Smart cities representatives
- Defense Advanced Research Projects Agency (DARPA) waveform specialists

Based on the existing UML descriptions, plus the FAA and NASA concept of operations (ConOps) for UAS, we examined what would be required for the UAM operations in a mixed environment with sUAS and traditional piloted aircraft. This led to extending and modifying some assumptions from those limited descriptions and ConOps. CNS requirements only have relevance in the context of the traffic management environment assumed. We defined CNS services for operating UAM aircraft as functions. Specifications were defined for these functions based on similar extant services in the national airspace system (NAS), to the extent possible, considering the new requirements. These requirements, shown in Appendix A, were intended to provide a basis for choosing recommended alternatives rather than to provide Minimum Operational Performance Standards (MOPS)-ready detail. Requirements should be read as indicative rather than prescriptive.

We examined nearly 50 technological alternatives with the potential to satisfy the requirements. The list of technologies deemed, through analysis, to be most promising for UML-4 are discussed in Chapter 2. The discussion includes development recommendations, best design practices, and requirements regarding the architecture of CNS avionics hardware and software. Chapter 2 then outlines approaches for integrating CNS functions into multi-purpose hardware and software avionic architectures to minimize size, weight, and power (SWaP). Chapter 3 provides recommendations on guidelines and standards for the design, certification, and maintenance of the UAM CNS avionics hardware and software. Chapter 4 discusses UAS-UAM integration challenges in the urban landscape. Chapter 5 summarizes recommendations in this report.

1.3 Initial State of Knowledge about UAM Ecosystem for This Task

Our one-year contract tasks this team to identify, evaluate, and recommend viable CNS systems and technologies to enable safe, secure, and efficient UAM operations in U.S. cities. Operationally, we began with the scoping assumptions that these UAM vehicles will be transporting people, in a commercial air-taxi service, to avoid urban surface congestion. We explicitly confined our study to commercial air-taxi service under Part 135, excluding the potential use case variations of private UAM ownership and use.

We were tasked to look at UML-4, described in the Task Order Statement of Work as "medium density and complexity operations with collaborative and responsible automated systems" supporting "100s of simultaneous operations; expanded networks including high-capacity UAM ports; many UTM inspired air traffic management (ATM) services available, simplified vehicle operations for credit; low-visibility operations." Identification of the CNS systems that will support an established UAM transportation system 10 to 15 years in the future is needed so that research to fill gaps can start now. Our alternatives must consider the evolution from present technologies and systems, as well as evolution to a future with denser operations, and the integration and interoperability with other aircraft in the airspace using varying degrees of automation in flight control and air traffic services.

According to the NASA UML-4 description, UAM vehicles in this timeframe will have limited landing and take-off spots, as opposed to ad hoc, land anywhere operations. We assume that UAM vehicles will have vertical take-off and landing (VTOL) capabilities, enabling landing at, and departing from, a purpose-built vertiport located upon, and approximately the size of, a parking garage rooftop. We also assume:

- The UAM vehicles will be electrically powered.
- The UAM vehicles will fly at low altitudes, under 5000 feet above ground level (AGL).
- The UAM vehicles may have pilots on board; may be autonomously piloted, with variations of autonomous function, and the UAM fleet may be mixed among these options.

Some of our assumptions were influenced by NASA concept diagrams, such as Figure 1-1, which shows electrically powered vertical takeoff and landing air vehicles using rooftop landing pads with origins and destinations within a dense urban environment.

Figure 1-1. An Artist's Conception of an Urban Air Mobility Environment
Where air vehicles with a variety of missions, and with or without pilots, are able to interact safely and efficiently.
Credits: NASA/Lillian Gipson. Picture and caption from NASA.gov.

Selection of recommended CNS alternatives requires the establishment of requirements. Range, altitude, rate of closure, clutter, and obstacles set the parameters for CNS operation. At task inception, UML level operating details were limited. No explanatory papers had yet been published. A contractor study for NASA on the UAM ConOps was underway, due shortly before the results of the CNS study were due. Thus, for a CNS UAM concept of operations, we examined both the existing NAS and the NASA[4] and FAA[5] UTM ConOps.

1.3.1 Airspace Rules

Under the NASA UTM construct, UAS can operate in various classes of airspace and observe the rules of flight in each. In uncontrolled airspace (class G), there is no interaction with controlled air traffic, and UAS share the airspace with other airspace users, such as general aviation aircraft, helicopters, gliders, balloons, and parachutists. In the FAA UTM ConOps, systems and procedures are described to guide interactions between remotely-controlled unmanned aircraft and the human-centric air traffic control (ATC) system. UAM operations will need to operate in controlled airspace, including the Class B and C airspace surrounding large airports. It would be unrealistic for UAM operators to assume that they will be able to operate widely in Class G airspace rules or under visual flight rules (VFR) in the most desired urban markets for this service. Coordination with the FAA will be required. A sample of the Class B and C airspace covering the largest U.S. cities' dense urban areas is shown in Table 1-1.

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[4] *Parimal Kopardekar, Joseph Rios, Thomas Prevot, Marcus Johnson, Jaewoo Jung, and John E. Robinson III, "Unmanned Aircraft System Traffic Management (UTM) Concept of Operations,"* AIAA AVIATION Conference, *13-17 June 2016, Washington, D.C.*
[5] *FAA, Concept of Operations v1.0 Foundational Principles Roles and Responsibilities Use Cases and Operational Threads, Unmanned Aircraft System (UAS) Traffic Management (UTM), FAA.gov, May 2018.*

Table 1-1. Densely Populated Urban Core Areas under Class B and C Controlled Airspace

U.S. CITIES	LOCATION OF CLASS B OR C CONTROLLED AIRSPACE
New York	Controlled from surface over much of Brooklyn, Queens, Manhattan, and the Bronx.
Los Angeles	Controlled from surface within approximately five miles of Paradise (Riverside), Santa Ana, Burbank, Van Nuys, and Ontario, and within 10 miles of LAX on flight path. Controlled from various floors of 2500, 4000, 5000 feet to 20 miles inland of LAX.
Chicago	Controlled from surface within five miles of ORD and MDW; MDW is about eight miles southwest of waterfront downtown Chicago, so restricts suburban air travel to south. Downtown Chicago (two to four mile radius area) is under 3000 shelf under Class B airspace.
Houston	A three to four mile wide east-west strip of downtown Houston lies under the 2000 feet floor of Class B airspace, between two controlled terminal areas from surface to 10,000 around HOU and IAH.
Dallas	Core downtown Dallas under controlled airspace from surface upward. South Dallas and surrounds controlled from 3000 up.
San Francisco	Controlled from surface over South San Francisco, San Bruno, San Mateo, Oakland, and San Jose; from 1500 over north Bay, north Oakland; from 3000 feet over north half of San Francisco City (Obstacles in SFO rising to 1000 feet and twin radio towers to 1814 feet).

Interviewed representatives from the FAA indicated that conventional air traffic services in the NAS would not be able to support the numbers of vehicles envisioned for UAM in close proximity to one another in a cluttered urban environment.[6] Voice communications, radar coverage, and ADS-B over 1090 MHz were cited as systems which would be overwhelmed by the expected numbers of vehicles and density in UML-4. The impacts of these constraints can be stated as:

1. The inability for ATC to track aircraft with radar implies a need for other means of separation and navigation, one that does not depend on centralized ground-based surveillance.
2. The inability of air traffic controllers to provide voice communication and surveil aircraft with ADS-B on 1090 MHz violates the entry conditions and provision of ATC services in Class B and C airspace, so alternate airspace rules need to be applied.
3. The expected density in the urban core and at vertiports requires less than the minimum of standard separation of three miles; thus new separation rules are needed.

These limitations create a requirement for UAM flight functions in the urban environment to be satisfied with non-traditional means.

Although ATC cannot provide services in dense urban operations, it is likely that UAM aircraft will need to connect the urban airspace and operate in Class B or C controlled airspace at the airport. Connecting traffic from a large airport in the middle of Class B or Class C airspace to an urban core is an obvious early profitable air-taxi application. We assume that UAM landing or taking off at a Class B or C airport will need to conform to existing air traffic requirements for voice communication, ADS-B, and instrument flight rules (IFR).[7]

Early UAM operators are offering services in controlled airspace (such as Blade, which can operate in instrument conditions) or using VFR flight corridors that tunnel through Class B and C airspace. By UML-4, such tunneling would be impractical. It would be highly congested, as hundreds of aircraft queue up to

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[6] We do not know of an official FAA position on whether the FAA will provide special services for UAM. All interviews were conducted on a not-for-attribution basis.
[7] Primarily this means aircraft are equipped with an ADS-B transponder and participate in voice communications.

fly through one of dozens of tunnels.[8] Without designation of multiple alternate tunnels, traffic would stop in off-nominal conditions. Such tunnels would never be able to support expansion to UML-6's traffic levels and ad hoc destinations. Autonomous Flight Rules (AFR), in which navigation and separation are the responsibility of the individual aircraft operators, provide a regime for navigation and separation under the three constraints listed above.

The urban environment also defies remote control operation because of the attenuating effects of buildings, structures, and elevated roadways on air-ground signals. Reliable communication between an aircraft and ground control occurs on a line of sight. Signals in the KHz and MHz range can be picked up within a city from a high power transmitter, but two-way communication at a power level appropriate to aircraft will not be reliable over both obstructions and distance. Thus, aircraft below rooftop level in an urban environment will not be able to operate on the basis of continuous contact with a remote operator. The command and control in urban aircraft will need to be designed to operate around these conditions.

1.3.2 Urban Signal Propagation Issues

The urban environment makes CNS functions difficult, by introducing barriers to good and reliable signal reception:

1. Line of sight (LOS) below the skyline is short, so signals have low range, often less than one statute mile.
2. Reflective surfaces in the urban core abound, increasing the probability and number of multipath signals, which increases errors in the received signal and makes signal decoding more difficult.
3. Networks that relay signals, mitigating LOS, introduce delay, and that delay violates the timeliness requirements for much of air-ground tactical CNS.

These limitations mean that turn-by-turn remote control or monitoring of an unpiloted UAM would not be feasible, other than in tightly controlled corridors. These constraints were also factors in our matching of requirements to technologies.

1.3.3 UTM Ecosystem

FAA and NASA's UAS ConOps describe the roles and responsibilities of UAS operators and UAS Service Suppliers (USS) as they connect through the UTM to the air traffic systems of the NAS (see Figure 1-2). The key principle carried from these documents to the UAM concept of operations was the idea of UAS service suppliers (USS) providing commercial services in communication, navigation, and data services. The FAA does not provide traditional ATC services in this ecosystem, relying instead on sanctioned nontraditional CNS.

[8] *Given the limited capabilities of battery propulsion today, we assume that hovering in place as an air traffic management technique would be discouraged.*

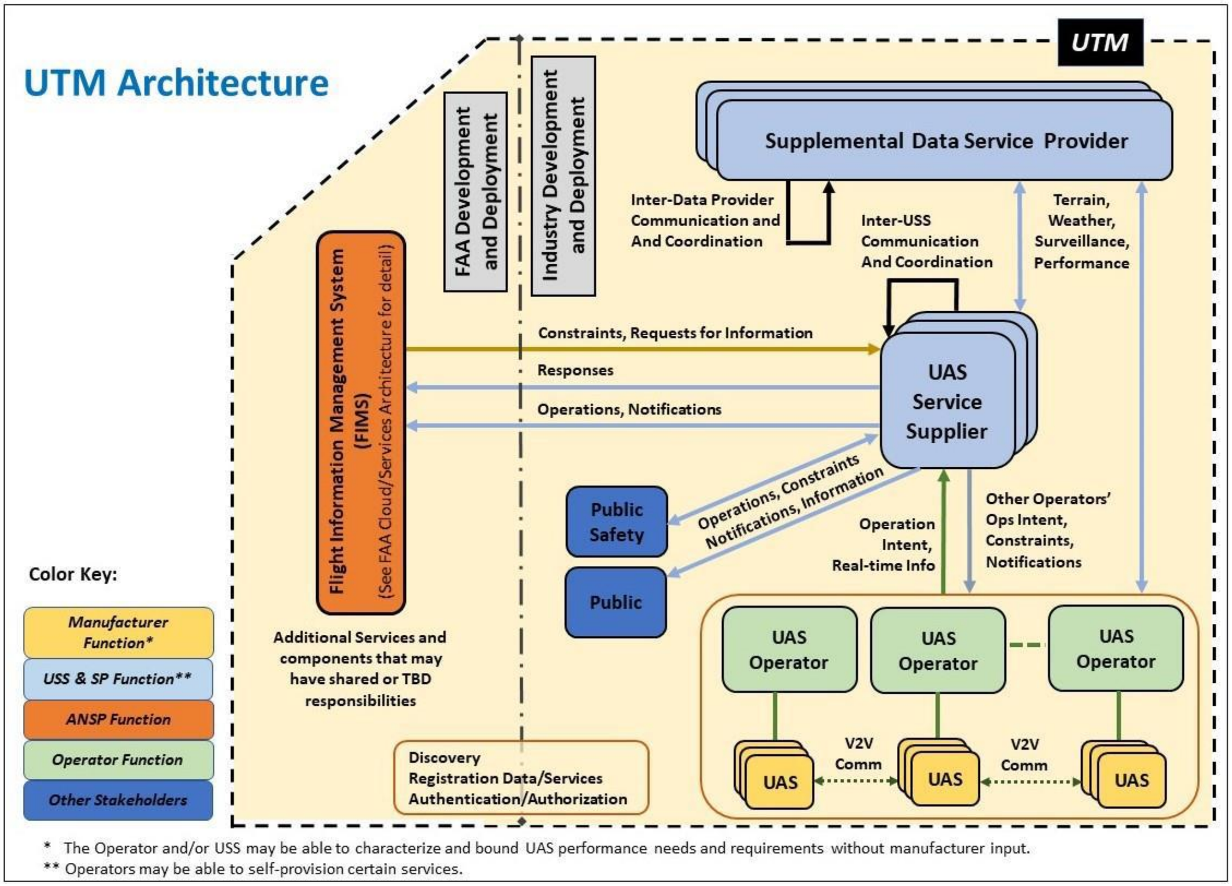

Figure 1-2. FAA's UTM ConOps (v 2.0) Describes an Unmanned Airspace Ecosystem

1.3.4 CNS Requirements from UTM

The FAA UTM ConOps v 2.0 describes a community based traffic management system where operators and operation support services are responsible for the coordination, execution, and management of operations. UTM details interactions of UAS with ATC interactions and controlled airspace. ConOps guidance creates communication requirements and constraints such as:

- Communication is through a distributed network of automated systems and not between pilots and air traffic controllers via voice.
- UAS operators may choose to use third party USSs to support their operations, or they may choose to provide their own set of services.
- USSs provide services to support the UAS community, to connect operators and other entities to enable information flow across the USS network, and to promote shared situational awareness among UTM participants.
- The Flight Information Management System (FIMS) supports information exchanges and protocols between UTM participants and FAA systems.
- Manned aircraft operators make their flight intent available to UAS operators participating in UTM via the USS network to foster situational awareness.
- Law enforcement may access information such as UAS id, operator information, UAS position reports, and other data.

- The operator monitors for vehicle non-conformance or onboard equipment failures or onboard degradation (e.g., lost link, engine failure) and notifies nearby flights.

In addition, the owner/operator of UAS must meet these command and control requirements that create communications expectations:

- The operator is responsible for tracking the aircraft during all phases of flight.
- Common situational awareness must be shared among all UTM stakeholders.
- UAS operations are cooperatively managed by those conducting flight.
- Beyond Visual Line-of-Sight (BVLOS) operations must manage their flight through strategic deconfliction, shared position and intent, data exchange with other nearby UAS, monitoring of flight for conformance, notification of in-flight conflicts, in-flight re-route, weather, surveillance, and navigation.

The UTM ConOps clearly indicates that any communication with the FAA would not be direct and would not use the traditional ATC voice communications channels. The requirement for operators to manage their own operations safety without FAA services relies on shared situational awareness based on self-navigation and shared deconfliction. This creates own-vehicle requirements:

- Information about planned operations in and around a volume of airspace is shared so that operators can ascertain the ability to safely and efficiently conduct the mission.
- Shared information allows UTM operators the situational awareness that visual cooperative operations shared.
- USS services support operations planning, intent sharing, strategic and tactical de-confliction, conformance monitoring, remote identification (RID), airspace authorization, airspace management functions, and management of off-nominal situations.
- Airspace authorizations are required in controlled airspace.
- UAS operators not receiving ATC services are required to participate in UTM.
- UAS operators are responsible for identifying unexpected operational conditions or flight hazards that may affect their operation.
- A USS may notify UAS operators of an emergency flight, and the UAS operator must determine if it can safely continue a planned flight, using detect-and-avoid (DAA) and/or flight changes.

In summary, the FAA UTM ConOps proposes UAS self-governance with minimal FAA-UAS interaction through a shared collaborative system of flight planning, position, and intent sharing, and owner/operator monitoring of flight route, flight route compliance, safety of flight, and remaining clear of obstacles and restricted airspace. Traditional FAA services in the urban environment may be performed by USSs on behalf of the operators.

The FAA UTM ConOps serves primarily small unmanned cargo aircraft (less than 50 lbs) in altitudes below 400 feet AGL. We used these guiding principles to provide operating assumptions for creating CNS requirements for UAM. However, we needed to alter and extend the UTM ConOps to create UAM assumptions that are consistent with safety, vehicle parameters, and interaction with the urban environment such as kinetic impact, urban windshear, wind amplification, and air-taxi location preferences.

1.4 Additional Operational Assumptions

Urban signal propagation issues and systems constraints bar ATC services in low altitude urban environments. Existing FAA IFR for commercial passenger transport flights, in which a controller locates an aircraft by primary and/or secondary radar, and ensures separation of the flight from other aircraft via voice commands, will not be able to provide service in a low altitude urban environment. The air traffic controller will not be able to locate all the UAM flights among the obstacles in the urban environment and voice frequencies will be too congested for timely maneuvering commands. In place of ATC, to provide safe UAM flights, we identified a system of needed functions. For hundreds of UAM vehicles to operate simultaneously in a city, vehicle-to-vehicle separation will need to be managed through decentralized collaboration. Consistent with decentralized control in the UTM ConOps, UAM vehicles will be cooperatively tracked by their ground-based owner/operator.[9] The FAA will not separate UAM vehicles, but the FAA may delegate and contract out management of the urban airspace. There is a need for an urban airspace density management and we assigned a USS called the Airspace Authority Service Provider to this function. Regardless of who manages the airspace, the presence of air-ground signal interference will make positive identification and tracking of every UAM at all times impossible; thus the whole air system will have to operate cooperatively.

1.4.1 Assumptions Lead to Requirements

The UAM vehicle will have to provide its own detect-and-avoid system and precision navigational capabilities. The FAA's UTM ConOps 2.0[10] requires 4-dimensional (time and space) Performance Authorizations for UAS flight airspace with collaborative pre-deconfliction computed prior to the UAS flight. Pre-deconfliction is not foolproof and does not scale. With or without pre-deconfliction, the UAM vehicle will need to tactically avoid cooperative and non-cooperative vehicles and obstacles. The UAM vehicle will need to know its own position (lateral and altitudinal) and communicate position and intent in a broadcast mode to all other cooperative vehicles.

The look-ahead range for avoiding collisions is determined from speed, maneuvering capability, and expected separation, which we determine from density. Hundreds of vehicles per urban area translates to an estimated density of more than one vehicle per 0.5 nm. Assuming a speed of 50 kts used on approach or ascent, and a response rate between 0.25 and 5.0 seconds (encompassing detect, identify, decide and execute), and unknown maneuvering capability, look-ahead needs to be approximately 1 to 2 km. At this density, encounter geometry prediction is paramount so vehicle position update of 1Hz is insufficient while flying in instrument meteorological conditions (IMC). We assume a vehicle own-position update rate of 10 Hz is required.[11]

In our interviews, we found some urban environments are not eager to embrace UAM traffic. Because of the potential for noise and the need for UAM-accommodating infrastructure, an urban authority would have to welcome and approve UAM traffic. Residents will want assurances through safety and security oversight bodies that they are safe from ill intent to the maximum extent possible. An urban Air Authority Service Provider (AASP) will need a means of tracking the total air traffic above an urban environment, to provide safety and security and orderly management of the total traffic volume.

Part 135 commercial transport operators are required to have independent communications with their ground-based owner to operate. An Airline Operations Center (AOC) prepares flight plans, files flight plans, collects and prepares weather briefings, prepares alternate flight plans, schedules the flights, and at varying levels of engagement, provides aircraft monitoring and tracking for systems health, position, and emergency support. The same will be required of Part 135 UAM operators, especially in a UTM

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[9] Legal operator, not a remote control operator. The UOC may use a USS-provided communication service or network to accomplish needed functions.
[10] FAA, Concept of Operations v2.0 Foundational Principles Roles and Responsibilities Use Cases and Operational Threads, Unmanned Aircraft System (UAS) Traffic Management (UTM), FAA.gov, March 2020.
[11] Prospective UAM manufacturers and operators advertise speeds well above 100 kts. High rates of speed require farther look-ahead. In an urban environment, this would be above the roofline; in other words, higher altitude. We assume UAM will travel at high speeds in cruise phase and slow speeds for approach and ascent. If response rates are slower than assumed, then greater look-ahead or slower speed is required to maintain safety.

environment. A UAM Operations Center (UOC) will track and monitor its own UAM flights. For example, a UOC will track aircraft battery levels in flight and direct the aircraft to divert or land to maintain safety. If a ground-based emergency occurs that affects the airspace (such as a building fire), the AASP will notify UOCs, and the UOC will contact its aircraft and manage new flight plans.

Every air-to-ground CNS system requires a ground infrastructure to support it. Examples include a network of antennas for air-ground communications, relay of aircraft position information to UOCs, vertiport coordination, and surveillance reporting. We do not assume the FAA will pay for these systems. The CNS alternatives evaluated for UAM may have to pay for themselves through user fees, which makes cost an important attribute of the technologies to be evaluated, as well as the ground footprint requirements: physical space and access to communication infrastructure and power. An urban environment presents challenges for siting needed ground equipment, including property owner resistance.

1.4.2 Operating Altitude

While the NASA and FAA ConOps limit UTM to a 400-foot AGL operating regime, we explicitly changed UAM operating assumptions to include airspace above 400 feet AGL. Confining UAM VTOLs to 400 feet AGL and below is likely to be hazardous due to urban vortices, interference to CNS signals, and obstructions. Downwash off VTOL vehicles will send objects flying; amplified by urban canyons, the downwash will move unsecured objects and create flying object debris on urban streets, from newsstands to food trucks. The downwash safe zone is outside two to three times the rotor diameter. Buildings block the many wireless signals UAMs will need to operate, including navigation and most forms of surveillance. Autonomous pilotage systems shut down without continuous incoming data.[12]

If UAM flights observe different flying altitudes based on direction of flight, as in the current NAS, then flying below 400-feet AGL leaves very little room for opposite directions of travel. Above 1000-feet AGL, there are far fewer obstacles, making loss of signal less likely and errors in positioning less of a hazard. See Figure 1-3 for heights of the tallest buildings in the U.S., which are concentrated in the densest urban environments, precisely where UAM will find a market. Aircraft flying at 1000 feet or above will encounter fewer hazards. However, greater altitude comes at the expense of range, which is particularly challenging for battery-powered electric vertical take-off and landing (eVTOL) aircraft. We assume eVTOL UAM will not operate significantly above 1000 feet.

We assume UAM will land on surfaces below 400 feet AGL. Windspeed increases with height due to decreasing pressure gradients, surface friction, and air density. Higher windspeed makes take-off and landing operations more difficult. The urban environment itself is subject to significant wind amplification that makes operating near buildings hazardous, so a landing pad adjacent to a large building may still be hazardous even at a lower altitude, but on balance, lower altitudes have lower winds.

Altitude is generally defined in feet AGL and at low altitudes "ground" includes structures. A sUAS restricted to 400 feet AGL can fly at 1200 feet above the ground if it is flying above a 900-foot tower. Strict adherence to the AGL above the roofline for cruising altitude would be a problem for passenger comfort, and transiting from 400 feet AGL above a tower to 400 feet AGL above the street increases UAS traffic management complexity. The issue of undefined UAM flying altitude created difficulties in identifying optimal altitudinal navigation technologies.

[12] *"F-22 Squadron Shot Down by the International Date Line," Defense Industry Daily, March 1, 2007.*

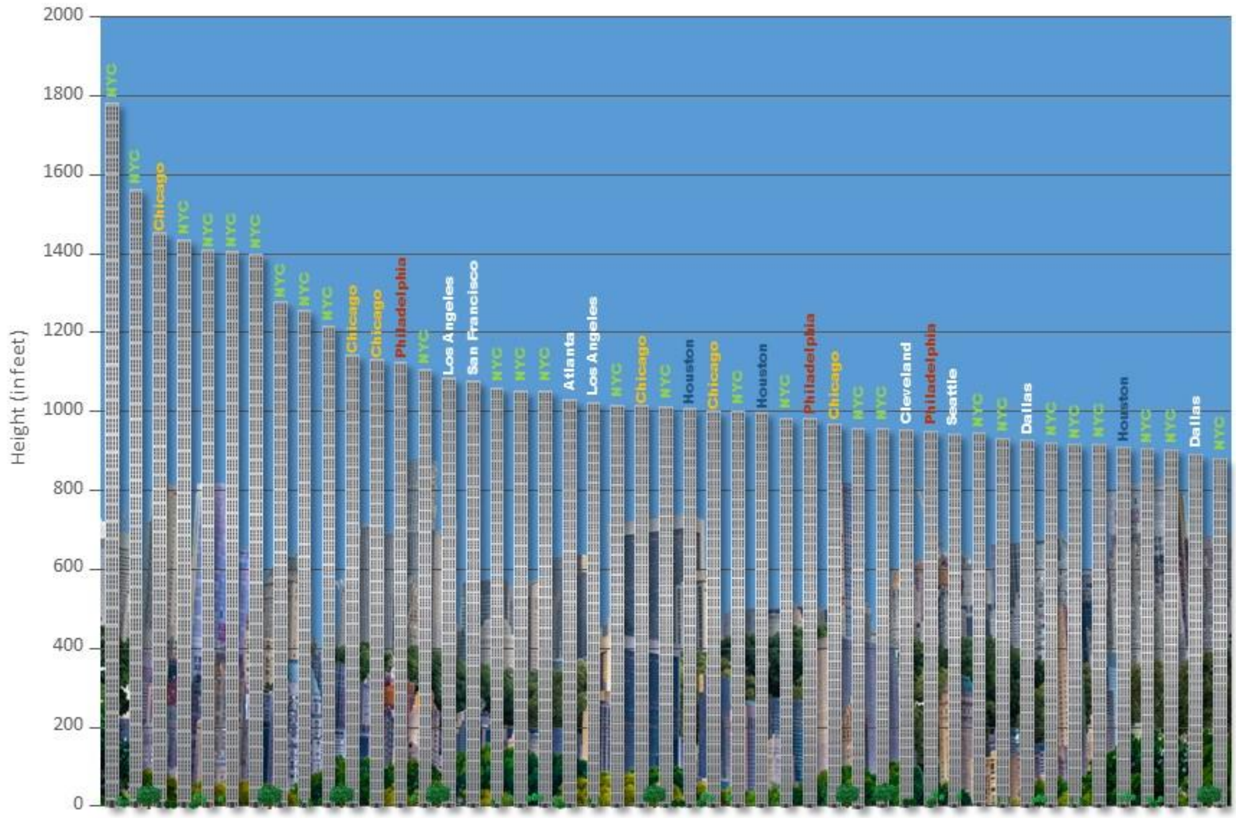

Figure 1-3. Tallest Buildings in the U.S. by Height and Location

1.4.3 Piloted and Non-Piloted Flight

Some prospective UAM manufacturers and operators plan for piloted operations, to gain revenue as soon as practical, while others plan for autonomous operations and are test-flying prototypes. Our study looked at both piloted and autonomous or “non-piloted” UAM vehicle operation. Because NAS function today is human-centric, non-piloted operation often posed the limiting case. Runway instrument approaches in the NAS employ guidance sensors to the last hundred feet, where human pilots visually acquire the runway and control the landing. A category IIIc landing is automated, though monitored by the human pilot. Sensors and automation with the capability to entirely replace the human pilot have higher operational requirements. In this task, CNS functions and specifications were identified for both piloted and non-piloted aircraft. The sensing requirements for operating in low to zero visibility with a human pilot are largely the same as operating with a non-pilot, as in both cases the automation is landing the vehicle. In the UAM VTOL case, the aircraft is not coasting into a runway but must come to a gentle stop in three dimensions, within a small space.

1.5 Functions and Specifications

Evaluation of the CNS alternatives requires a statement of requirements. Our goal was not to state requirements at a design level, but to describe the functions that CNS would have to fulfill for UAM in UML-4. This necessitated defining the precision, capacity, range, and availability that the CNS functions would require of their avionics, because it is difficult, for example, to recommend a surveillance technology without specifying the required range for detection.

To provide those specifications, we defined the functions of UAM CNS operation from the UTM ConOps and the assumptions listed above. These functions are illustrated in diagrammatic overviews, in Figures 1-4, 1-5, and 1-6.

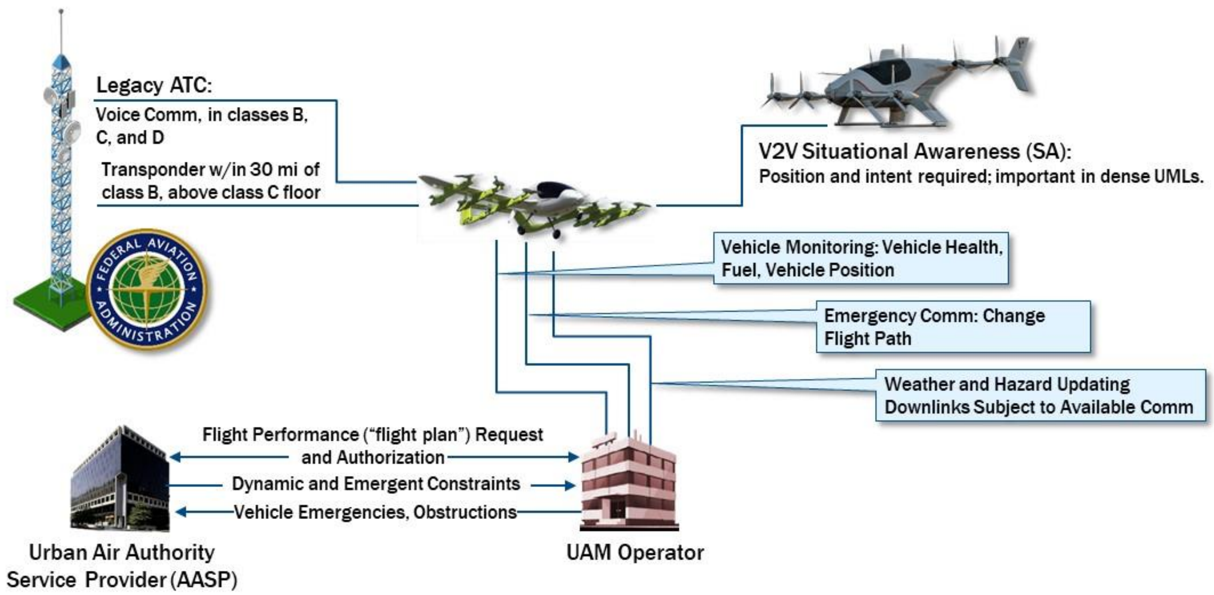

Figure 1-4. Communication Functions for UAM Operation

In Figure 1-4, each communication function under analysis is illustrated with a solid line from the UAM vehicle in the center of the diagram. The communications lines between ground providers are part of networked solutions.

Figure 1-5 illustrates the UAM vehicle knowing its own position laterally and altitudinally in the urban environment, including in IMC conditions, with increasing precision closer to buildings and highest precision upon landing. En route flight requires less precision because we assume that vehicles will fly above most structures. In approach, UAM vehicles will be below some buildings' rooftops and thus must have an absolute reference laterally and vertically, particularly for autonomous operation. Landings may be accomplished autonomously or in low visibility and those operations require the highest precision, namely sub-meter positioning, to provide a gentle touchdown for passenger comfort.

Operating at a density of hundreds of UAM flights within an urban core requires positional separation of less than 0.5 nm in places of high demand. Examining the fastest rate of closure (head on), at high density operations, with a 0.2-5 second pilot reaction time, the vehicle needs to know its own position at 10 Hz[13], and we recommend 10 Hz position and intent broadcasting for conflict avoidance. This cooperative surveillance function creates a requirement for navigation accuracy and for communication.

[13] *ADS-B reporting currently is 1 Hz and GPS WAAS can achieve 5 Hz under current manufacturing; 10 Hz is technically achievable with today's manufacturing methods.*

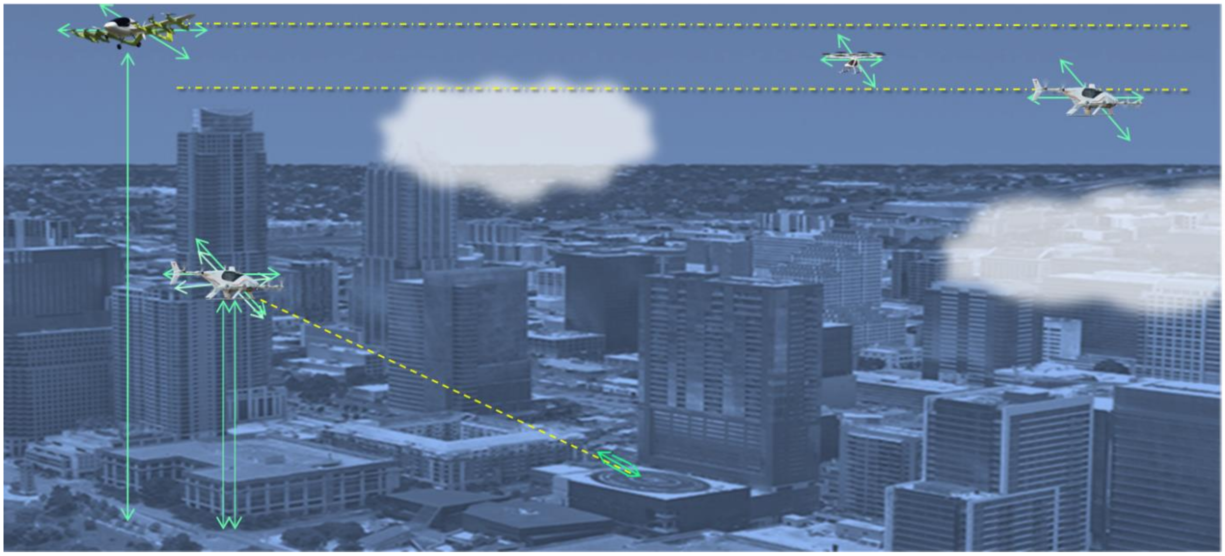

Figure 1-5. Navigation Functions for UAM Operation

Figure 1-6 illustrates both cooperative and non-cooperative surveillance relationships for the UAM that give rise to the required surveillance functions. The UAM must communicate position and intent with other cooperative aircraft, and must be able to detect non-cooperative aircraft and obstacles, to avoid collisions. The UAM operators are required to monitor position and health of the UAM vehicles under Part 135. In addition, an AASP or FIMS will need a means to measure and mitigate density, particularly for range-limited electric vehicles in dense urban operations with limited landing spots. Thus, there is a need for some form of airspace density monitoring, either through independent surveillance or through flight reports from UAM operators to the AASP.

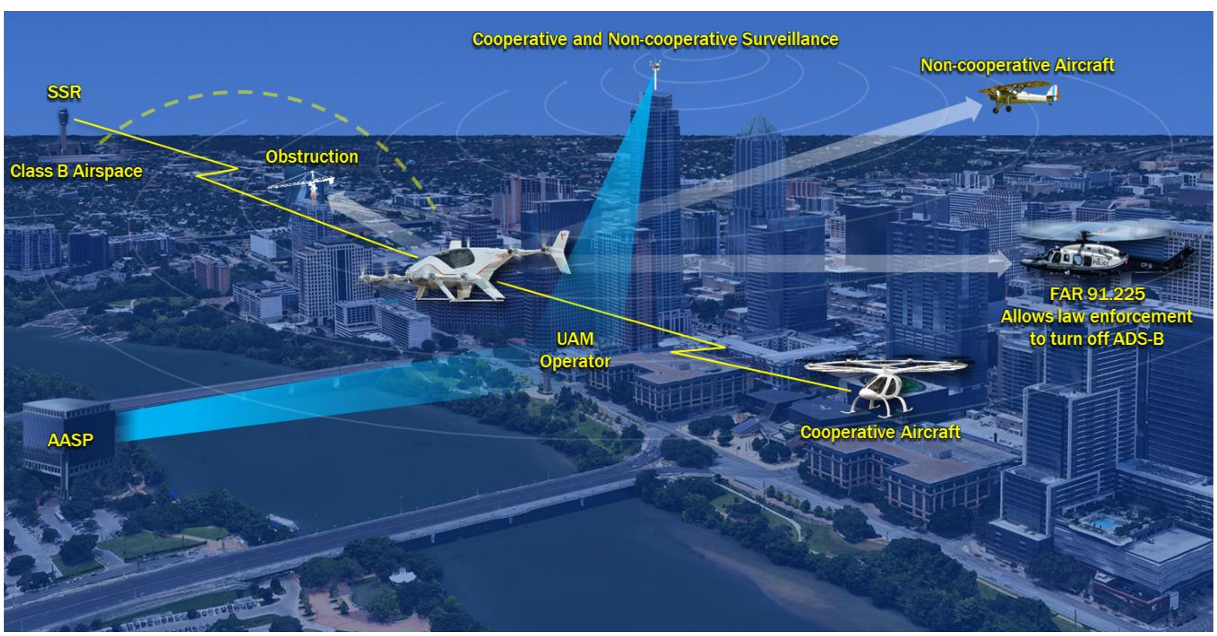

Figure 1-6. Surveillance Functions for UAM Operation

While this could be accomplished through the UAM ecosystem, the urban environment will want to ensure that the urban air vehicles are properly equipped and authorized to be there, for privacy, safety, and security.

Non-cooperative ground-based surveillance for urban security becomes a focused sociological need under widespread UAM operations.

The resulting discrete list of functions and their definitions are given in Table 1-2. Functions fall into communications, navigation, or surveillance areas, and can be divided into elements by domain, range, or communicator. Functions apply to piloted aircraft, non-piloted aircraft, or both, noted in the fourth column. Detailed specifications and references associated with these specifications are detailed in Appendix A. The application of technologies to these functions is discussed in Chapter 2.

Table 1-2. Derived Functional Requirements for UAM

AREA	ELEMENT	FUNCTION	PILOTED OR NON-PILOTED	DEFINITION
Comm	C2	AOC: Vehicle position	P, NP	Vehicles need to be monitored by owner/operators to ensure conformance with flight plans.
Comm	C2	AOC: Flight Plan	P, NP	Like for-hire aircraft today, an aircraft owner/operator maintains an operational center (AOC) where flight plans are created, sent to the pilot/aircraft, and filed with the FAA. When the aircraft needs to change its flight plan due to weather or other hazards, often the AOC negotiates and plans the new flight plan and transmits it to the flight deck.
Comm	C2	AOC: Vehicle Health	P, NP	Like for-hire aircraft today, aircraft owners are required to maintain an independent communication with aircraft that monitors aircraft condition and issues. Non-piloted vehicles in particular need to be monitored by owner/operators to ensure conformance with flight plans, and vehicle health.
Comm	C2 Video	Vehicle Situational Awareness, Out The Window (OTW) Video, Downlink	NP	OTW video, downlink. A great deal of weather expertise and judgment is incorporated in a human pilot. A vast suite of sensors would be required to fully replace the pilot's situational awareness of hazards, including weather, both before take-off and en route. For instance, many airports do not have lightning sensors. Incorporating an OTW video to remote surveillance is an additional needed safety net.
Comm	ATC	FAA: Voice Comm	P, NP	Required communications with ATC in Class A/B/C/D airspace.
Comm	ATC	Broadcast position and intent to cooperative vehicles, AASP	P, NP	Includes UAM-to-UAM and UAM to non-UAM cooperative aircraft detection and tracking. Supporting technologies include ADS-B, TCAS, and DAA solutions. Specifications for this function are closely linked with related FAA requirements for "well clear", collision avoidance, and surveillance (transponder, Mode C, S, ADS-B out). Surveillance sensor specifications should be addressed within this line item, including DAA. This item could have been classified as "Surveillance," but was included in "Communications." Position is required under Mode C veil; intent is required for commercial aircraft with more than 30 passenger seats. Given the high density of urban airspace, and lack of ATC-provided separation, intent increases safety.

AREA	ELEMENT	FUNCTION	PILOTED OR NON-PILOTED	DEFINITION
Comm	Pax	Communications, Passenger Welfare, Passenger Emergency Communications	NP	Passenger emergency communications: video and voice (PTT) to AOC, potentially to ANSP/USSs/police.
Comm	Wx	AOC: Wx uplink	P	FAR 135.175 & 121.357 require approved weather radar equipment for aircraft over 12,500 lbs. max gross take-off weight. FAR 135.173 requires approved thunderstorm detection equipment for aircraft over 9 passengers.
Nav	En Route	Lateral	P, NP	The aircraft must know where it is and be able to self-locate on the basis of sensors in order to complete a flight to a destination and to avoid known obstacles and hazards.
Nav	En Route	Vertical	P, NP	The aircraft must be able to conform to an assigned or suitable altitude for its speed, phase of flight, vehicle size and potentially other considerations. Altitudinal separation is assumed to be used to prevent collisions and thus the aircraft must know its altitude.
Nav	Approach	Lateral	P, NP	The aircraft must self-locate with greater precision in the x,y coordinate plane for approach.
Nav	Approach	Vertical	P, NP	The aircraft must self-locate with greater precision than in en route when on approach to a vertiport with uneven obstacles potentially in its flight path. Unlike a public airport, the flight path may not be obstacle free.
Nav	Landing	Lateral	P, NP	The aircraft must be able to sense location in low visibility conditions and with sufficient update rates to land safely on a vertiport at a high degree of availability.
Nav	Landing	Vertical	P, NP	The aircraft must be able to sense location in low visibility conditions and with sufficient update rates to land safely – and without a “hard landing” on a vertiport at a high degree of availability.
Surv	Ground	Monitor	P, NP	AASP and/or USSs need to monitor the airspace to 1) verify that authorized aircraft are where they say they are and are operating normally and 2) monitor dynamic density.
Surv	Ground	Non cooperative surveillance	P, NP	AASP and/or USSs need to monitor the airspace to detect non-cooperative and unauthorized aircraft.
Surv	UAM	Airborne	P, NP	The UAM needs to be able to detect and avoid non-cooperative aircraft that present a hazard, whether they are cloaked police/security vehicles, UAS, or potentially unauthorized aircraft.
Surv	UAM	Non-aircraft Detection	P, NP	UAM vehicle must avoid obstacles including cranes, flagpoles, wires, buildings, etc.

CHAPTER TWO

2.0 COMMUNICATIONS, NAVIGATION, AND SURVEILLANCE

2.1 CNS Technologies

Chapter 1 described how CNS requirements were derived. We evaluated technologies to meet requirements, defined in functions and specifications, to identify and recommend technologies for maturation for meeting the needs of a mature UAM operational ecosystem. Chapter 2 describes that selection, makes recommendations specific to those recommendations, and further investigates the development of these technologies in integrated avionics, with recommendations and identification of gaps.

Technology alternatives were identified in the project proposal and additional alternatives were added from interview suggestions, research, and evolving technologies. Since we are projecting forward to the design of a new air vehicle 10 to 15 years in the future, we deliberately looked for technologies that were not yet in the NAS, and not yet on the market, but that had the potential to mature over the next decade into promising solutions with greater capabilities. Some existing technologies, such as 4G LTE and airport surveillance radar, had technical disadvantages and lacked advanced functions, which caused them not to advance as recommendable technologies.[14] Table 2-1 depicts the technology alternatives considered in the study.

Table 2-1. Technology Alternatives Studied

COMM	NAVIGATION	SURVEILLANCE - AIR	SURVEILLANCE - GROUND
• 5G Cellular • 5G Satellite Integration • Bluetooth • C Band • DME Whitespace • Laser Communications • LEO (Commercial) • VDL Mode 2 • VDL Mode 3 • UWB MIMO • Frequency Management	• Barometric Pressure Altitude • Radar Altimetry • Altimetry with Broadcast References • GNSS only • GNSS + INS/IRS (FOG/MEMs) • GNSS + PNT Nav • GNSS + eLoran • GNSS + GBAS (LAAS) • GNSS + WAAS • GNSS + RF mapping • GNSS + SAR/ISAR • LIDAR • Machine Vision • IR • RF Beacon • Sensor Fusion	• ACAS-X, TCAS • ADS-B (current) • UAT2 • Dedicated Short Range Communications • FLARM (European) • LIDAR • FMCW RADAR in GHz Range • K Band RADAR • Acoustic Detection • RF Detection • 5G Cellular	• Advanced Doppler Range Gating Radar • Bistatic Radar • Army Ground Based Sense and Avoid • IR Sensing • Lasergate Monitoring • Machine Vision • Holographic RADAR • K Band FMCW RADAR • UWB MIMO • Mode C/S Multi-Lateration • Acoustic Detection • RF Detection • 5G Cellular

[14] 4G LTE is the subject of a 2007 FCC ban on cellular use for aircraft. An FCC Guide states: "Federal Communications Commission (FCC) rules prohibit the use of cellular phones using the 800 MHz frequency and other wireless devices on airborne aircraft. This ban was put in place because of potential interference to wireless networks on the ground." (http://www.fcc.gov/guides/wireless-devices-airplanes). In addition, 3G services were turned off for all subscribers on December 31, 2019, due to security loopholes in 3G. Logically, 4G and 5G will face similar turning off points in the future: 6G is likely to be the dominant service in place in the 2030s. However, the best representative model for evaluating future 6G services at present is 5G.

2.1.1 Limits of Alternatives

Except for sensors used with GNSS for enhanced precision navigation, Table 2-1 lists individual technologies instead of combinations. Sensor fusion is a valid and recommended approach to many UAM functions, but we avoided evaluating all the possible permutations of combined technologies. Additionally, frequency managers, including artificial intelligence frequency managers, were discussed. FAA certification standards are a barrier to use of artificial intelligence (AI)-enabled technologies except in limited applications, and flight-critical frequencies at present require an assignment that assures air traffic communication prioritization, which at present could not be assured with AI frequency management. We concluded that frequency hopping and advanced waveforms would be difficult to enable by UML-4 but would be strong candidates for UML-6.

2.1.2 Technology attributes

Each technology was defined in terms of its attributes, to assist in measuring whether each technology met or could meet the functional specifications. The attributes were:

- Description
- Size, weight, and power in order of magnitude terms
- Bandwidth: how does this spectrum handle obstructions, loss of LOS, and urban clutter; range of the signal; whether the spectrum is open, licensed, or Aero-reserved
- Cost in order of magnitude terms
- Precision
- Use case evaluations: is the operation of the technology affected by any of these conditions?
    - Fog, rain, snow obscuring vision and some wavelengths
    - High traffic/low traffic affecting quality of service or resolution
    - Night obscuring vision and changing ionospheric performance
    - City emergency (impact of an external hazard or failure such as earthquake, power failure, or terrorist action)
    - Onboard vehicle emergency (passenger emergency or equipment failure)
    - Presence of flocks of birds around vehicle
- Advantages
- Disadvantages
- FAA acceptance: has this technology been used by the FAA? Have standards describing this technology for aerospace been started?
- Cybersecurity and privacy: possible vulnerabilities and concerns
- Maturity in time: UML readiness
- Ground-Based Network Architecture: what ground equipment is needed?

As a result of the detailed examination of specifications, some functions were combined into single function categories; for example, the grouping of all C2 functions. Some technologies were examined for multiple functions. Attributes and descriptions for the candidate technologies appear in Appendix B.

2.1.3 CNS Recommendations

Tables 2-2 through 2-6 list the recommended technologies. The alternatives are not ranked. The cells of technologies that were deselected from further research are shaded. The final column in each table includes comments on research needs or relative disadvantages of the technology. **14 CFR 135.165 requires the**

use of two independent navigation sources and under IFR, two independent communications sources. Independent is interpreted to mean different bands and different sensors, such as VOR-DME and GNSS navigation. Tables 2-2 through 2-3 list single technologies, out of which two would be used for UAM operation under Part 135 with IFR authorization.

Table 2-2. Technologies for Communications Functions

TECHNOLOGY	RESEARCH NEEDS, DISADVANTAGES
VDL Mode 3	Appropriate bandwidth and FAA acceptance.
5G, Satellite Integration	Latency is a concern and may be inappropriate for some functions.
LEO (commercial)	May have dual function (communication and navigation enhancement).
C Band for C2	Consider but investigate whether bandwidth is sufficient for both UAS and UAM.
5G, Cellular	Prioritization, market case, and antenna pointing issues must be resolved. Capacity claims may be overstated.
VDL Mode 2	Not recommended. Cost, capacity, and latency were concerns.
DME Whitespace	Not recommended. Capacity is insufficient in largest U.S. urban environments.
Laser Communications	Not recommended. Not mature for UML-4. Suitable alternative for UML-6.
Bluetooth 5	Not recommended. Short range requires too many ground stations for viability; interference from nearby emitters limits the usability for flight-critical applications; a consideration for cooperative surveillance only if UAM speeds are low, e.g., 25 mph.

In addition to the communications functions identified for UML-4, in UML-6 a "land anywhere" UAM vehicle will need to communicate cooperatively with ground infrastructure, vehicles, and people (potentially via cellphones), to signal landing intent. Under UML-6, communications will need to include broader communications, known as V2X.

Navigation functions were defined to reflect increasing levels of precision needed as the UAM vehicle maneuvers in increasingly obstacle-rich environments, from en route travel to approach to landing. The defined functions for each environment are divided into lateral and vertical and appear in columns 2 through 7 in Table 2-3. In Table 2-3, recommended technologies are noted with "Cons." for "consider" and down-voted technologies are labelled "Not rec." for "Not recommended."

Table 2-3. Technologies for Navigation Functions

TECHNOLOGY	EN ROUTE		APPROACH		LANDING		RESEARCH NEEDS/ DISADVANTAGES
	LAT	VERT	LAT	VERT	LAT	VERT	
GNSS + PNT augmentation	Cons.	Cons.	Cons.	Cons.	Cons.	Cons	Suitable.
GNSS + LAAS (GBAS)	Cons.	Cons.	Cons.	Cons.	Cons.	Cons.	Suitable.
GNSS + WAAS	Cons.	Cons.	Cons.	Cons.	Cons.	CAT 1&II	Suitable for most uses but not suitable for complete autonomy or CAT III landing.
LEO	Cons.	Cons.	Cons. GNSS + LEO	Cons.	Not rec.	Not rec.	Opportunity for joint GNSS+LEO alternative with greater number of satellites to acquire. Onboard LEO clocks have insufficient precision for non-visual landings.
GNSS + RF mapping	Cons.	Not rec.	Cons.	Not rec.	Not rec.	Not rec.	Uncertain business case, reception, and precision for

TECHNOLOGY	EN ROUTE		APPROACH		LANDING		RESEARCH NEEDS/ DISADVANTAGES
	LAT	VERT	LAT	VERT	LAT	VERT	
							landing. Insufficient precision for vertical navigation.
GNSS + SAR/ISAR mapping	Cons.	Not rec.	Not rec.	Not rec.	Not rec.	Not rec.	Cost and weight; lack of dual function.
GNSS (only)	Cons.	Not rec.	Not rec.	Not rec.	Not rec.	Not rec.	Precision insufficient for IFR operations and under autonomy. Vertical use depends on flight path distance from structures.
GNSS + INS /IRS (FOG /MEMS)	Cons.	Not rec.	Not rec.	Not rec.	Not rec.	Not rec.	Appropriate for coasting during loss of GNSS signal but does not serve as an enhancement for precision. Insufficient precision for vertical.
GNSS + RF Beacon	Not rec.	Not rec.	Cons.	Cons.	Cons.	Not rec.	Line of sight not available in en route.
GNSS+LIDAR	Not rec.	Not rec.	Not rec.	Cons.	Cons.	Cons.	Limited beams insufficient for lateral navigation resolution at gross level.
GNSS + K band radar	Not rec.	Not rec.	Not rec.	Not rec.	Cons.	Cons.	Dual function in landing and obstacle avoidance. Would face interference hazards in en route and approach flight.
GNSS+ FMCW in GHz	Not rec.	Not rec.	Not rec.	Not rec.	Cons.	Cons.	Limited beams insufficient for lateral navigation at gross level; Dual function in landing and obstacle avoidance.
GNSS+Machine vision (optical)	Not rec.	Not rec.	Not rec.	Not rec.	Cons.	Not rec.	Machine vision has insufficient maturity for locational range-finding at gross level or for altitude. Consider for UML-6.
GNSS + eLoran	Not rec.	Not rec.	Not rec.	Not rec.	Not rec.	Not rec.	High cost to re-start and comparative lack of precision.
Radio/Radar Altimeter	N/A	Cons.	N/A	Cons.	N/A	Cons.	Not appropriate for lateral navigation.
Barometric Pressure Altitude	N/A	Depends on proximity to structures.	N/A	Not rec.	N/A	Not rec.	Urban pressure altimetry can have altitude errors of 500 feet, making pressure unsuitable without human eyes as primary navigator. **A fusion radar altimeter-pressure altimeter may be the best alternative**.
Barometric Pressure with References	N/A		N/A	Not rec.	N/A	Not rec.	

There were numerous technologies suitable for navigation and for non-cooperative detect and avoid, thus the creation of a performance-based standard such as a Minimum Aviation System Performance Standards (MASPS) would be useful. Since these functions are not cooperative or interoperable across vehicles, MASPS would be suitable to promote development. Many UAM manufacturers are investigating navigation fusion, using a combination of three or more sensors working together to produce highly accurate and available navigation. These fusion solutions are a superior alternative and navigation standards need to allow for their use.

Evaluating altitudinal navigation technologies was complicated by undefined UAM flight altitude. Neither radar altimetry nor barometric altitude will be feasible on its own. Urban canyons commonly amplify normal winds, which creates errors in pressure differentials equivalent to hundreds of feet of altitude. When flying without visual reference, either with automated altitude function or without visibility, passing closely above structures would require knowledge of absolute, not relative (pressure), altitude. However, flying a defined distance above absolute ground level would create a sawtooth-like altitude path, unsuitable for passenger comfort. The solution requires establishment of UAM flight altitudes, and maintaining safe altitude will likely require multiple sensors working in concert.

Table 2-4 shows the recommended cooperative surveillance technologies. The first two, UAT2 and Mode C multilateration, also provide a means of ground-based cooperative surveillance. The ability to surveil the urban airspace and identify cooperative traffic will become important for dense operations due to security concerns.

Table 2-4. UAM Cooperative Surveillance Technologies for Air and Ground

TECHNOLOGY	RESEARCH NEEDS, DISADVANTAGES
UAT2 (1104 MHz)	Highly advantageous for UAM. Compliant with ADS-B mandate so satisfies dual-stack while also being filterable by ATC.
Mode C Multilateration	Compliant with ADS-B mandate so satisfies dual-stack while also being filterable by ATC.
ACAS-X	1090 MHz congestion is an issue.
5G	Requires network infrastructure changes to enable prioritization, sidelink, and upward pointing tower antennas; requires multiple antennas for multiple directions.
ADS-B 1090 MHz	Not recommended. Out of capacity, particularly for dense urban operations of hundreds of additional vehicles inside a 20 x 20 mile range.
Dedicated Short-Range Communications (DSRC)	Not recommended. Spectrum availability highly uncertain; allocated for ground vehicles but desired for cellular use. Severely range limited. Message sets undefined.
Flight Alarm (FLARM)	Not recommended. Used only in Europe on a frequency not available in the U.S. Would have to identify a set of frequencies for U.S. operation.
Bluetooth 5	Not recommended. Considered due to sUAS use but has insufficient range for UAM.

In the function of ground-based non-cooperative surveillance (shown in Table 2-5), none of the considered technologies scored as feasible. The urban environment presents too many obstacles for positive surveillance supporting high density control. Surveillance could be effective if the intent is control of entry or compliance, through perimeter monitoring and spot-checking. Monitoring vertiport operations is also feasible. The better alternatives among the non-feasible are shown in the top rows of Table 2-5. As with altitude sensing, resolution of the uncertainty around this function's use (whether security-based perimeter sensing, flight-tube separation verification, or overall sensing of flight numbers and types) would lead to better identification of the superior alternatives.

Table 2-5. Ground-Based Non-Cooperative Surveillance Technologies

TECHNOLOGY	RESEARCH NEEDS, DISADVANTAGES
Advanced Doppler Range Gating Radar	Cost and size are a concern.
Infrared (IR) Sensing	Range limited. May be a superior option fused with machine vision for day and night detection; but may be a better candidate for UML-5/6.
Bistatic Radar	Exportability currently not allowed, though the technology is developed independently in several countries. Export restrictions may affect availability timing.
Acoustic Detection	Requires research and development.
5G	Not recommended. Easily defeated by operator with ill intent.
Army Ground Based Sense And Avoid	Not recommended. Cost and size are a concern.
RF Detection	Not recommended. Short range.
Machine Vision (Optical)	Not recommended. Limited in fog and all-weather conditions. Combined with IR, may be an option.
Lasergate Corridor Monitoring	Not recommended. For limited perimeter monitoring.
Ultra Wide Band (UWB) MIMO	Not recommended. Very short range.

Table 2-6 details the possible air vehicle-based non-cooperative surveillance technologies for use in detect and avoid. Manufacturers are prototyping multiple sensor inputs for sensor fusion, with superior results for detection. We recommend allowing multiple sensor fusion for non-cooperative surveillance, by formulating a MASP for standardization.

Table 2-6. Air-Based Non-Cooperative Surveillance Technologies

TECHNOLOGY	RESEARCH NEEDS, DISADVANTAGES
Sensor Fusion	Combination of sensors; superior alternative.
K-Band RADAR	Range-limited so effectiveness depends on vehicle speed. May have dual function with precision landing (an advantage).
RF Detection	Requires development but many companies are interested and the technology is understood. Range is a concern.
LIDAR	May have dual function with precision landing (an advantage).
Infrared (IR) Sensing	Range limited. May be a superior option when fused with machine vision for day and night detection.
Acoustic Detection	Not recommended. Requires research and development.
RADAR FMCW in GHz	Not recommended. Deployment may be limited by exportability. Multiple antennas on vehicle required, making cost a concern.
Machine Vision (Optical)	Not recommended. Limited in fog and all-weather conditions. Combined with IR, may be an option.
Ultra Wide Band (UWB) MIMO	Not recommended. Very short range.

2.2 Recommendations

Tables 2-2 through 2-6 captured our recommendations for technology alternatives deserving of further research or development work for UML-4. Our most strongly supported recommendations include:

- Cooperative surveillance for vehicle-to-vehicle separation is a must-have function for UAM, and UAT2 (on proposed 1104 MHz) is a highly superior alternative to satisfy that function, due to ab initio message set design and because it is ATC compliant but filterable.
- Using 5G for airspace requires infrastructure changes at the carrier and cell tower level in prioritization and antenna pointing; without these required changes 5G is not a suitable alternative.
- Certification standards for non-cooperative navigation and detection solutions for UAM should be performance based.

As a culmination of the technology selection research, we have identified gaps in technology, implementation, or research needed for UAM CNS. Our recommendations concerning these gaps follow. Additional recommendations appear in Section 3.2 and are collected in Chapter 5.

2.2.1 Gap 1 - Start Maturing Non-Cooperative Surveillance for Urban Environments

At low UMLs, flights will be infrequent and may consist entirely of emergency medical transport and trusted agents, leading to a sentiment that non-cooperative surveillance is not needed. When density or public sentiment reaches the point that non-cooperative surveillance becomes socially necessary, a well-functioning system will take years to mature and implement. Terrorist attempts, unintended airspace incursions, or UAM accidents are events that could trigger compulsive fielding of ground-based non-cooperative surveillance. Research and development efforts starting now, and extending over the next decade, would permit deployment of a lower cost, more effective surveillance system when the need arises. We recommend development of a distributed, robust, low-cost sensing system that could be placed pervasively, yet inconspicuously, and would not impair personal privacy.

One interview subject suggested a ubiquitous upward-pointing sensor deployed on city vehicles, lamp posts, or power poles. Two different sensors are needed for detection and tracking. Networked together, detection and tracking sensors match detections to authorized vehicles using the cooperative surveillance comms, distinguishing the known from unknown air vehicles.

2.2.2 Gap 2 - Lack of 5G Research and Implementation

FAA has enforced a standard that the air-ground frequencies used for aviation communication must be able to prioritize aviation messaging, particularly during an emergency. Cellular infrastructure does not do this. Using 5G for airspace requires infrastructure changes at the carrier and cell tower level in prioritization. In addition, aviation-use 5G proposals use sidelobes, rather than pointing to the proper elevation. Beamforming for aviation would require retrofit of cell towers. Even with such retrofit, the extent of signal die-off over range and elevation has not been properly quantified. The cellular providers so far have concluded the market for aviation use does not close, as aviation use causes dropping of terrestrial calls. There is evidence that implementing aviation prioritization would multiply terrestrial calldrops more than 1-for-1. [See the 5G entries in Appendix B.] Use of sidelink phone-to-phone communication holds much promise for ad hoc networking for cooperative surveillance, however, no U.S. cellular carriers have implemented sidelink in their infrastructure; and, in fact, the operational 5G networks in the U.S. at present are closer to 4G in software capabilities. GHz frequency use promises very high capacity gains that would be useful; however, to explore this alternative requires:

a. Fielding of 3GPP's Release 17 capabilities in software in 5G networks.
b. Prioritization for aviation use or the further definition of this requirement with FAA relative to the communication needs in an AFR-guided UAM vehicle.

c. Testing of signal elevation die-off.
d. Testing of clear air die-off of GHz signals to define the suitable range for a signal and the ground network requirements (geography of cell towers to ensure coverage).
e. Fielding of antennas pointing at aviation elevations.
f. Use of secure network slices for aviation instead of reliance on geographical cells for security.

Without this research and concomitant infrastructure investment, 5G is not suitable for UAM.

2.2.3 Gap 3 - Implement Local GNSS Augmentation with GNSS Back-Up

It is well established that the wildly popular GNSS locational system has vulnerabilities including localized jamming, solar flare disruption, and blocking by structures. GNSS augmentation is needed for use in low visibility and in automated applications. Widespread GNSS augmentation would benefit automated air and ground vehicles, emergency services delivery, UAS deliveries, and smart cities automation.

"Widespread GNSS augmentation" consists of local RF broadcast that provides corrections to GNSS signal errors. The more precise augmentations require additional ground equipment and investment. Broadcasts in the format of GNSS signals are receivable by devices that already use GNSS signals. Wide Area Augmentation differential GPS (DGPS) requires five or more non-faulting satellites in view, redistributes precision information by satellite, and reduces positioning error to meters 95% of the time.[15] Ground Based Augmentation (GBAS, formerly known as LAAS), reaches accuracy within one meter with the aid of multiple local reference receivers.[16] Real-time kinematics (RTK) cluster broadcast on a dedicated ultra high frequency (UHF) band and are accurate to an inch or two within six miles.

Given the broad set of potential beneficiaries of augmented GNSS services, a study of shared models may point to an efficient implementation path of GNSS augmentation for vertiports that includes local compensation. Many rural states fund an RTK network free for public use, while other public entities use public-private partnerships. This implementation would have widespread benefits and enable UML-4.

2.2.4 Gap 4 - Develop Secure Spectrum-Free Future Comms for UML-6

Our recommendations for UML-4 air-ground communication functions are for technologies over radio frequency spectrum. Radio frequency spectrum is scarce and air-ground transmissions can be eavesdropped or can be jammed. These vulnerabilities are answered with advanced waveforms, coding, and encryption. Complexity increases the time it takes to certify the equipment. As hacking threats increase through time, the complexity of measures to protect air-ground communications will increase, causing increasing effort to be expended in certifying more advanced air-ground communications. Add in the 100-year trend for increasingly complex and denser airspace operations to increase communication requirements, and it is likely that UML-6 will have additional communications needs that we can't foresee but cannot be satisfied with the UML-4 recommended solutions. RF spectrum demand will grow more intense over time, squeezing the availability of RF spectrum for aviation.

Laser communications provide a possible solution. Lasers focus a light beam between communicators and modulate the light beam with encoded data. Laser communications cannot be eavesdropped upon in the air-ground component. Laser communications have no capacity limit. Laser communications currently have limited deployments in corporate, industrial, and military applications. We recommend development of air-ground laser communications technology for UML-6. An estimated minimum of 10 years will be needed to create the infrastructure, processes, and guidance needed to transition air-ground communications to a

[15] *FAA, "Global Positioning System Wide Area Augmentation System (WAAS) Performance Standard, v. 1.0, October 2008.*
[16] *FAA, "Satellite Navigation — Ground Based Augmentation System (GBAS)" Fact Page, www.faa.gov*

system that is channel agnostic, which would allow laser communications to complement, and eventually replace, radio frequency communications for air-ground links to UAM vehicles.

2.2.5 Gap 5 - Evolve the Separation Paradigm in Cooperative Surveillance

UML-4 involves flying between known endpoints, and many of the concepts in use in the NAS today can be used or modified to accommodate this model, including defined flight routes, separation of direction of flight by altitude, and creation and use of approach procedures. Continuing to rely solely on existing technologies and procedures to get to UML-4, defers and may prevent evolution to UML-6. An approach that matures AFR should be considered.

It is clear that UML-4 traffic density cannot be supported under standard separation, even a modified version of standard separation that merely reduces the distances between vehicles. UML-6 density will be much more dense and dynamic than UML-4. Operating under UML-6 will be so complex and computationally intensive that a new system must be started before UML-4, to allow time for the evolution of increased system performance needed to accommodate UML-6. Networking protocols and redundancy requirements for vehicle-to-vehicle separation will need years to perfect.

Cooperative surveillance and autonomous UAM-to-UAM separation is needed to accommodate thousands of flights in urban airspace. Onboard systems will need to communicate vehicle-to-vehicle to coordinate intent for safe passage. The distance or angle approach mechanics that will define safe separation under such a system need to be defined and designed into software that also accepts the recommended 10 Hz position updates, with accuracy within 4.5 meters.

2.2.6 Gap 6 - Altitudinal Navigation Solution

Flight in the NAS follows pressure altitude. All aircraft altimeters are set to the same reference barometer for the region. If the pressure altitude differs from measured altitude, all aircraft are off by the same amount in the same direction. Pressure altitude is adequate for high altitude flying. Supplementation of GPS with WAAS is required under reduced separation flying and landing (RNP 0.3 for example).

To reduce controlled flight into terrain (CFIT) accidents, many aircraft are equipped with terrain warning systems such as the Helicopter Terrain Awareness and Warning System (HTAWS) and Ground Proximity Warning Systems (GPWS). Unlike radio/radar altimeters used with GPWS, HTAWS[17] is forward-looking with an obstacle and terrain database. Automatic Ground Collision Avoidance System (Auto GCAS) also works on sensor inputs, with a terrain database, and complex logical software to prevent CFITs. The need for HTAWS is highest when: ATC is not providing navigation, as on approach; when there are uneven terrain obstacles; or when there is danger of horizon confusion, as in clouds. These three conditions describe the urban airspace.

Defining the recommended altitudinal sensing solution depends on the use case for UAM flying, approach, and landing. There is a large specification gap between the NAS's established flight routes with obstacle-free terminal approach procedures and the concept of flying from rooftop to rooftop in an urban environment at 400 feet AGL. If UAM follow fixed routes above the roofline, then RNP 0.1 may be adequate for en route navigation. If UAM have defined approach paths that navigate between obstacles, an HTAWS-like system with a very accurate urban environment database, combined with a greater RNP accuracy, may be needed. Definition of flight altitudes and traffic protocols (such as separation of direction by altitude layers and ascent/descent practices) need to be developed and then altitudinal solutions can be optimized.

[17] *A version of TAWS called Enhanced Ground Proximity Warning System (EGPWS) is also forward looking.*

2.3 Spectrum Efficiency

Cellular carriers and the age of the Internet of Things place increasing pressure on available and usable RF spectrum. Coupled with the trend for more complex airspace and denser flights to require more communication, the forecast is increasing scarcity in the future for spectrum for UAM air-ground functions.

The FAA controls use of multiple bands for aero-reserved functions, as depicted in Figure 2-1. FAA requires a designation of flight-criticality for allocation of a band. Flight critical means "necessary to continued safe flight." Remote control of unpiloted air vehicles would qualify but because of the signal obstacles, meaningful remote control or command of an aircraft in a dense urban environment BVLOS will be so unreliable as to be unworkable.

Although the FAA spectrum contains a great many bands, demands of existing systems are large and continuing. It is not the case that there are vast swaths of open spectrum for the tasking. For all urban vehicles on the unpiloted to piloted spectrum, cooperative surveillance to avoid collisions is flight critical and should be on an aero-reserved frequency.

Given that UAT2 is unused, if assigned to UAM, a message set and messaging protocols could be designed to suit the needs of UAM cooperative surveillance, conferring more information than just the required position and intent. A working group similar to the RTCA S/C-206 ADS-B message set working group would be ideal for establishing protocols and the blank space needed to accommodate future data.

Flight criticality is usually defined at the point of vehicle certification. With a ConOps requirement still in development, given the signal obstacles of the urban environment, we recommend use of vehicle-to-vehicle cooperative surveillance on a reserved frequency. We recommend a ConOps that does not depend on external air-ground command and control. We recommend not replicating ATC voice commands for separation, but instead rely on operations in which each vehicle is responsible for its own flight functions and communicates that intent to other nearby vehicles. Airborne cooperative communications may also be received by a ground surveillance function; identifying the cooperative targets makes discriminating unauthorized targets easier, and the UAM ecosystem may evolve so that ground-based traffic information rebroadcast is also desired. Air-to-ground communications other than when on ground are minimized. In bandwidth intensive applications such as AOC communications for video from the flight deck, we provide recommendations, including commercial systems, to provide choice of bandwidth and allocation of enough bandwidth for the expected users of the system and their frequency of use.

To minimize use of scarce spectrum as this new industry is launched, communications in particular and navigation as well should be digitized and handled as data communications. Digitized message formats allow for terser coded representations and rapid encoding for error correction and encryption. We recommended investigation of phase interpretations in satellite-to-vehicle or ground-to-vehicle communications for precision navigation information, to minimize the need for RF rebroadcasts of GNSS augmentation information. We recommend navigation from non-RF or harvested data, such as map-matching techniques.

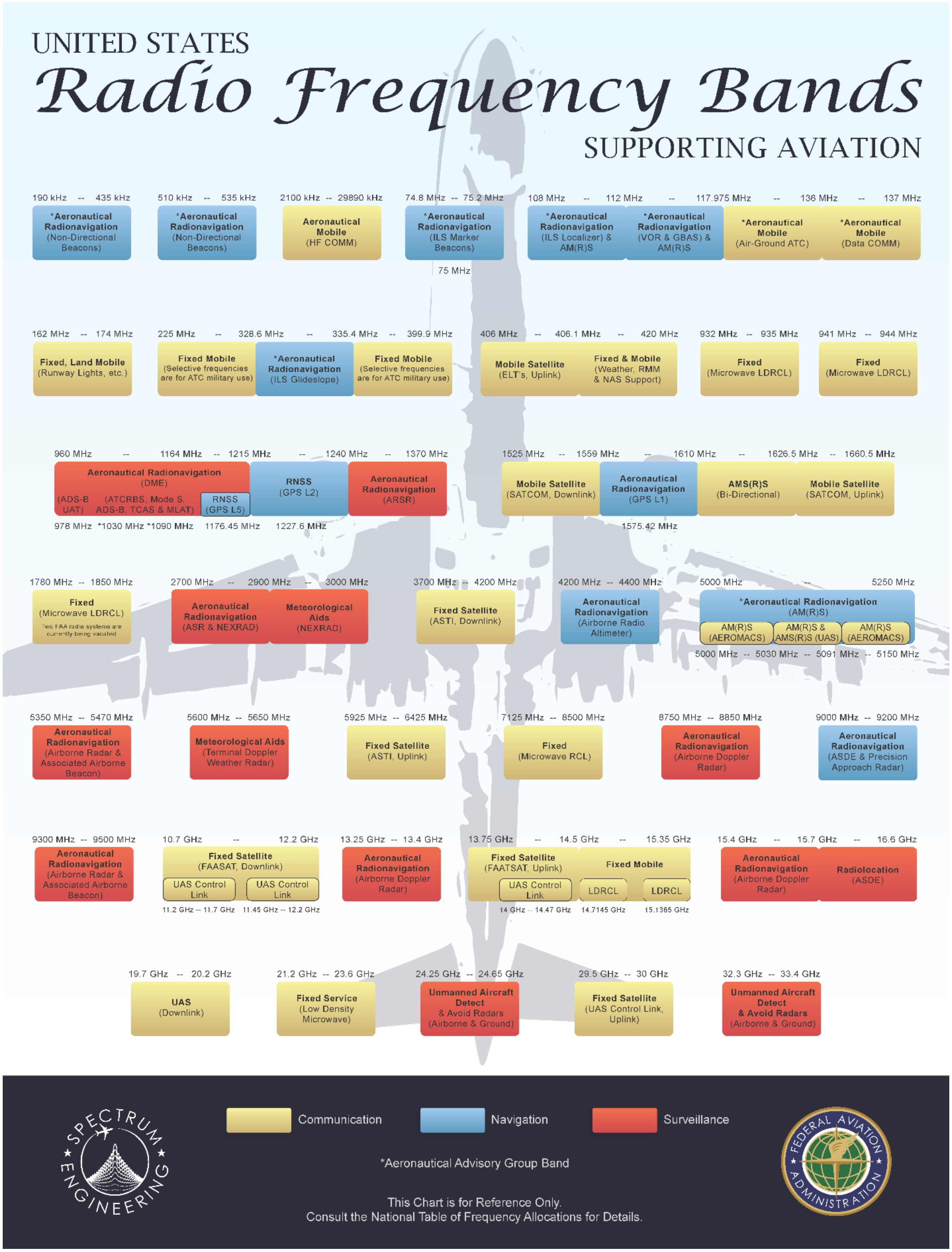

Figure 2-1. Protected Frequencies for Aviation (Source: FAA)

New spectrum saving measures such as orthogonal waveforms and ultra-wide band (UWB) will be difficult to certify. In any new waveform, a period of research is needed to ensure highly accurate reception of transmitted data; intersymbol interference (ISI) is a problem for orthogonal waveforms and phase carrier information that results in somewhat noisy or lossy signals, and a period of research and test is needed to establish the high level of reliability needed for aviation applications. FAA certification processes for radio bands request confirmation of available channels on the proposed frequency; UWB does not do this because it spreads signal across a band of 50 MHz, much of which is already occupied by other signals. It is difficult to certify that when the UWB message needs to go through, it will find an open channel, as required by the FAA process, because use is stochastic and if the channel is not available, UWB searches for another one. These restrictions on spectrum-preserving techniques held us back from recommending these technologies; more time is needed to optimize them for use.

We recommend laser communications, air-to-ground and vehicle-to-vehicle, for UML-6. Light waveforms can hold tremendous amounts of data due to their high frequencies, transmission is very fast, and cannot be "overheard" for security purposes in the air-to-ground component without being in the line of sight. The increased capacity will be needed for UML-6, but more than a decade of research and development needs to occur before laser communications can be ready for market; that research needs to start now.

2.4 Systems Engineering and Integration

A principal goal for avionics architecture requirements and the design best-practices described herein for CNS hardware and software is to minimize the size, weight, and power demand of the CNS avionics. In the mid to late 1990s, aircraft manufacturers, and their avionics suppliers, started moving towards an integrated modular avionics (IMA) architecture concept. This was a move away from the previous federated avionics approach to a modular approach that incorporated various aircraft system functionalities into a single avionics cabinet design. With standards and certification guidance established, this IMA approach has since been incorporated in more than 15 transport aircraft designs. The timeline of this evolution is shown in Figure 2-2. IMA has now been adopted within general aviation, and is readily extensible to UAM. We now have many functions in each line replaceable module (LRM) IMA unit, and they are redundant and checking on each other. The next generation design, as shown, provides greater redundancy and automatic checking of the output of each LRM.

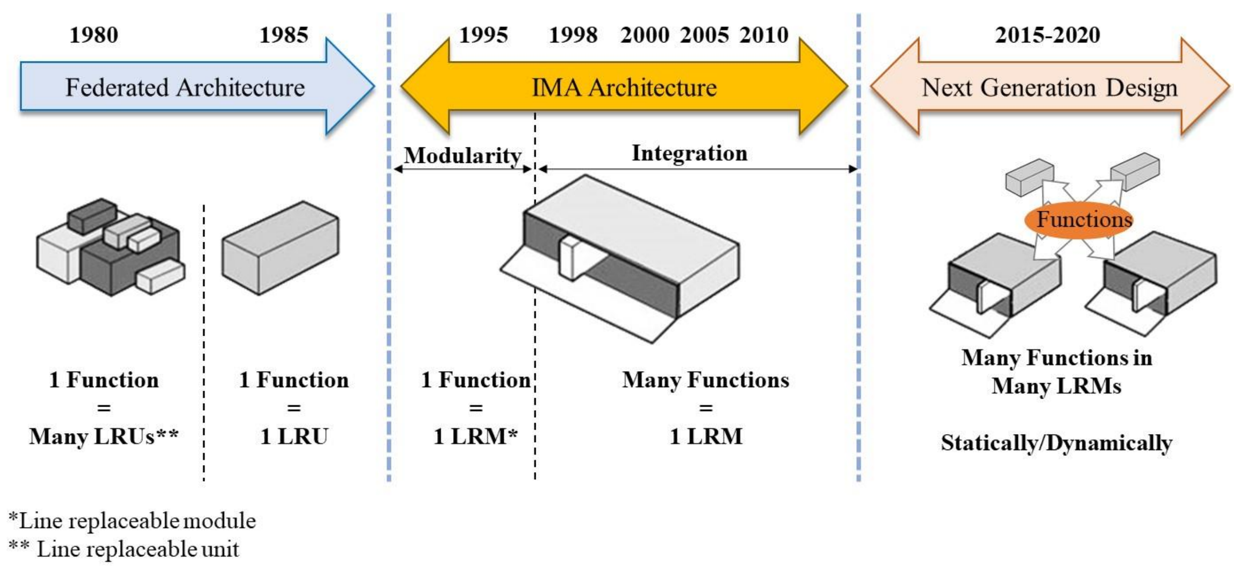

Figure 2-2. Integrated Modular Avionics (IMA)

IMA is already part of the avionics landscape, and will be used to enable Simplified Vehicle Operations and sensor fusion.

(Figure credit: FAA)

2.4.1 Guidelines for Avionics

The UAM industry and market segment will benefit from the use of systems engineering principles for a structured approach to UAM CNS avionics design. This approach will bring order to this dynamic, highly competitive, and nascent market. Systems engineering practices, as used in the various phases of a typical aerospace engineering program, may be used to identify specific research and analysis required to evaluate UAM CNS requirements and challenges. As UAM will operate in the same airspace with conventionally piloted aircraft, all interoperable avionics must comply with their standards.

2.4.1.1 Systems Analysis

Complex systems such as aircraft or airspace systems require more than a simple design; they require a systems analysis to match requirements with system capabilities and operational modes, and to prevent post-production rework. A systems analysis of UAM includes:

- Definition of the "baseline mission" at UML-4.
- The CNS product architecture (starting with a technology-independent solution – see Figure 2-3).
- Feasibility assessment of the UAM operating environment, given the implementation and integration of viable CNS technology alternatives.
- Identification of the operational requirements needing validation; validation relates back to the ConOps where the intended operating environment is defined – ultimately, UAM will need to be tested under realistic conditions in order to validate that both the vehicles and the entire system accomplish the intended purpose, i.e., safely moving passengers from point A to point B with the demonstrated time savings and other conveniences as expected by the customer community.
- Hardware and software certification requirements that flow down to the specific technologies.
- Identification of advanced development required to ensure availability of the selected technologies for the UML-4 timeframe.
- A strategy for managing technical risks.

A gap exists between the maturity of UAM vehicles and the development of the system in which UAM vehicles are expected to operate, analogous to the development of the automobile. The first carriage-sized automobile suitable for use on existing wagon roads in the U.S. was a steam-powered vehicle invented in 1871. In its infancy, driving on America's roads was chaotic – as there had never been a need to establish rights-of-way. The first automobiles had to co-exist with pedestrians, bicycles, horses, and streetcars. After the Ford Motor Company started mass producing its Model T in 1908, it was clear that a system of regulations was necessary to manage the orderly flow of traffic and reduce the likelihood of accidents. The world's first electric traffic signal would be installed in 1914. Technology that improved safety and provided information about the driver's intent would not be added to vehicles for several more decades. Brake lights were required by 11 states starting in 1928. Turn signals were introduced by vehicle manufacturers in 1939, but not actually required by law until much later. Analogous to the automobile development, UAM vehicles have progressed into the hardware and software intensive phases of design, fabrication, assembly, integration, test, and even certification. The challenge for UAM is that vehicles are being designed in the absence of a UAM traffic management system. In essence, we are designing the vehicles before we have roads and rules-of-the-road. Without the transportation system in place, we are under-informing the UAM design and development community, thus pre-ordaining a future UAM fleet with mixed equipage and capabilities, especially as we look ahead to UML-4.

2.4.1.2 System Standards

The need for standards, typically a government role, are so indicated because of the relative immaturity of the UAM system. These roles fall in the area of technical management of a viable UAM system and include:

- Requirements Management - in many cases, current FAA airworthiness regulations (e.g., Parts 23, 27) and operational regulations (e.g., Parts 91, 135) are also valid for UAM, but will require some adjustments to accommodate the new and novel UAM design and operation.

Recommendation: Develop as quickly as practicable, to the maximum extent possible, standards and guidelines necessary to provide for more efficient vehicle development. NASA is well positioned to provide system technical management.

- Interface Management - describing how the CNS technologies successfully "connect" to other vehicle subsystems, to the ground infrastructure, and with other UAM and non-UAM vehicles; and
- Technical Risk Management – who within the public sphere is responsible for ensuring the safe implementation of UAM vehicles into a workable and orderly system, especially given that the vehicle concepts and technologies will inevitably vary from manufacturer to manufacturer.

2.4.2 Systems Engineering in Practice

Lessons learned and best practices from the development and implementation of complex systems in the NAS, and particularly NextGen, can be applied to UAM. Two large civil FAA programs, particularly relevant because of their CNS implications, are ADS-B[18] and DataComm[19]. ADS-B is the cornerstone of NextGen implementation and DataComm is a key enabling technology. These NextGen capabilities have been successfully fielded, but not without challenges and delays.

2.4.2.1 Lessons Learned

In the avionics area generally, and CNS technologies specifically, the key to successfully fielding systems and technologies is to ascertain what industry is willing to invest in, and why, and by when. There are examples of government, and specifically FAA, initiatives that have failed to achieve industry adoption because industry already had a different and workable solution. For example:

- The microwave landing system (MLS) - an all-weather, radio assisted landing system that, while technically superior to ILS, did not offer sufficiently greater capabilities to justify adding MLS receivers to U.S. aircraft equipage.
- For both ADS-B and for DataComm, the FAA utilized lessons learned for implementation
  - They could incentivize equipage by the operators by investing first in the appropriate ground infrastructure and system.
  - DataComm doesn't require all vehicles to be best equipped - but service providers will require that some minimum percentage of aircraft are; otherwise procedures aren't used often enough for the service provider to be efficient.
  - Similar challenges exist for the implementation of Required Navigation Performance - Authorization Required (RNP-AR) approach segments. If only a small segment of the aircraft can fly those procedures, it does not make sense to rearrange the traffic flow so that those few aircraft which are equipped can fully utilize RNP capabilities.
  - Best equipped operators can be incentivized with services not available to less-equipped operators; this can be a powerful incentive to equip.

UAM presents a clean slate. Once an operational system is in place, it will quickly involve multiple vehicle types that will be equipped differently – known as mixed equipage. This will drive the provider of air navigation and traffic management services to use existing solutions and technologies. The UAM system should instead be prepared to be adaptable and expandable. In addition, and for a given geographical location, the issue of mixed equipage can be expected to be managed by the operators in that they want

[18] *https://www.faa.gov/nextgen/programs/adsb/; March 10, 2020 6:20:32 PM EDT*
[19] *https://www.faa.gov/nextgen/programs/datacomm/; December 13, 2017 11:08:06 PM EST*

their fleet of aircraft to be consistent in terms of maintenance, flight training, and parts replacements. That is why it is common, in the large civil transport part of the industry, for an airline contract with Boeing to specify the engine (P&W, GE, Rolls Royce) and often the avionics suite, e.g., a Collins transponder versus a Honeywell transponder - to maintain fleet commonality.

- A key to advancement is to be mindful that the UAM community will not converge on its own. UAM is currently being advanced by multiple actors, in multiple locations.
- Without a common architecture and a common integration plan at the national level, the U.S. could end up with architectures that are configured differently in every city or metropolitan area. This outcome would stunt the business growth in this industry.

2.4.2.2 Best Practices

UAM industry is building vehicles for the current NAS architecture; however new CNS solutions, different separation procedures, and simplified vehicle operations (SVO), or pilotless flight will require new NAS architecture solutions. To plan for this growth, NASA should work toward architectures and solutions that prioritize ease of making changes, such as:

- Plan for software upgrades through a secure data link ("over the air") and not through swapping out hardware boxes, thus ensuring no disruption to air vehicle availability for software upgrades. Implement over-the-air or loadable software capabilities – avoid taking a vehicle out of service for prolonged periods for the purpose of making software upgrades.
- Plan for upgradability of components in integrated units from their inception, to better position the industry for growth.
- Avoid retrofits, as the implementation ripples through many subsystems and the implications may or may not be caught prior to fielding. Some implications may exist in training systems, in details as minute but important as the speed of the ARINC buses inside a flight simulator; if they are out of sync with the field units, pilots cannot be trained on a flight upgrade to the cockpit.
- Be mindful of data corruption, cybersecurity, and verification processes/requirements. If you didn't test it, don't assume it will work as planned.

> **Recommendation: Plan to do software upgrades through a data link, and not through swapping out hardware boxes.**

- Plan for scenarios that have not yet been imagined, by increasing the robustness of avionics systems through user and penetration testing as much as possible.
- Ground and avionics software should match - you cannot enable a procedure for which an air crew or air vehicle is neither enabled nor trained. Otherwise you run the risk of a ground instruction asking the flight pilot to perform an action they cannot perform, due to equipment.

> **Recommendation: Do not focus solely with the on-the-vehicle technologies – ground-based technologies may offer operational and SWaP advantages. Air and Ground work in concert and shortages in one create requirements in the other domain.**

- For cooperative systems, since there is a regulator, but not a system manager, a service provider (trusted agent) of some kind must be the keeper of the system configuration for every vehicle operating in the system. This helps to identify mixed equipage and is necessary to keep avionics and ground equipment synchronized.
- Standards are inadequate for managing mixed fleet configurations of the industry, and should not be used as substitutes to attempt to do so. At UML-4, some of the UAM fleet of vehicles will be equipped as needed, other older vehicles that are not equipped for UML-4 type operations will need to be accommodated through

> **Recommendation: Using standards to attempt to manage mixed fleet configurations in industry will be inadequate.**

procedural workarounds. Knowing which vehicles are equipped to the UML-4 performance standards, along with vehicles that are not, is tantamount. In practice, a trusted agent is a superior method for dealing with mixed fleet equipage and differing aircraft capabilities in a performance-based airspace.

2.4.2.3 SWAP Opportunities Identified

We examined the moves by the UAS industry to combine avionics in small packages. The lessons learned here may be applicable to UAM. Size, weight, and power (SWaP) allowances will be a concern to the UAM vehicle manufacturer as they design for gross weight goals/useful load budgets, but it will likely fall to the avionics manufacturer to make CNS-related size, weight, and power trade-offs. The necessity for redundant equipment to ensure safety of critical functions will make opportunities for SWaP reductions even more of an imperative.

As avionics have evolved to their current state, advantage has already been taken of microelectronics and IMA so that radios supporting all CNS functions and navigation processors are much smaller and an order of magnitude lighter than their earlier counterparts and can cut in half the part numbers of processor units, at least for large civil transport aircraft. An array of round dial instruments, each completely separate in function, has been replaced with a single touch screen display integrating the human-machine interface of all functions. The weight that used to be in multiple displays and control heads used by pilots for tuning radios and weather radar, setting transponder codes, and programming the navigation system to follow an intended path has been reduced accordingly. The radios themselves used to be so bulky and heavy that they were remotely located in the radio rack, away from the control heads used by the pilot. Microelectronics has shrunk the radios so that an ADS-B Out radio now fits within a wingtip or tail mounted navigation light and is powered by the same wire, and protected by the same circuit breaker, as the original light. The new navigation light is also contained in the same housing and is brighter than the original.

In unpiloted vehicles, the human machine interface display and control unit itself can be removed as the last major contributor to weight and power draw, since there is no human onboard with whom to interface. Vehicles designed for SVO would still have a display for vehicle status and simplified control inputs, but it would be smaller, lighter, and draw less power than existing multi-function displays because it would support fewer functions. As an added advantage, this complete suite of integrated avionics equipment would likely be covered under the vehicle's type design, especially if integrated with fight management under SVO.

Multi-function display (MFD) integrates the display of avionics information onto a single screen. In the light sport aircraft category, if multiple functions are integrated into one radio, the loss of that radio could causes the loss all the functions that are integrated with that radio. For UAM applications, if you adopt this concept, then the MFD will be required to use redundant independent sensors, not two MFDs integrated to one sensor.[20]

Were such an application to be used in UAM, the DO-178C (Software Considerations in Airborne Systems and Equipment Certification) software design assurance level for the equipment would be established at the beginning of the certification effort, but would likely be at least Level C, or higher.

There are SWaP implications and considerations to be mindful of when trying to draw conclusions from what is happening in the sUAS community. While on some sUAS vehicles, the communication, navigation, and processor are all on one 1" x 1" board, the sUAS operates with a pilot-in-the-loop and in a non-precision

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[20] An example is the Dynon HDX MFD. This MFD has a 10" screen with 3" x 3" circuit card box with all digital inputs. It incorporates sensors and communication in one box. Additional services such as flight vector can also be displayed. Features of the system include: can be used in certain Part 135 operations, discriminated by aircraft type as it was configured initially for flaps, engines, etc.; certification requirements depend largely on flight criticality; includes ADS-B In/Out with alerting and ADS-B Traffic Awareness System (from RTCA SC-186), which does not alert in the pattern.

environment, relative to UAM. This will dictate different SWaP opportunities for UAM. Also, sUAS is currently testing the move from Remote Pilot in Command (RPIC)) operations to that of remote monitoring. This will require a surveilled pre-planned flight route executed by autopilot with pre-determined emergency landing opportunities. This pre-planned flight, as executed by an autopilot, is not really autonomy. We might anticipate UAM pilotage developing similarly, given that for UML-1, that UAM vehicles will be piloted. Lastly, UAM will have higher safety requirements, requiring redundancy and precision, and communications or DataComm transmission speed. These more stringent requirements dictate separate equipment for redundancy. Cross-sensor comparisons, for example, for voting on a navigational solution, may inspire a different architecture than the civil transport standard of three independent navigation solutions on three circuit boards.

2.4.3 Integrated UAM CNS Architecture

A key feature of the CNS architecture is the identification of the avionics/instrumentation on the vehicle and what is on the ground. Ground-based technologies that perform CNS functions can help to realize important size, weight, and power savings on the vehicle. However, requiring vehicles to operate as a federated system will require the cooperation of the manufacturers and operators, and will require public or private investment, or some combination thereof. To best serve the nascent UAM industry, a consensus ConOps will be key to writing requirements for CNS. There are lessons that can be learned from the recent past, during which time the aviation industry has implemented optimized avionics installations. Occasionally, there can be a mismatch between technology maturation and aviation specific performance specifications and design guidelines. When this happens, there can be misunderstandings and missed opportunities between regulators and the industry. This is a concern for UAM, where many of the vehicle manufacturers do not come from traditional aviation backgrounds. A built-in advantage for the UAM industry is that it is an entirely new concept. As such, the UAM industry is well positioned to implement design solutions that might facilitate a simpler process for the re-certification of the avionics system when making changes to its software and hardware.

Recommendation: Include as a key feature of the CNS architecture, the identification of the avionics/instrumentation that is on the vehicle and that which is on the ground.

Recommendation: Avoid, as best possible, mismatches between technology maturation and aviation specific performance specifications and design guidelines.

Avionics architecture for UAM needs to be forward looking - especially for capabilities such as vehicle-to-vehicle communications and situational awareness. An approach for integrated CNS architecture options for all altitudes of UAS operations, in both controlled and uncontrolled air space, is instructive for UAM, as those architecture requirements include both air-to-air and air-to-ground data exchange and communications.[21] Once the architecture is implemented, operators will resist changes or upgrades that they see as duplicative of existing capabilities, especially where they might incur costs. The consensus UAM ConOps should include the minimum avionics needed for interoperability to set this architecture. Even as more autonomous vehicles are introduced as UAM transition to UML-4, the UAM industry will live with the initially defined architecture for a long-time - through multiple vehicle lifetimes, many of which will be entered into service after the vehicles which are part of the initial operating capability. The system will operate at the level of the least capable operator, as multiple operators start to provide UAM services.

[21] *"Requirements For An Integrated UAS CNS Architecture;" Fred L. Templin, The Boeing Company, Seattle, WA, et.al.; Report No. GRC-E-DAA-TN40439; Presented at 17th Integrated Communications, Navigation and Surveillance Systems (ICNS) Conference; April 18, 2017.*

It is recommended that UAM avionics systems architecture, shown schematically in Figure 2-3, be designed to accommodate new or novel, advanced technologies, while achieving reliable, highly available, cyber secure and affordable CNS services. The architecture should allow the introduction of suitable candidate technologies for UAM air-to-air and air-to-ground data exchange for the environments and the system in which UAM vehicles will operate. These environments include urban areas where UAM vehicles may be isolated from other air vehicles, the sUAS UTM environment where, as a minimum, UAM vehicles will pass through the UTM environment, and the NextGen NAS environment. The architecture must satisfy the CNS requirements for UAM vehicles operating primarily in Class B airspace, in both controlled air space and in "excepted" corridors which will not be controlled or possibly even monitored by ATC. We envision this concept to be valid through UML-4, as the industry and public authorities will want to evaluate the efficacy of increasing autonomy in the established UAM system.

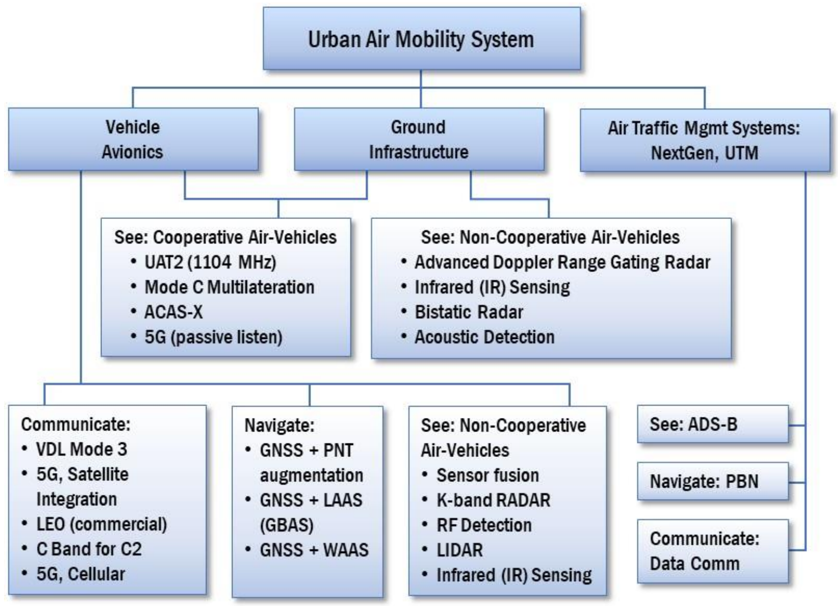

Figure 2-3. Simplified UAM Architectural Hierarchy: Avionics and CNS

The operational requirements must address evolving cybersecurity, the future of communication technologies, augmented satellite-based navigation, surveillance, and situational awareness scalable to UML-4 and beyond, and UAM operations which also anticipate interoperation with sUAS.

CNS integration, consolidation, and miniaturization requirements are important to support UAM deployment as the air vehicle and avionics manufacturers will face strict size, weight and power (SWaP) constraints.

2.4.4 The Advantages and Disadvantages of Integrated Modular Avionics as Part of the Integrated Architecture

In researching integrated CNS architectures, we conclude that it is inconceivable that UAM would utilize a traditional federated system of avionics instead of IMA. Our findings and conclusions about IMA follow.

IMA modularity simplifies installation since the IMA backplane and bus eliminates the need for individual wiring runs to the traditional federated components. With IMA, the cabinet and its installed software functional boards are certified as meeting environmental requirements as it eliminates the need to test individual components separately. It simplifies the development process of avionics software, as the structure of the modules network is unified. A common application programming interface is used to access the hardware and network resources, thus simplifying the hardware and software integration. The downside of IMA is that as complexity is added to the systems, novel verification approaches are required since applications with different criticality levels share hardware and software resources such as the central processing unit and network schedules, memory, and inputs and outputs. Partitioning is used to help segregate mixed criticality applications and thus ease the verification process. Since IMA is part of the type-design certification, the functional hazard assessment (FHA) and system safety assessment will establish the required level of testing rigor. These assessments define testing required to show that the IMA is transmitting the correct data and answers through the bus, thus demonstrating rule compliance (e.g., 14 CFR §23.1309) to the Aircraft Certification Office (ACO) during the certification process.

The software part of a flight critical system, such as the FMS, is type certified with an aircraft.[22] After introduction, newer procedures or technologies or capabilities may become available. In most cases, FMS software is written for the as-is airspace, without imagining the need for a new procedure, and so the extant technology (here the FMS) cannot perform the new procedure with a software patch or rewrite. However, because the code is part of the type certification, manufacturers are hesitant to add functions, or "open-the-box," since it will require documentation, testing and recertification of the software change by the ACO.

The tight coupling of avionics to the flight management systems to the automated flight and guidance systems under SVO, and especially so for fully automated vehicles, lead us to the conclusion that UAM will employ IMA. The ability of the vehicle manufacturer to demonstrate compliance using FHA will be key to upgradeability. This will require complex software design tools and thorough automated test suites. An unforeseen consequence of more highly capable cockpits has been that some training simulators also require hardware upgrades to match vehicle performance in computational speed. For SVO to work, UAM vehicles will be sensor intensive. The likelihood of re-locating sensors is high during the vehicles in-service lifetime. Vehicle manufacturers need to be mindful of hardwire location and ability to "rewire." The software must be capable of handling sensor data from a different location, than in the original vehicle design. Terminated wiring runs (inert runs) placed in advance as "provisions only" for future use can be identified and documented in the type design for future use, saving work later.

2.5 Research Challenges and Questions

2.5.1 Challenges

It is vital to characterize the nature of past missteps in avionics specification and/or misuse of guidelines. Adopting systems engineering best practices and rigorous systems engineering approaches will not suffice to meet certain challenges associated with UAM avionics and CNS technologies specifically. The industry will face decisions whether to field vehicles with technologies that are commercially available, and have been previously certified in other air vehicles, or whether to certify vehicles with new technologies that have not yet been approved for aviation. UAM entrants are entering a market using existing avionics and existing air traffic systems. This current suite of avionics, and the air traffic system, will not suffice for the density of operations forecast for UML-4. At some point between now and UML-4, new systems will be certified and sold for the UML-4 marketplace. This assures that by the time of UML-4, UAM will be dealing with significant mixed equipage issues.

> **Challenge: This current suite of avionics, and the existing air traffic system, will not suffice for the density of operations forecast for UML-4.**

[22] *The IMA cabinet hosts software enabled boards, many of which host TSO compliant functions. However functions specific to the vehicle, like flight guidance, are likely to be Type Certificated with the aircraft. In the end, both are included in the type design data.*

Another challenge for UAM manufacturers and the regulatory authority will be the proclivity for the UAM community to seek COTS solutions. Commercially available technology solutions often have product life cycles far shorter than certified avionics life cycles, thus creating a mismatch in expectations, if not also performance. COTS software updates are also more rapidly paced - quickly creating a mismatch in COTS products, performance, and user experience in even a small fleet. In most cases, COTS parts are not utilized to support critical functions, but can be used in not-critical-to-flight-safety applications, such as passenger communications. Mainly, this is the COTS manufacturer resisting coming under FAA manufacturing quality control that freezes the part design. Doing so takes away the COTS manufacturer's flexibility to do changes for what is usually a much larger customer base than a relatively few aviation customers. Updates to certified aircraft performance software, or to IMA, may require additional related activity such as an evaluation by the FAA Aircraft Evaluation Division, change to the FAA approved Flight Manual and/or Maintenance Manuals, changes to the crewmember training program, and Standard Operating Procedures. For a 14 CFR part 135 operation, these changes may be required to be accomplished in parallel, and prior to in-service use.

Challenge: COTS parts cannot be utilized to support critical functions, even as COTS manufacturers resist coming under FAA manufacturing quality control that by necessity freezes the part design.

Electromagnetic interference in urban settings from sources such as concrete and rebar in buildings are known causes of errors in magnetic headings in the sUAS vehicles. Signal interference is both attendant on this operating environment and new in its severity compared to traditional aviation. Interference alone requires rethinking of CNS procedures, which will cause experienced avionics manufacturers to fundamentally rethink their accepted design principles.

In addition, eVTOL vehicles will face the imposition of large magnetic fields generated by the electric motor operation, and this will create new challenges for shielding the electric generation from avionics in the vehicle and sensors possibly on the skin of the vehicle. The FAA is likely to write new requirements to address high intensity radiated fields (HIRF), including static discharge and lightning immunity.

There are cybersecurity related risks for UAM vehicle CNS avionics systems and components. Transmitting traffic information over UAT2 to a ground monitor may require additional security. Existing ADS-B signals are not secure in that they do not have end-to-end encryption and can be hacked and spoofed. Since the operators may opt to rely on automatic terminal information service (ATIS), security is important. The industry may strongly desire an encrypted data link for situational awareness and data.

Challenge: UAMs unique operating environment coupled with the high degree of autonomy will require low weight and power engineering solutions to electromagnetic interference, communication of traffic information, and interoperability with the existing NAS.

Interoperability with ATC will be required for access to traditional airspace. The weight penalty associated with requiring two, possibly non-overlapping communications and navigation capabilities (such as under Part 135 requirements), will have to be paid. The operator may also have to consider voluntary equipment redundancy, especially if it impacts the ability to dispatch.

2.5.2 Research Questions

In investigating good principles for advanced avionics integration, we raise several research questions for developers and designers to consider.

2.5.2.1 When does the co-location of electronics pay off in speed without the downside of limiting upgradeability?

> **Recommendation:** Visualize the Flight Management System of the future – ask yourself what will be useful in 10 years?

UAM will be best served by visualizing the FMS system that would be useful in 10 years. Design in extensions to processor capabilities so that you can input data, even though you don't know what that data is today. Attributes of the system that are likely to change include sensor technology including type of sensor and location on the aircraft, increasingly autonomous pilotage, cityscape navigational features, separation standards, and separation approaches. Software should be coded to be upgradable and should be hardware agnostic, for example, communications channel agnostic and navigation sensor agnostic through modular design. Hardware should include excess memory, for example, using quad processors, even if only two processors are currently required. While this requires positively ensuring that the two unused processors are "turned off," this accommodation for future greater required capability and capacity will be beneficial over the long term.

> **Recommendation:** Overdesign the FMS processor capabilities – allow for the flexibility to input data for future systems, even though you don't know what that data is today.

> **Recommendation:** As UAM matures, sensor technologies, including type of sensor, locations on the aircraft, increasingly autonomous pilotage, cityscapes, separation standards, or separation approaches, will all change. Software should be written accordingly.

If we were to flip the question, meaning, "would technologies of non-similar maturity work for UAM?," the answer is no, in light of aviation's FMS experience. One such example was the aviation industry's integration of GPS with the FMS. However, this first iteration was not WAAS capable – an example of where non-similar technologies proved to be a hasty and untimely investment. So how can the UAM industry avoid integrating technologies that prove to be short-timed? First, as discussed previously, UAM being a "clean slate," simplifies the adoption and application of non-traditional CNS technologies; so long as there is a roadmap that makes a commitment to non-traditional technologies clear and less risky. Second, adding excess capacity to account for future and greater data storage or processing speeds is a continuous process that is well understood by the avionics manufacturers. Standards are not the answer as by definition, they cannot address software updates. Ultimately, it is the responsibility of the operator to ensure that databases are current – however they do require that the avionics manufacturer has appropriately accounted for future growth.

In interviews conducted with avionics manufacturers, they noted that the duration and difficulty of certifying avionics is related to the complexity of the avionics. This makes it difficult to commit to new technologies such as ultra-wide band, spectrum re-use, and nondeterministic software.

2.5.2.2 How does something like positioning error point to the necessity of a ConOps and a well-define UAM Traffic Management System?

> **Recommendation:** The need for precise position awareness and corresponding flight management is greater than exists in aviation today and will be a certification challenge for the manufacturers and regulators. The timely definition of the UAM airspace design and a concept of operations are critical to meeting this challenge.

Avionics manufacturers use rules of thumb derived from existing NAS procedures and certifiable engineering practices. For example, for accumulated positioning errors, building positioning precision to a level above what the autopilot/flight control can do is considered wasted effort. However, UAM requires greater traffic density and will use automated or autonomous flight, requiring a new way of thinking for highly precise positioning. Separation assurance, which is currently set at three miles in controlled airspace, will not work in a dense urban environment. The lesser separation requirements for UAM will require higher update rates. The accuracy and performance for navigation in an urban environment and the accuracy and performance for detect and avoid systems in an urban environment are key parameters. They are required to get to a design architecture, which in turn will promote the development of avionics. Knowing the navigation accuracy and performance capabilities of sUAS may make the requirements for UAM be less onerous, assuming some level of interoperability. All of this points to the need for the UAM airspace design and ConOps.

With the demand placed on the avionics by increasing levels of autonomy, the avionics complexity will need to be managed. Several tools are available to assist in managing this complexity, including model-based systems engineering[23] and structured interface control[24].

2.5.2.3 What is the ease of adjusting data versus "opening the box?"

Data integration with a common processor must be weighed against the ability to do data, software, and hardware updates. Most avionics manufacturers allow you to make software changes on the airplane. The real issue is the cost of touching software after getting the approved data. In aviation's experience with Flight Management Systems (FMS), co-location of navigational databases led to lesser-equipped fleets when procedures and navaids expanded. An operator was faced with the choice of less agile flight routes or a costly upgrade, because the database was part of the certified software of the system. In time, FMS systems that rely on databases updatable by a trusted partner evolved. UAM avionics and navigational design must embrace the likelihood that such redesigns will be found everywhere (particularly in the four fields we name here[25]) as the ecosystem progresses from UML-2 to UML-4, and then again to UML-6. These redesigns will be driven by sensor independence – including hardware upgrades or different hardware types; sensor placement on the aircraft changing; changes in CNS coding; reduced separation; reduced reliance on pilots; and changes in the urban destination landscape.

2.6 Recommendations

This review of integration practices has led to recommendations based on best practices and lessons learned - these are embedded throughout the text. In addition, for integration issues in UAM at UML-4, specific novel recommendations appear below. These recommendations, with those from other chapters, are consolidated in Chapter 5.

2.6.1 Recommendation: Software Maturity Capability

The complexity of SVO operations and the modular design processors and code will drive sensor operation. The sensor data that is integrated with the flight management computers and the auto-pilot / auto-emergency software modules will be more complex than the software designs of today's airline cockpits. Over time, and by UML-4, the software modules will become even more complex as UAM transitions to autonomy of flight. The FAA of today is ill-suited to lead this revolutionary change. This points to the need for industry consensus working group standards on modular design and software design, code, and implementation maturity for the writing and maintenance of these codes. A consensus standard should include a maturity model for the requisite software capabilities. The FAA can then lean on these bodies for standards and guidelines for software validation, and to help facilitate the certification process. If industry standards and guidance already exists, then the applicant doesn't have to wait on an FAA developed means of compliance (MoC).

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[23] *Model Based Systems Engineering, 1st Edition, A. Wayne Wymore, CRC Press, 1993*

[24] *Systems Engineering Interfaces: A Model Based Approach; Elyse Fosse, ,Christopher L. Delp, Jet Propulsion Laboratory, California Institute of Technology; IEEE 978-1-4577-0557-1, 2012*

[25] *Sensor independence, with hardware upgrades or different hardware types, different sensor placing on the aircraft, and changes in CNS coding; reduced separation, reduced reliance on pilots, and changes in the urban destination landscape.*

2.6.2 Recommendation: An Avionics Test Suite

For the Boeing 787, Boeing, with assistance from its prime avionics suppliers, GE Aviation and Collins Aerospace, built a laboratory test suite, or "iron bird" to test the aircraft's proposed IMA architecture. In so doing, they were able to work out issues before flight, including the identification of coding errors and common mode fault vulnerability.

- The first UAM vehicle manufacturer will encounter the heavy lift associated with proving the function of the unit under all circumstances, including common mode fault vulnerabilities – this will likely drive the early participants to propose the creation of an industry standard to lighten their test load.
- There will be a need to build a prescriptive standard for manufacturers if the market is too small to support a return on investment required to justify building "iron bird" test sets for every vehicle. Boeing and its avionics suppliers were willing to make the investment because the business case was based on sufficient projected sales.
- Government, or a public-private partnership, could make such an investment in development of standards for an avionics test suite. This would promote standardization and lower cost.

2.6.3 Recommendation: A Simulated City Environment

The ability to perform simulations, including flight testing, will likely be required by the regulators, service providers, and municipalities/port authorities to assure that novel CNS technologies for UAM applications will have the required performance to meet safety-of-flight functions and regulations. A simulation could be used to test the navigation sensors' performance and capabilities, primarily, but not exclusively, to determine if the UAM vehicles can safely land under nominal and emergency conditions. It could also be used to test the required positional accuracy standards for sufficiency as well. The simulation would start with numerical models and could proceed to a combination of numerical and physical testing. A physical testing area available for use over multiple generations of UAM Maturity Levels – conceivably from UML-1 to UML-6 - would be most useful. Some useful examples of what has been done previously in the transportation sector are noted below.

- The FAA contracted to JHU-APL to accomplish simulation studies on minimum power levels at the antenna (for various classes of UAT equipment) and probability of reception (to ground and air-to-air), to support development of the UAT MOPS, RTCA DO-282B (See DO-282B Appendix K[26]).
- NASA has done UAV flight demos in 2019 in Reno, NV, and in Corpus Christi, TX, where in a simulated environment, they tested the robustness of communication and navigation off-nominal contingency management.[27]
- The Department of Transportation and the University of Michigan constructed MCity[28] as a proving ground for testing the performance and safety of connected and automated vehicles and technologies under controlled and realistic conditions.
- UAS test sites have limited cityscapes for UAS testing and drone racing grounds with vacant structures in various spots around the country should be considered, rather than starting from scratch.

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[26] *Technical Standard Order-C154c: Universal Access Transceiver (UAT) Automatic Dependent Surveillance-Broadcast (ADS-B) Equipment Operating on Frequency of 978 MHz; Federal Aviation Administration; 12/02/09*

[27] *"Automated Management of Small Unmanned Aircraft System Communications and Navigation Contingency;" Jaewoo Jung and Sreeja Nag; AIAA 2020-2195; AIAA Scitech 2020 Forum; 6-10 January 2020*

[28] *https://mcity.umich.edu/our-work/mcity-test-facility/; 2020*

CHAPTER THREE

3.0 AVIONICS CERTIFICATION, STANDARDS, AND PROCESSES

This section discusses recommendations, guidelines, and standards for UAM CNS avionics hardware and software design, certification, and maintenance.

3.1 Overview of FAA Type Certification Process

The following step-by-step discussion is based on Figure 3-1, which is greatly simplified. There are many "little" items that require coordination with policy groups, other ACOs, etc.; however, it hits the high points of a typical type certification process, and each step may go through various iterations (for a more detailed understanding of the certification process, the reader should review FAA Order 8110-4C). The assumption is that the application vehicle is a small, fixed wing and rotorcraft hybrid UAM vehicle certified under Title 14 of the Code of Federal Regulations (14 CFR) Parts 23/27.

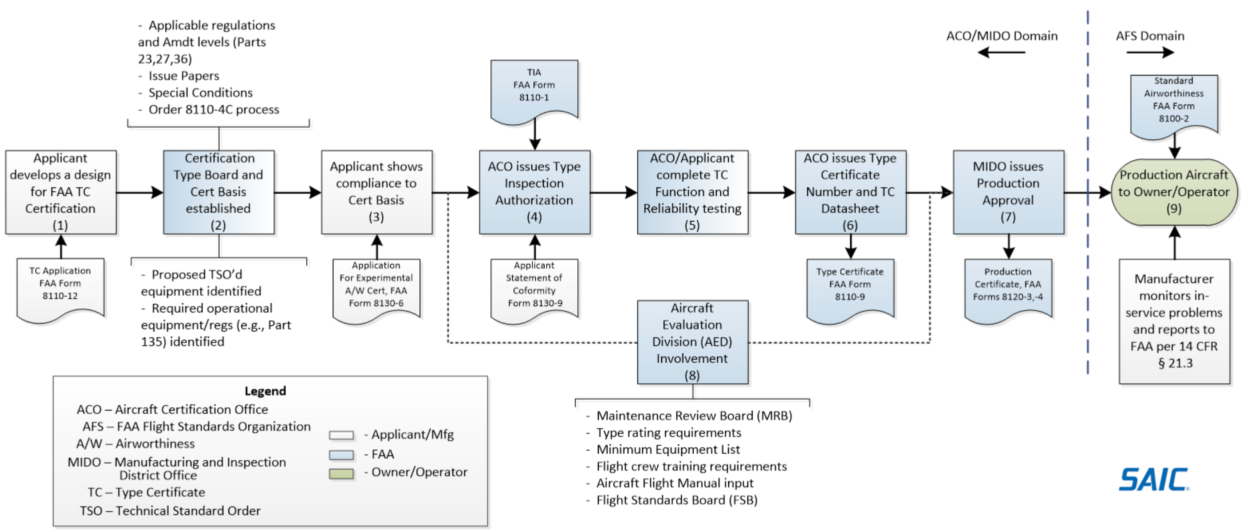

Figure 3-1. Overview of FAA Type Certification Process

Step 1: The manufacturer makes application to the geographical ACO using FAA Form 8110-12. The application usually accompanies a 3-view drawing, the vehicles' velocity/load (V-n) diagram, and a detailed explanation of the design/systems/operation of the intended vehicle. In support of Step 3, the applicant will develop a Preliminary Hazards Assessment (PAH) to identify those functions on the vehicle whose failure would/could lead to major (10^{-5}), hazardous (10^{-7}), or catastrophic (10^{-9}) results[29].

Step 2: Based on the application information submitted in Step 1, the ACO, working with the applicant (which is why the block is shaded blue/white), will start to develop the certification basis on which the applicant will need to show compliance. The MIDO (Manufacturing and Inspection District Office) will concentrate on conformity inspections (usually a "rolling" or "incremental" conformity approach), and an evaluation of the applicant's quality system to establish an aircraft/vehicle production approval (Step 7). In addition to identifying the appropriate portions of 14 CFR Parts 23 (small airplanes), 27 (small rotorcraft)

[29] *Note that it is the loss of the function that is evaluated, and that a function, such as attitude, may be supported by one or more systems depending on its analyzed criticality. Functions whose failures are considered hazardous or catastrophic will typically need multiple or redundant paths.*

and 36 (noise), various Issue Papers (IP) will be established. For a type certification project, it will begin with a G-1 (General) IP, which will define the certification basis to the applicant. It is likely that there will also be a P-1 (Propulsion) IP to identify MoC with electric propulsion, an S-1 (Systems) MoC IP, and an A-1 (Airframe) MoC IP. Due to the new and novel nature of the UAM vehicle, there will likely be Special Condition (SC) Issue Papers applied to address areas where existing regulations are not adequate to define airworthiness requirements. It is expected, that at a minimum, there will be SC IPs established for: the battery technology (assuming Lithium Ion), the electric propulsion, the stability and guidance system, and perhaps cybersecurity. All Special Conditions must be published in the Federal Register for public comment, and become part of the final certification basis as documented in the vehicles' TC datasheet. FAA Order 8110-4C defines the certification processes that the ACO/MIDO must follow. At this time, the applicant will list TSO'd equipment and any Parts Manufacturer Approval (PMA) parts which will be incorporated into the vehicle's design. For a Part 23 aircraft, the certification basis is frozen (don't have to chase new/revised regulations) for three years, for a Part 25 aircraft, it's five years. The ACO will establish a TC Board and have meetings with the applicant and may convene throughout the certification process; however, at minimum, there will be an initial, pre-TIA, and final review TC Board meetings prior to type certificate issuance.

Step 3: The applicant now starts to show compliance with the certification basis that was established. This can be done in numerous ways such as by drawing (e.g., a box must be "international orange" and the drawing notes "paint international orange"), by analysis (safety assessment, loads analysis, etc.), or by physical testing (bench, ground, or flight testing). A TC applicant will typically use FAA Designated Engineering Representatives (DER) to make compliance findings using the FAA Form 8110-3. The applicant usually applies to the ACO/MIDO for a special airworthiness certificate (FAA form 8130-6) to "show compliance" to accomplish applicant-required flight testing to substantiate compliance to the regulations prior to final showing to the FAA. Conformity inspections are accomplished incrementally throughout this testing period, usually using the services of a Designated Manufacturing Inspection Representative (DMIR), via an FAA Form 8130-9.

Step 4: By this time the applicant has cleared the flight envelope and has documented compliance to much of the certification basis requirements, and is now ready to do final ACO-witnessed compliance testing. The ACO will develop a Type Inspection Authorization (TIA) that has two parts. Part 1 is the conformity inspection to the declared design configuration (the applicant declares this in the Form 8130-9, Statement of Conformity, that the MIDO collects), and ensures the aircraft is in a safe configuration for flight testing. Part 2 of the TIA lists the FAA approved ground and flight test plans that need to be accomplished. Problems detected during testing are corrected, the vehicle is re-conformed, and retesting accomplished. Successful completion is documented in the Type Inspection Report (TIR).

Step 5: For a new small aircraft Type Certification, the FAA (per 14 CFR § 21.35) requires approximately 150 hours of flight testing to exercise various systems to ensure that they perform as expected (i.e., to surface any early operational issues), and that flight manual procedures are adequately defined. This is known as function and reliability (F&R) testing. All issues that may arise are corrected and configuration control adjusted.

Step 6: Assuming all certification and F&R testing are successfully completed, the ACO issues the formal Type Certificate (FAA Form 8110-9) to the applicant, publishes the TC datasheet, and approves the vehicle's Flight Manual. It should be noted that an applicant can apply for a class I provisional type certificate (prior to full TC issuance) in accordance with 14 CFR 21.81 for restricted early uses per 14 CFR 91.317 (e.g., demonstration flights, marketing, flight crew training, etc.).

Step 7: Although the FAA may provide inspection responsibilities for initial vehicle production, the FAA eventually wants this responsibility to be undertaken by the manufacturer under a Production Certificate. During the TC development cycle, the MIDO is working with the applicant to establish an acceptable quality system (and manual) to manufacture/inspect vehicles that conform to the approved Type design. A major aspect of the quality system is supplier control, and how the manufacturer ensures that the various tier-level suppliers provide products that comply with the approved type design. When the MIDO is satisfied (via onsite quality audit) the MIDO issues two documents: the Production Certificate (FAA Form 8120-4) and any production limitations (FAA Form 8120-3).

Step 8: Early in the Type Certification cycle, the Aircraft Evaluation Division (AED) will get involved to establish a Fight Standards Board (FSB) to evaluate appropriate maintenance requirements, and establish the Master Minimum Equipment List (MMEL) of equipment/systems that must be operational in order to dispatch A typical MMEL may show, for example, two comm radios installed, one required for dispatch (and may also list the number of days the equipment can be deferred for maintenance). The AED also helps determine the fight crew training requirements, and whether the vehicle requires a pilot to have a Type Rating (this is currently limited to turbojet aircraft, but uncertain how a future multi-fan UAM might be treated). The AED typically stays informed of the vehicle operation during the vehicle's life cycle, should operational/maintenance conditions change.

Step 9: We are now in the Flight Standards (AFS) vehicle in-service domain. At this stage, the applicant/manufacturer has a Type Certificate and Production authority to build, conform, and issue a standard airworthiness certificate (FAA Form 8100-2) for the vehicle sold to the owner/operator. For Part 135 operation, the UAM operator, upon satisfying Flight Standards requirements (in accordance with FAA Order 8900-1) would receive a certificate for Part 135 operation (FAA Form 8430-18). The geographic Flight Standards District Office (FSDO) would assign a Principal Inspector (PI) to oversee the UAM Part 135 operation. During in-service operation, the manufacturer monitors service difficulty reports for possible 14 CFR § 21.3 reporting to the ACO, which may lead to an Airworthiness Directive (AD) action. The manufacturer is expected to support required corrective action with service bulletins, as necessary.

3.1.1 FAA Type Certification for UAM Vehicle CNS Avionics

For UAM CNS avionics, the ACO will evaluate the application for type certification submitted and will start to develop the certification basis the applicant will need to show compliance. For a VTOL vehicle, the ACO will take the appropriate portions of 14 CFR Parts 23 (small airplanes), 27 (small rotorcraft) to develop various IPs. It is also likely that there will be Special Condition (SC) Issue Papers applied to address areas where existing regulations are not adequate to define airworthiness requirements. See also 3.2.6, Identified Gap 6 – Establish the Type Certification (TC) Basis.

UAM vehicle manufacturers may desire to adopt recent advancements in software development such as machine learning (ML) or AI to process sensory inputs. A review of FAA and industry activity related to ML and AI has been performed. Industry consensus standards, clear definitions and methods for safety assessment are still very early in the development process and are not expected to mature or be published for several years. FAA guidance related to nondeterministic ML or AI software certification is not yet available.

AI and ML are likely applications to enable SVOs. Amalgamation of lower level functions to stabilize the air vehicle and perform lower level navigation functions are needed under SVO.

If a UAM vehicle manufacturer were to propose nondeterministic ML or AI software to perform a CNS function, the FAA would most likely consider if a "Special Conditions Issue Paper" classification and certification process is appropriate to establish an MoC (i.e., what further analysis and safety assessment would be required). This process requires an Industry applicant with a specific, defined, application in mind.

Another emerging option to certify complex software behavior is Run Time Assurance (RTA). This approach assumes that flight control and autopilot systems, from the certification perspective, are considered capable at a lower certification standard. This would assume that, without additional testing and inspection, the autopilot software may not be compliant with all FAA certification standards at the rated criticality level. RTA concepts feature a real-time monitor and failsafe back-up system and may be a key component to enabling the certification of automated, increasingly autonomous, and highly complex systems. RTA can be defined as a structured argument supported by evidence, justifying that a system is acceptably safe and secure, not through reliance on offline tests or verification methods, but through reliance on real-time monitoring, prediction, and failsafe recovery mechanisms.[30] RTA acceptance could enable future improvement in autonomous guidance systems. However, its use in UAM guidance system development would likely lead to a Special Condition due to its new and novel concept.

3.1.2 Maintenance and Inspection Program Requirements Summary

Usually, a 14 CFR Part 135 operator is required by the FAA to maintain and inspect an aircraft with nine passenger seats or less in accordance with the manufacturer's inspection program or an AAIP (Approved Aircraft Inspection Program). This section outlines maintenance and inspection requirements for a human piloted, FAA Part 135 certificated air carrier, operating for hire a type certificated aircraft, with nine or less passenger seats, with authority to carry passengers under IFR.

The manufacturer's maintenance and inspection requirements are initially derived during the certification process as described by 14 CFR Parts 21, 23, 25, 27 or 29 as applicable, and throughout the life cycle of the aircraft. Maintenance requirements are specified to ensure that the aircraft will be maintained in a manner that conforms to its original type design or properly altered configuration (e.g, Supplemental Type Certificate, Type Certificate or Amended Type Certificate). Manufacturer maintenance and inspection program requirements are often broken down into requirements that are on a calendar basis (e.g., monthly, yearly), a per cycle basis (e.g., landings, on/off), flight time basis, overhaul or life limits (e.g., component expires at six years), or can be specified as "on condition" (e.g., remove and replace as required).

A manufacturer's inspection program (per 14 CFR part 21, § 21.50) or an AAIP will typically include the following:

- Requirements to maintain each aircraft engine, propeller, rotor, and each item of emergency equipment required by the regulations. The "manufacturer's inspection program" may contain maintenance, preventative maintenance, inspection, and repair instructions from multiple manufacturers (e.g., manufacturers of required emergency equipment, engine, propeller, propeller governor, and rotor).
- Requirements arise under Part 91 for aircraft equipment. Examples: 91.171 (VOR check), 91.207 (emergency locator transmitters), 91.213 (Minimum Equipment List), 91.225/227 (ADS-B Out equipment), 91.403 (airworthiness), 91.409 (inspections), 91.411 (Altitude system test), 91.413 (Transponder test), 91,609 (data and voice recorder), 91.613 (flame retardant interior material).
- Part 135 operating regulation requires interval-based maintenance for an aircraft under revenue service, including the equipment under Part 91. Examples: 135.185 (center of gravity calculation), 135.151 (voice recorder), 135.152 (data recorder), 135.156 (digital data filters), 135.421 (combustion engine maintenance plan), 135.411 (requirement for a maintenance plan or AAIP).
- Manufacturer Service Bulletins.
- FAA Airworthiness Directives.
- Maintenance, Preventative Maintenance, Rebuilding, and Alteration is performed in accordance with 14 CFR Part 43. Part 43 contains requirements for performing maintenance and maintenance practices, maintenance record keeping, approval for return to service, airworthiness limits, and more.

[30] *Hook, L., Clark, M., Sizoo, D., Skoog, M, Brady, J., "Certification strategies using run-time safety assurance for part 23 autopilot systems"* https://ntrs.nasa.gov/search.jsp?R=20170007254 *[Retrieved May 18, 2020]*

An aircraft operated under commercial service may be subject to requirements of 14 CFR Parts 1, 21, 23, 25, 27, 29, 43, 91, 119 and 135, as applicable. There are applicable regulations and guidelines. Key regulations include:

- 14 CFR Part 1.1, Definition of *Maintenance*, which includes inspection: 14 CFR Part 1.1, Maintenance means inspection, overhaul, repair, preservation, and the replacement of parts, but excludes preventive maintenance.
- 14 CFR Part 21.50 *Instructions for continued airworthiness and manufacturer's maintenance manuals having airworthiness limitations sections*. The manufacturer of an aircraft, aircraft engine, propeller, or rotor is required by 14 CFR part 21, § 21.50 to make available manuals or instructions that it considers essential for proper maintenance of its product.
- 14 CFR Part 91.409 establishes the requirement for frequent periodic inspections of critical flight systems and avionics, covering the items to be inspected and their periodicity, for turbojet multiengine airplanes, turbopropeller-powered multiengine airplanes, and turbine-powered rotorcraft. It also details required maintenance plan documentation and progressive inspection guidelines, and under what circumstances an aircraft may, or may not fly, if it has not met the inspection requirements.
- 14 CFR Part 119.7, *Operations Specifications*, provides for specific authorizations and limitations that may be issued to address regulatory and administrative requirements unique to *each kind* of operation and *certain other procedures under which each class and size of aircraft is to be operated*. **Operations Specifications is a regulatory administrative tool that may be amended to address the unique aspects of 14 CFR Part 135 UAM operations and maintenance requirements in the future.**
- 14 CFR Part 135.411 *Applicability*. This regulation prescribes rules for the maintenance, preventative maintenance, and alternations for each certificate holder. Variations in regulatory applicability occur for aircraft that have passenger seating configurations of nine seats or less, 10 seats or more, and single engine, and more.
- 14 CFR Part 135.421 *Additional maintenance requirements*. Requires a Part 135 nine or less passenger seat aircraft to comply with the manufacturers recommended maintenance program or a program approved by the Administrator.

The relevant guidance includes:

- FAA Order 8900.1, VOLUME 2, CHAPTER 4, Section 8 Safety Assurance System: *Evaluate a Part 135 (Nine or Less Passenger Seats) Certificate Holder/Applicant's Maintenance Requirements*.
- FAA Order 8620.2, *Applicability and Enforcement of Manufacturer's Data*.
- FAA Advisory Circular 135-7, Part 135 *Additional Maintenance Requirements for Aircraft Type Certificated for Nine or Less Passenger Seats*.
- FAA Advisory Circular 20-77, *Use of Manufacturers' Maintenance Manuals*.
- FAA Advisory Circular 135-10B, *Approved Aircraft Inspection Program*, designed by an aircraft operator to suit the aircraft's operational demands.

3.1.3 Maintenance and Inspection Program Considerations for UAM CNS

The maintenance, inspection, alteration, and repair requirements for UAM will depend largely on the certification process of the airframe, engines, or motors, props, rotors or fans, flight controls, and other critical components. Current certification processes typically reflect the type design characteristics of today's aircraft form factors, having delineations of aircraft or rotorcraft and are type certificated under Parts 23, 25, 27 or 29. Current aircraft certification processes include an assessment of manufacturer recommendations for component inspection intervals and life limits.

Many proposed UAM vehicles employ design configurations that have yet to be certified for commercial air-taxi use. These include multi-engine ducted fan, tilt-rotor, non-articulating rotors with differential power, vectored thrust, and lithium ion battery powered engines. Anticipated CNS augmentation includes high data rate connectivity and various degrees of autonomy. Some of these challenging designs are proposed by new entrant aircraft manufacturers that do not have previous experience with aircraft production. **It will take some time for maintenance program standards and practices to mature for the new and novel aspects of UAM design that have insufficient data for conclusive data analysis.**

The advancements of aircraft avionics of the last decade have created foundational CNS capability for UAM operation. Maintenance and inspection program requirements for the implementation of new technology are often managed with the issuance of a specific FAA Operations Specification (referenced by a paragraph number) to the operator. These documents may also include requirements for design, operational procedures, flight crew training and certification, and more. Mature exemplars of recent CNS advancements and implementation controls include:

- ***Controller Pilot Data Link Communications (CPDLC) and Performance Based Communication Systems (PBCS):*** Data link replacement for voice communications is now an option for authorized operators across the U.S., Europe, and other parts of the world, and on many "tracks" in Oceanic airspace. Applications of CPDLC include Departure Clearance (DCL), En Route and PBCS (Oceanic/Remote operations). Certain routes/altitudes now require CPDLC and/or PBCS capability and authorization. FAA authorization is granted per Operations Specifications paragraph A056. **Although an enhancement to communications efficiency, CPDLC is not sufficient as a means of compliance to voice communication[31] equipment requirements of 14 CFR parts 91, 121 and 135, and is not required by these rules. CPDLC functions are not yet consistently supported across the domestic U.S.**
- ***Enhanced Flight Vision Systems (EFVS):*** The use of imaging sensors such as forward-looking infrared, millimeter wave, radiometry, millimeter wave radar, low-light level image intensification, or other real-time imaging technologies to provide electronically aided vision to the pilot to meet the operational requirements of the visual segment of an instrument approach. However, EFVS regulations (14 CFR Part 91.176, 135.225) **ultimately rely on the pilot's human eyes, as at this time, sensor-only based landing is not permitted**. FAA authorization is granted per Operations Specifications paragraph C048.
- ***Standards for Performance Based Navigation (PBN) and Required Navigational Performance (RNP):*** Describes an aircraft's ability to navigate in terms of performance standards. RNP augments area navigation capability with onboard performance monitoring and alerting functions and provides high confidence that an aircraft will follow a desired path with a specified precision (i.e., procedure), enabling instrument procedures with smaller protected airspace requirements, complex curved paths, and reduced traffic and obstacle separation minima. **An extension of RNP concepts for urban tolerances provides one way to achieve dense urban traffic for UAM and UAS.** FAA authorization is granted per Operations Specifications paragraph B035, B036, B054, C052, C063, C384, and C358, as applicable.
- ***Aircraft Synthetic Vision Systems (SVS):*** Synthetic vision is a computer-generated image of the external scene topography from the perspective of the flight deck, derived from aircraft attitude, high-precision navigation solution, and database of terrain, obstacles, and relevant cultural features. **At this time, "operational credit" has not been approved for certified systems; however, in time, these systems may play an important role in the future of UAM CNS when combined with an array of other sensor capabilities.**

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[31] FAA AC 90-117, Data Link Communications

Relevant to UAM CNS certification and related maintenance requirements, we can estimate certain conclusions from the progress of the avionics advancements cited above:

- The development and implementation of new technology certification standards, operational and maintenance guidelines, and practices is years and sometimes decades in the making. In particular**, the use of the cellular network or other spectrum not assigned for aviation use for critical communications may present particularly challenging issues for certification**.
- The criticality and redundancy of an avionics component function is assessed at aircraft certification as part of an overall systems safety risk assessment. Maintenance, maintenance deferral procedures, inspection requirements, and life limits are derived from this process. Individual avionics components are often "on-condition" as the electronics perform operational checks upon power up or upon selection of "test" modes. This may be supplemented by system checks to determine that overall system performance meets its intended function and specifications. The certification process also establishes specifications for redundancy and the components that must remain operative (maintenance deferral restrictions). **Thus, COTS-based technologies not previously developed for avionics may require redesign as the result of hazard classification assessment at certification. This may drive test mode, health monitoring, alerting, event recording, maintenance or inspection intervals, or system level check features.**
- Increased automation is often accompanied by other system requirements intended to manage risk. For example, at CPDLC implementation, the pilot's voice could no longer be recorded by the cockpit voice recorder (CVR), so new requirements for the recording of CPDLC data-link messages became required per 135.151. At the implementation of advanced RNP operations, the Flight Management System navigation database must be demonstrated to higher accuracy and quality standards, along with strict configuration control procedures. **Automation levels associated with pilotless flight can be expected to have similar higher requirements established at certification to manage risk;** additional redundancies in equipment will be required, with maintenance checks on any redundancy or failover modes.

Provided that the FAA and industry stakeholders continue to refine and mature aircraft certification methods, requirements and standards for new or novel designs and functions, related requirements and practices for aircraft maintenance, inspection, repair, and alteration are largely a subset of that process.

3.1.4 FAA Current Acceptance of Identified Technology

The following tables (Tables 3-1, 3-2, and 3-3) are intended to identify what current acceptance status (airspace and/or certification) the FAA has with the technologies identified. The column titled "FAA Use/MPS" identifies if the technology is either used in the airspace by air traffic (e.g., VHF radio, ground navigation aids), or if the technology has an aviation industry accepted minimum performance standard (MPS) and/or an FAA TSO that recognizes an MPS. The columns titled "Installation AC" and "Operations AC" are not to infer that an installation or operations Advisory Circular (AC) is required for the technology, only that one exists. If an AC does not yet exist, "None" has been entered. It should be noted that not all equipment will have an accompanying AC for guidance on installation and testing (or operational use) of a particular TSO'd technology. An AC is typically written to provide a consistent MoC for certification applicants when the TSO'd technology is of a complex nature and subject to possible confusion on regulatory compliance during installation, certification testing, and/or use in the airspace.

Table 3-1. Standards Covering Recommended Communication Technologies

TECHNOLOGY	FAA USE/MPS	INSTALLATION AC	OPERATIONS AC	REMARKS
COMMUNICATIONS, AOC: Health, flight plan, position, weather				
5G	MPS for use in the NAS does not exist	None	None	FAA Spectrum Office has indicated acceptance possible if service provider gives air communications priority over ground, including in emergencies. EUROCAE ED-260 (MASP) covers 4GHz Wireless Avionics Intra-Communications Systems on aircraft.
5G Sat	MPS for use in the NAS does not exist	None	None	Plan is to place thousands of satellites into low earth orbit (LEO) to support 5G satellite, but no timeframe, and will require service provider priority.
C-Band	RTCA DO-362	None	None	RTCA DO-362 is a MOPS for UAS Command and Control (C2) via Data Link from SC-228, includes C-Band and Ku/Ka sub-bands. No related TSO has followed. The C-band TSO 213a restricts one UAS to one ground station, and no ground station may be closer to another ground station than 10 nmi. TSO 213a will be a stumbling block for urban C-band C2.
LEO	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
VDL-3	TSO-163a	None	None	FAA dropped the VDL Mode 3 concept in 2004. Installation AC exists for the Aeronautical Telecommunications Network (ATN-B2).
COMMUNICATIONS, ATC relay				
5G	MPS for use in the NAS does not exist	None	None	FAA Spectrum has indicated acceptance possible if service provider gives priority.
5G Sat	MPS for use in the NAS does not exist	None	None	Plan is to put thousands of satellites into low earth orbit (LEO) to support 5G satellite, but no time frame, and will require service provider priority.
C-Band	RTCA DO-362	None	None	MOPS for Command and Control (C2) Data Link from SC-228, includes C-Band and Ku/Ka sub-bands, but no TSO.
LEO	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
VDL-3	TSO-C163a	None	None	FAA dropped the VDL Mode 3 concept in 2004, Installation AC does exist for ATN-B2 (VDL M2).

TECHNOLOGY	FAA USE/MPS	INSTALLATION AC	OPERATIONS AC	REMARKS
COMMUNICATIONS, AOC video				
5G	MPS for use in the NAS does not exist	None	None	May be acceptable for AOC use, but not for UAM control unless service provider gives priority.
5G Sat	MPS for use in the NAS does not exist	None	None	May be acceptable for AOC use (when available), but not for UAM control unless service provider gives priority and safety analysis.
LEO	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
COMMUNICATIONS, Passenger emergency				
5G	No	None	None	May be acceptable under emergency conditions for AOC use.
5G Sat	No	None	None	May be acceptable under emergency conditions for AOC use.
C-Band	RTCA DO-362 TSO-C219	None	None	NASA GRC supported testing of C-band C2 for MOPS development.
LEO	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.

Table 3-2. Standards Covering Recommended Navigation Technologies

TECHNOLOGY	FAA USE/MPS	INSTALLATION AC	OPERATIONS AC	REMARKS
NAVIGATION				
Augmented GNSS (WAAS, LAAS, PNT)	TSO-C145c/-146c WAAS TSO-C161b/-162b LAAS	AC 20-138D	AC 90-105A AC 90-107	Standards needed to address commercial PNT/ground beacon. Would likely need a radio altimeter to support low visibility or autonomous landing and flare command.
GNSS+ISAR	No integrated MPS	None	None	Standards for Inverse Synthetic Aperture Radar (ISAR) integrated with GNSS needs to be established.
GNSS+RF Mapping	No integrated MPS	None	None	No industry consensus standards exist.
LEO	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
Radio Altimeter	TSO-C87a	None	None	Sometimes referred to as Radar Altimeter.

TECHNOLOGY	FAA USE/MPS	INSTALLATION AC	OPERATIONS AC	REMARKS
NAVIGATION				
RF Beacon/RF Guidance System[32]	TSO-C34e TSO-C35d TSO-C36e	None	None	Standards apply to current deployment of ILS and marker beacon systems.
LIDAR	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
Machine Vision	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
Radar K-Band, FMCW	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.

Table 3-3. Standards Covering Recommended Surveillance Technologies

TECHNOLOGY	FAA USE/MPS	INSTALLATION AC	OPERATIONS AC	REMARKS
SURVEILLANCE, Cooperative Surveillance				
5G	MPS for use in the NAS does not exist	None	None	FAA Spectrum has indicated acceptance possible if service provider gives aviation priority.
ACAS/TCAS	TSO-C118a TCAS I TSO-C119e TCAS II	AC 20-131A AC 20-151B	AC 120-55C	Requires vehicle to have a transponder for TCAS interrogation.
UAT2 ADS-B	TSO-C154c UAT TSO-C166b Mode S	AC 20-172B	AC 90-114	For UAT2, RTCA MOPS DO-282B could be basis for development of 1104 MHz MOPS application and new TSO.
Multilateration	Yes, FAA ASDE-X Specification FAA-E-2942	None	None	An example of multilateration, Airport Surface Detection Equipment - Model X (ASDE-X), requires transponder equipage, implemented at numerous Class B airports.
SURVEILLANCE, Air Non-Cooperative & Obstacles				
Infrared (IR)	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
LIDAR	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.

[32] *An ILS system at a runway is also a set of two RF signals with overlapping signals indicating the glideslope, with marker signals at particular geographic positions relative to the runway end. The constraints of the urban environment make precise marker signals difficult if not impossible to site where desired; however, perhaps a beacon-only system could be developed for this need.*

TECHNOLOGY	FAA USE/MPS	INSTALLATION AC	OPERATIONS AC	REMARKS
Radar K-Band	RTCA DO-366	None	None	MOPS exists for air-to-air for traffic surveillance from SC-228, although not frequency specific.
RF Detection	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
SURVEILLANCE, Ground Non-Cooperative				
Acoustic	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
Advanced Radar	None	None	None	FAA Primary and Secondary Radars (ASR-9, ASR-11, etc.) are in the L and S Band.
Bistatic	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.
Infrared (IR)	MPS for use in the NAS does not exist	None	None	No industry consensus standards exist.

3.2 UAM Avionics, Integration, and Interoperability

In consideration of UAM CNS avionics integration and interoperability, the following issues are identified gaps in the current state of UAM-related technologies and operations procedures that will require either research and development, or engineering development; efforts for UAM to be realized beyond present plans to offer air-taxi services in demonstration mode. Each is identified along with our thoughts on how to proceed in order to address the issue. These gaps could be addressed via a future NASA project, or sub-project, or through the FAA's Research, Engineering, and Development portfolio.

3.2.1 Identified Gap 1 – Creation of new information formats for an ADS-B compliant filterable UAT frequency

UAM manufacturers will be challenged in maximizing their electrical power budget (propulsion and essential system buses) and useful load, while minimizing gross vehicle weight. Similar to the constant demand to minimize parasitic mass of launch vehicles within the space launch community, operators will continually pressure OEMs to minimize the "parasitic weight" of UAM vehicles. Parasitic weight being defined as the weight of all the UAM vehicle structure and systems (batteries, electric motors, avionics, etc.) necessary to enable lifting the payload, or passengers. With that in mind, the UAT2 frequency of 1104 MHz offers an opportunity to develop a broadcast/receive capability for use by the UAM community that could support multiple equipment functions, thus saving weight and power consumption.

- **Communication** – An autonomous UAM community would not need constant weather uplink (i.e., FIS-B)[33], the 176 ms UAT2 ground segment could be repurposed to provide UAM addressable data link messages. In UAM autonomous mode, there is no human to receive a textual message, so an uplink message might be as simple as "EX(ecute) 41"[34] statement to the flight management computer.

[33] *For autonomous UAM vehicle operation there would be no benefit in broadcasting a ground FIS-B segment. The UAM operation center and the UTM center could get this information via the internet.*
[34] *As example, an "EX(cute) 41" could mean "proceed on alternate route", or "send battery power remaining", etc.*

The important aspect of this proposal is that a “close-loop” confirmation to the uplink message could be made through the ADS-B message broadcast format. These addressable uplink messages would be via “private” encryption to provide proprietary security to the UAM UOC.

- **Passive Surveillance** – The State Vector (SV) message would be the same format as with the 978 MHz UAT message. The vehicle identification, position, velocity, and altitude information would be in a “public” encryption format to allow other UAM vehicles to receive/share the SV position report to support surveillance monitoring and avoidance algorithms. However, to get a complete picture, the onboard surveillance monitor may need to receive civil ADS-B and remote ID input to form a complete surveillance picture. This could be accomplished by the UAT2 (or the local FAA) ground station via rebroadcast of 1090 MHz and 978 MHz ADS-B SV messages (and possibly UAS Remote ID messages) on the UAT2 frequency format. Alternately, the UAM UAT2 equipment could support independent reception of 1090 and 978 MHz ADS-B target information.
- **Active Surveillance** – As with the above bullet on Communication, the repurposed UAT2 ground segment could also be used by the UAT2 onboard equipment to output an addressable target vehicle request for response (note the own-ship UAT2 equipment would have already received this address through the target vehicle’s passive surveillance broadcast). With a developed traffic algorithm along with accurate timing and known latency, the target vehicle response (via 1104 MHz) to the own-ship request could be used to independently calculate range to the target vehicle to validate its passive position (SV) broadcast, similar to a TCAS interrogation. Utilizing TCAS Hybrid surveillance concepts (RTCA document DO-300 MOPS), the need for constant response/requests could be reduced from every second to perhaps every 10-20 seconds as long as the target vehicle’s track remains outside the DAA algorithm’s alert/resolution envelope. Utilizing this hybrid concept would also aid in spectrum efficiency.
- **Health Monitoring -** The optimal use of a UAT2 message format would be to output UAM vehicle health information that is important to the UOC operator, such as:
  - Fan No X amperage high
  - Fan No X RPM Low
  - Battery charge level/%
  - Battery temperature high, etc.

These messages (and others important to safe UAM operation) could be via a “private” encryption format for the specific UOC operator. In addition, the ADS-B segment could be used to provide a downlink message to the UOC to acknowledge reception of an addressable uplink (ground segment) message (e.g.,” EX 41 acknowledged”).

- **Accident/Incident Investigation -** As an added benefit, the UOC recording/storage (for a reasonable time) of all UAM vehicle messages (addressable uplink, SV position data, UAM health data, ground rebroadcast targets) might also meet the timely needs for accident/incident investigation. The recorded messages could also be used by the UOC to improve flight operations/safety through trend analysis.
- **ATC Monitoring/Coordination** – Since many large urban areas are under/within Class B airspace, it is expected that these UAM operations will be geo-fenced[35], and that UAM UAT2 targets will not need to be displayed on ATC screens. However, should a UAM blunder outside this geo-fenced area (and the FAA ground station is modified to receive the UAT2 broadcast), these targets could then be displayed so that ATC can inform the UTM or AASP center, and provide separation to civil traffic in the local area.

[35] *Restricted to a geographic boundary and maximum altitude within the urban city landscape.*

Much of the UAT2 Standards development can be taken directly from RTCA DO-282 MOPS, relocating the center frequency to 1104 MHz as opposed to 978 MHz. Modulations, Forward Error Correction (FEC), spectrum masking would still apply. The UAT2 can provide the same SV messages as UAT (and with UAT2 ADS-B, "in" would be one input to the onboard UAM surveillance processor). Standardized UAM health messages in the ADS-B Segment could be developed, or could be original equipment manufacturer (OEM) specified. The main effort will be defining how the Uplink Segment can be restructured to provide addressable uplink messages, and how the ground station will format, sequence, and broadcast these messages. Probability of uplink message reception simulations and a ground station deployment investigation/scheme would need to be developed.

3.2.2 Identified Gap 2 – Coordination of sUAS and UAM Operations in the Same Urban Landscape

An urban sUAS delivery operation will need a detect-and-avoid (DAA) system to navigate around people, buildings, temporary obstacles, and other vehicles—the question is how to design an adequate system for a shared urban airspace? NASA (along with the FAA) needs to set the expectations (performance) of the DAA (and other) technologies in an urban environment to achieve harmonization in day-to-day operations. This should be easier to accomplish with UAMs, since they will be subject to a formal certification/operation approval process which is to enforce higher safety requirements on the vehicle/operator. This is not so clear in the case of sUAS development. The question is how much performance burden will be placed on each of the vehicles. This is the gap that needs to be addressed.

NASA should take the lead in simulating various expected sUAS/UAM speed and approach scenarios (head-on, crossing angles, overtake, etc.), so as to develop appropriate performance requirement targets for DAA equipment to be used by both sUAS and UAM vehicles. These simulation results would add credibility to both DAA standards development and equipment designs.

One way to help mitigate this DAA performance requirement burden would be to establish more definitive rules for both parties and then test, e.g., via simulation. Gaps that NASA could help fill include:

- Rules of airspace access.
- Operational guidelines for airspace coordination.
- Procedures surrounding shared use of vertiports.

In summary, in order for a sUAS to operate beyond visual line of sight (BVLOS), the vehicle will have to detect and avoid objects. Will the sUAS DAA system have the performance to harmonize with the UAM community? The UAM AOC does not need to be overly concerned with the sUAS's navigation or communication performance capability. However, the UAM operators do need to know the surveillance awareness capabilities that the sUAS community can contribute.

3.2.3 Identified Gap 3 — Better Understanding of Urban Signal Blocking and Reception

GNSS WAAS is widely available and widely accepted but may suffer from signal degradation and jamming, particularly in the urban environment. While urban multipathing and blocking is known to occur, in practice, dealing with these impediments is done on an installation and experimentation basis. For UAM use in multiple cities, particularly to support required air-ground CNS functions, better understanding of the urban signal environment is needed.

3.2.4 Identified Gap 4 – Performance vs Prescriptive Based Requirements

There are many areas where performance-based requirements make very good sense, such as in basic structure construction (aluminum vs composite). The performance-based requirements allow applicants to propose new and novel techniques which might otherwise be dismissed because of the time it might take to request a legal interpretation or a rule change. However, there are times when a prescriptive rule requirement can aid the furtherance of industry and safety. For example, TCAS and ADS-B are basically prescriptive requirements that improved airspace safety and efficiency. ATC uses VHF voice or data link to help interoperability and to keep operators (and ATC) from having to support various additional communication methods. It is for this reason that we should not pre-judge the merits of performance-based versus prescriptive based. There will be areas in the urban operation environment where both sUAS and UAMs might benefit with prescriptive requirements that lead to interoperability and economies-of-scale in terms of equipment costs.

Numerous navigation alternatives in this study were recommended for the derived requirements, among them sensor fusion for navigation, which would be time-consuming to certify on a prescriptive basis. Performance based requirements are recommended for UAM vehicle navigation and surveillance. In general, non-cooperative technologies are more amenable to performance based requirements while cooperative technologies need to be very specific to function and coding, and require MOPS.

3.2.5 Identified Gap 5 – Establish the Target Design Assurance Level (DAL) for Passenger-Carrying UAM

The Federal Aviation Act of 1958 was recodified to Title 49 of the United States Code (USC), Transportation, Subtitle VII Aviation Programs, Chapter 447 Safety Regulations, in the mid-1990s. Chapter 447 is what gives the FAA Administrator the authority to propagate rules and regulations in promoting safe flight of civil aviation and air commerce in the NAS. In §44701, General requirements, specifically §44701(d)(1)(A) states it is "the duty of an air carrier to provide service with the highest possible degree of safety in the public interest," then goes on to differentiate between air transportation and air commerce, allowing the FAA Administrator to classify a regulation or standard appropriate to the differences. This is the reason why 14 CFR Parts 25 (transport category airplanes) and 29 (transport category rotorcraft) airworthiness standards are more stringent then Parts 23 (small airplane category) and 27 (normal category rotorcraft). The target DAL for Part 25 aircraft, typically used in air commerce, is 10^{-9} for functions whose failure would be catastrophic.

In a recent speech[36] by the FAA administrator on the subject of UAMs, he re-emphasized "*Our [FAA] job is to make sure that any aircraft or systems coming to market will meet the public's sky-high expectations for safety. If the public perceives a new entrant as unsafe, that business is simply not going to fly*." The Administrator further stated "*We at the FAA will lead globally by working with other authorities around the world to ensure we meet the public's expectations of the highest possible levels of safety*." Some in the FAA have taken this to mean that the target DAL for passenger carrying UAMs to also be 10^{-9}. This statement is consistent with the European Union Aviation Safety Agency (EASA) Special Condition for VTOL aircraft, No. SC-VTOL-01[37] of 10^{-9} for the category "enhanced" to support 3rd party (passenger for-hire) services.

A DAL level for the U.S. UAM market needs to be established in order for the industry to go forward. UAM designs will have to consider redundant battery buses, data/control buses, and avionics to assure continued safe flight and landing under various failure conditions (e.g., a bird strike takes out electric bus A). Whether it results in a target DAL of 10^{-7} or 10^{-9}, the UAM manufacturer will need to develop a very thorough safety assessment. On the Boeing 787 development, Boeing and its prime avionics integrator developed a very sophisticated system mock-up to enable "wring-out" of various failure conditions to

[36] *Dickson, Stephen M., "Back to the Future: The Winged Gospel," speech made by the FAA Administrator to the U.S. Chamber of Commerce Aviation Summit, March 5, 2020, Washington, DC, URL:* https://www.faa.gov/news/speeches/news_story.cfm?newsId=24697

[37] *European Union Aviation Safety Agency (EASA), Product Certification, Document No. SC-VTOL-01, Issue 1, "SPECIAL CONDITION: Vertical Take-off and Landing (VTOL) Aircraft," 2 July 2019, URL:* https://www.easa.europa.eu/document-library/product-certification-consultations/special-condition-vtol

improve the final design, a recommended best practice. Industry, FAA, and NASA need to find the appropriate balance of required DAL and safety practices, without imposing undue or unnecessarily high requirements, with proper consideration for safety equipment as appropriate for the risk.

3.2.6 Identified Gap 6 – Establish the Type Certification (TC) Basis

Based on the application for type certification submitted, the ACO will start to develop the certification basis that the applicant will need to show compliance. Assuming that it will be a VTOL vehicle, the ACO will take the appropriate portions of 14 CFR Parts 23 (small airplanes), 27 (small rotorcraft) and 36 (noise), to develop various Issue Papers (IP). For a type certification project, it will begin with a G-1 (General) IP, which will define the certification basis to the applicant. Note that this IP will be significantly influenced by the target DAL defined for certification of the vehicle/project. It is also assumed that there will be a P-1 (Propulsion) IP to identify MoC with electric propulsion, an S-1 (Systems) MoC IP, and an A-1 (Airframe) MoC IP. It is also likely that there will be Special Condition (SC) IPs applied to address areas where existing regulations are not adequate to define airworthiness requirements. It is expected, at a minimum, SC IPs will be required for: the battery technology (charging and thermal runaway containment), flight path control, automated functions, fly-by-wire, flight performance under non-normal and emergency conditions, and cybersecurity. NASA can accelerate UAM achievement by tracking and participating in standards bodies (e.g., ASTM) to develop informed standards in these areas that will lead to industry markets for common items. All Special Conditions must be published in the Federal Register for public review and comment. FAA Order 8110-4C[38] defines the certification processes that the ACO will follow. After TC issuance, should the holder desire to update the vehicles capability (i.e., from a piloted to semi-autonomous or autonomous vehicle), a new S1 (or P1) MoC issue paper may be needed to address these changes in support of the amended type design application.

3.2.7 Identified Gap 7 – The Needed Relationship Between the UAM Manufacturer and the Avionics Suite Supplier to Support Avionics Safety Analysis and Certification

Compliance with the developed Type Certification basis will require knowledge of, or experience with, navigating the FAA's certification process. A third party such as the General Aviation Manufacturers Association (GAMA) should constructively convene and facilitate industry conferences and discussions between the UAM manufacturers and the potential avionics suite providers (e.g., uAvionics, Garmin, Collins, Honeywell, Universal, Aspen, L3) that have proven track records in development of avionics safety analysis and certification. The need for standards developed from these discussions may subsequently be addressed by an industry standards consensus body, such as RTCA, Society of Automotive Engineering (SAE), or ASTM (formerly known as American Society for Testing and Materials).

If an operator wants to use proprietary or "in-house" developed technology, then they will have to develop their performance and testing requirements, whereas a common TSO can apply to rest of industry. Proprietary processes will be reviewed (between FAA and the manufacturer) on a case-by-case basis, as described in Section 3.1. The RTCA DO- to TSO- process tends to operate when a piece of equipment is a standard piece, widely accepted across the industry, or requiring interoperability across the NAS.

[38] *Federal Aviation Administration (FAA), Regulatory and Guidance Library (RGL), Orders/Notices, Order 8110.4, CHG 6, "Type Certification ," March 6, 2017, URL: https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgOrders.nsf/0/D21193AF2D37A8BA862570AB0054C104?OpenDocument*

3.2.8 Identified Gap 8 – New and/or Unproven Technologies (COTS) Need to Be Evaluated for Performance and Availability for Civil Aviation Use

There are various new COTS technologies that, on first appearance, seem like they will also be appropriate for use in UAM vehicles but have never been used (stressed) in an aviation environment. This includes environmental testing (i.e., shake and bake) as well as establishing a probability of reception/availability that meets the rigor necessary for the operation.

For example, the UAT 978 MHz ADS-B MOPS RTCA document DO-282B Appendix K was developed by Johns Hopkins University Applied Physics Laboratory (JHU-APL). APL determined power levels (at the antenna) and the required forward error corrections necessary to achieve 95% message reliability/availability for the various classes of UAT equipment. NASA Centers also test industry equipment in support of MOPS creation. Any of the recommended CNS solutions that have not previously been proven in aviation use must undergo a similar testing to determine their appropriateness for use in a civil UAM vehicle.

3.2.9 Identified Gap 9 —Use of Sensing Automation Instead of Pilot Visual Acquisition

The EFVS rule, §91.176, governs the use of an electronic-based vision system to augment the pilot's natural vision during a landing approach in IMC conditions. The rule requires the EFVS sensor image to be overlaid on a head-up display (HUD), which must display appropriate flight symbology/guidance information. When approved, this combination of EFVS and HUD can allow the aircraft to descend below the published decision altitude (DA)/decision height (DH), using the EFVS sensor image to acquire the airport landing environment down to 100 feet above touchdown zone elevation, at which time the pilots' natural vision must acquire the airport environment to allow continued descent and landing.

Existing installation and operational guidance (AC 20-167A and AC 90-106A, respectively) support installation certification and help the operator secure an operation specification (OpSpec) approval. This guidance also identifies a listing of the sensors that might be used for EFVS, so some of the approach sensor technologies we considered in the alternatives are already FAA accepted in some form pending performance testing during certification. Imaging sensors can be forward-looking infrared, millimeter wave radiometry, millimeter wave radar, low-light level image intensification, or other real-time imaging technologies.

However, the §91.176 rule does not support autonomous landings. The §91.176 rule requires the installation of a costly HUD to overlay the EFVS sensor image. Additional studies are necessary to evaluate the use of the above referenced imaging sensors to allow development of performance standards to approve an image-based autonomous landing system. In addition, the §91.176 rule will need to be amended or a new 14 CFR 91 rule established to support image-based autonomous landing for UAMs.

3.3 Summary

CNS avionics can be certified as part of the aircraft, in the type certification process, or added on as distinct pieces of equipment. The RTCA DO- to TSO- process certification tends to operate when a piece of equipment is a standard piece, widely accepted across the industry. If a piece of equipment is newly introduced and needs to be added to an aircraft, the manufacturer looks at getting a Standard Technical Order (STO) or Supplemental Type Certificate (STC) for adding, e.g., that radio to the aircraft. If an operator wants their own conformity checklist or own special technology, they must write their own processes, whereas a common TSO could apply to the whole industry. Proprietary processes will have to be reviewed by the FAA with the manufacturer.

For example, consider the test case of certifying a UAT2 for ADS-B for a UAM aircraft. This could go the MOPS route, which defines functions that lead to a TSO and then modification of existing ACs and TCs.

It could also go the route of putting a new technology on a newly certifying aircraft, so the UAT2 would not have its own MOPS and TSO, but would need to be flight tested on each new aircraft type. Maintenance of consumables would be incorporated in the certification of the vehicle standard, covering both the install and the lifetime operation.

Requirements for flight-critical avionics are higher where there is no pilot on board. The flight criticality of navigation and communications equipment is likely to apply to the avionics boxes; thus the certification requirements for reliability, availability, and fail-safe operation are higher under automated flight, navigation, and separation functions.

A SAE working group is working toward acceptance of a nondeterministic software to perform a particular aviation function. They will likely recommend evaluating the criticality and use of that software in context and the creation of tests for that application as a means of demonstrating compliance for that function. This is but one example of the impediments that must be overcome to address the numerous Special Conditions anticipated in the UAM vehicle and CNS certification process.

CHAPTER FOUR

4.0 GAPS IN INTEROPERABILITY BETWEEN UAM AND sUAS IN CNS AND ATM SERVICE

We researched the technologies being used by advanced civilian sUAS operators who are flying sUAS commercially with FAA special approval or are conducting trials at FAA-designated Integration Pilot Program (IPP) test ranges.[39] In order to operate commercial delivery services in an urban environment in UML-4, sUAS will need to be able to operate BVLOS, over people, and will need to be adequately equipped for navigation in a communications-denied environment with potential transitory obstacles in the flight path. SUAS operators and researchers are testing sensor and communication technologies to achieve operations in that environment. The feasible technologies under research now provide the most likely forecast of the technologies that would enable sUAS operations under Part 135, since the advanced sUAS operators will work with FAA to create the standards to enable the envisioned safe flight in the NAS. This look ahead represents the path that Part 135 sUAS may take over the near term. Our forecasts of sUAS and UAM CNS equipage in the urban airspace are summed up in Table 4-1. In the table, the technologies delimited by commas are inclusive "or," meaning any of the list, a combination of them, or all of them may be employed in that function. The UAM technologies in column 4 echo our UAM technology recommendations.

Table 4-1. CNS Technologies of sUAS and UAM in UML-4

FUNCTION	SUAS UNDER PART 107 OR IN IPP (TODAY)	SUAS UNDER PART 135 (FUTURE)	UAM
Communications with LOS Owner/Operator	Bluetooth, Wi-Fi	Bluetooth, Wi-Fi	Not applicable
Communications with BVLOS Owner/Operator	Autonomous flight without comm, other proprietary solutions	Satcom, C band	C band, Satcom, VDL-3, 5G
Primary Navigation	GPS	Augmented GPS	Augmented GPS
Cooperative Surveillance	LAANC	InterUSS, RemoteID, cellular applications[40], LAANC	UAT2, ACAS, sidelink 5G[41]
Navigation and Operation in Low Visibility	No operation	Augmented machine vision with IR and/or other sensors	Augmentations with sensors and/or beacons
Non-Cooperative DAA	None	Sensor suite + logic	Radar, IR, Acoustic Sensors, Sensor fusion

[39] *Our research in future sUAS Part 135 operations, beyond reading FAA position papers, was informed primarily by interviewing industry representatives on a not-for-attribution basis.*
[40] *Cellular applications, or "apps" refer to situational awareness maps on a cellphone that utilize incoming Bluetooth and Wi-Fi signals to create a traffic map*
[41] *Sidelink (phone to phone signaling without going through the network) would specifically need to be enabled in 5G/6G to provide cooperative surveillance. Sidelink in 4G would also work if 4G is still available in this timeframe. Sidelink was approved by 3GPP for both 4G and 5G, but to date has not been implemented in either generation.*

In this examination of UAM and sUAS interoperability, the end goal is integration. Our guiding operational principal is equal access for all aircraft, rather than starting with dedicated, separate airspaces for the two types of vehicles. We assume that both sUAS and UAM will share the same airspace and must have equal access in order to meet their respective business cases. Urban sUAS delivery users should not suddenly be denied sUAS service, for example, if a UAM vertiport is established across the street. To establish the technologies needed for these vehicles to operate together in the same environment, it is necessary to examine the external constraints and rules we assume will apply in the urban airspace in the UML-4 timeframe. We define urban airspace to mean the airspace above ground in an area characterized by a population density of greater than 2,500 persons per square mile and a substantial number of conterminous square miles in area.

4.1 Operational Assumptions

In UML-4, UAM will operate in all classes of airspace except Class A and will interact in that airspace with conventionally piloted VFR and IFR traffic in addition to sUAS traffic when flying in urban airspace within 400 feet of the surface. UAM will be limited to designated vertiports as endpoints, but sUAS may be ahead in their market development; sUAS may have achieved on-demand urban BVLOS from any departure and arrival point. While there may be hundreds of UAM vehicles operating in a city, it is equally likely that there will be thousands of sUAS below 400 feet AGL. We assume that sUAS may also land at UAM vertiports.

Both UAM and sUAS will operate in VMC and IMC with means to fly their missions while maintaining safe separation from obstacles and other vehicles in both conditions. It is further assumed that UAM may be conventionally piloted, piloted using SVO, or remotely piloted. sUAS may be remotely piloted or autonomous. Means to carry out their operational responsibilities will, alternatively, be provided on the vehicle, provided using external services, or accomplished using a mix of the two. These alternatives are discussed below.

Some flight rules contained in 14 CFR Parts 91, 61, and 135 will have to be modified, amended, or exempted to permit the operations described here. In particular, the rule on minimum flight altitudes would not permit operations in urban airspace and the requirement for being on an ATC clearance during flight in urban, low altitude Class B airspace has already been rejected as not feasible for UAM and sUAS. Other rules and differences from conventional operations are identified below but the concentration is on identifying requirements for UAM and sUAS interoperability.

4.2 Communications

Data communications are expected to be used by both classes of vehicles to provide vehicle status to the operator and position and intent to other authorities. Weather, infrastructure status, and traffic information services may also be received over this medium. Due to signal obstructions in the urban environment, we have assumed that all UAM communications would be digital/data, which creates better encoding and decoding opportunities. Unlike traditional voice communications in which traffic situational awareness is maintained through a party line voice communication channel, the UAM surveillance function relies primarily on a data-comm driven continuous cooperative interaction. While the UAM also has non-cooperative target detection mechanisms, reliance on those would be eased if interactions with local sUAS could also be carried on cooperatively. This would create a requirement for sUAS to broadcast on a protected UAM surveillance frequency for collaborative coordination. Alternatively, sUAS could interact with the UAM via a ground rebroadcast system, e.g., a UAT-like ground rebroadcast (ADS-R).

Other communications common to the two users include the coordination of movements to and from vertiports or other landing areas. Vehicle positions and landing ETAs are needed by a landing assignment system (likely automated) that would be facilitated by a common frequency and message protocol established for this service. No such universal service is yet defined.

There are cybersecurity concerns about sUASs having a direct communications link to a passenger aircraft. These concerns stem from a lack of assurance about the ownership and cybersecurity of the sUAS as well as onboard communications network insecurity. Of particular concern is the potential use of 5G, which at present relies upon geolocational uniqueness as a security measure: the idea that the beam is directionally focused and therefore can only be picked up by the receiver that is in the narrow beamwidth. This ignores the possibility of sUAS shadowing UAM, remora-like, and intercepting signals in that beamwidth. As sUAS operators plan to take advantage of communications over existing commercial networks, these vulnerabilities must be addressed. One answer involves authenticated and certificated senders and authenticated network paths, such as network slices. Encryption and signed communications may be part of the solution when pursuing direct vehicle-to-vehicle communications, for example communicating position and intent, and cooperative surveillance data.

4.3 Navigation

When either a UAM vehicle or a sUAS performs its basic navigation from origin to destination, there is no requirement for any common means to accomplish it. It is only when the navigation solution for position and velocity is used in cooperative surveillance that the navigation performance on each vehicle must be known. This is the same principle behind Navigation Accuracy Category for Position (NACp) and Navigation Integrity Category (NIC) performance standards. Both the accuracy and the update rate of the navigation solution are used to derive appropriate separation values and maneuvers to be used in the automated separation function, either aboard the vehicles, or from a ground service provider. Use of the navigation solution in the provision of separation safety also requires a level of integrity and reliability appropriate to this function.

One alternative for UAM navigational altimetry is barometric, augmented with radio altitude for use in vertical autoland and maneuvering in close proximity to the surface and buildings. Precision is required for low altitude urban operations. SUAS perform “nap of the Earth” flying, conforming to the variations in surface height using GNSS and barometric altimeter fusion to provide the vertical position. If vertical separation is used between the two aircraft types, there may be incompatibility between the height measurements as well as difficulty in projecting the vertical profiles in the encounter modeling and resolution schemas. Even if UAM also uses GNSS and barometric fusion as sUAS does, active Wi-Fi networks, structures, and altitude can affect the GNSS signal and thus the estimated altitude. When vertical separation is provided among UAM and sUAS vehicles, the method for determining height and the reference datum (sea level, surface, or a citywide agreed datum) must be established as the universally used standard. No such agreed height keeping methodology is yet established for the urban airspace.

4.4 Surveillance

Surveillance of both UAM and sUAS vehicles is required for operational control, aircraft separation safety, and for public safety and security concerns. Surveillance performance required for each of these functions is quite different, however, and may, as a result, be fulfilled through different means. Operational control can be done with relaxed accuracy and latency requirements. Safety and security may require non-cooperative surveillance, but only at a secured perimeter. Separation safety may be performed using ground-based surveillance and a control service or may be performed on board using air-to-air surveillance. If self-separation is used in the airspace, centralized surveillance may only be needed in the area in which centralized control of arrivals and departures is exercised. If you have cooperative UAM-sUAS surveillance, then non-cooperative surveillance for security is only needed at the perimeter of a securitized airspace.

Cooperative surveillance between sUAS and UAM provides situational awareness and enables self-separation. According to Table 4-1, UAM and sUAS are not planning to share a cooperative surveillance broadcast or band under the predicted sensor technologies. To interoperate, the two vehicles will have to share a flight critical frequency such as UAT2, Mode C or Mode S. The technology options for sUAS under Part 135 were considered and not recommended for UAM. Since sUAS have lean weight budgets, a new sensor should not be required without assessing operational impacts. NASA should consider research to determine which of the alternatives in Table 4-1 provides the best shared situational awareness between UAM and sUAS (Cooperative Surveillance row).

Alternatives include requiring UAT2 or ACAS sensors on urban sUAS, rebroadcasting UAS position from LAANC and RemoteID on UAT2, and detect and avoid sensors on both UAM and UAS. Selection of a single band for both sUAS and UAM must consider whether appropriate spectrum exists to support the expected number of vehicles, though use of an intelligent ID assignation scheme in UAT2 would alleviate many of the cell-based limits that 1090 MHz experiences with conventional aircraft.

Spectrum congestion has been most prominent on the 1090 MHz frequency that is used for ATC radar, TCAS, and ADS-B. A solution has been to reduce transmitter power when congestion worsens and for receivers to listen for the strongest (hopefully the closest) signal when used for collision avoidance. These techniques have worked for the numbers of aircraft currently in use but may be inadequate for the numbers of expected sUAS. There is a direct relationship between the surveillance range required for collision avoidance, the planned separation, and vehicle speed and maneuverability. There is a need to evaluate proposed interoperability for spectrum congestion and loss of safety margins for recovery brought on by this congestion. If something other than a protected frequency is used, such as 5G, then congestion brought on by non-aviation uses must also be considered in this evaluation.

4.5 Air Traffic Management Assumptions

UAM airspace is undefined at this point; we know that conventional ATM processes and procedures are inadequate to manage UAM, particularly at medium to high density, and while there are many proposed airspace rule solutions, none have been endorsed by FAA for UAM. It is possible that at low UML levels, UAM vehicles will need to participate in the UTM reservations system through LAANC. Because of signal difficulties, we have assumed that UAM and sUAS operators will pre-load both flight plans and contingency plans into the flight computers while the vehicle is on the landing pad. These departure and arrival airspace reservations could be made before flight as well. Note that because of the difficulties maintaining reliable communications in the urban environment, we assume that sUAS, as well as UAM, will need to operate independent of a ground-based remote pilot "in-the-loop"; the signal environment will not support turn-by-turn or even tactical responses to emerging hazards.

The accuracy and performance of UAM and sUAS positioning systems used for surveillance in an urban environment may create different separation standards within the same airspace. If a UAS has a lower precision DAA system, either through lower navigational requirements or a lower position update rate, then there are larger buffers required for separation from other vehicles. This variable and dynamic separation requirement introduces complexity not commonly found in dense parts of the NAS, and the urban airspace is predicted to be much denser. Complexity such as this is best handled in an automated separation system, such as the proposed AFR.

Class B, C, and D airspace all contain areas that extend upward from the surface so it is not possible to freely traverse an urban area below 400 feet without going through them. Accordingly, the requirements to be in radio contact with the tower in Class C and D, and to be on an ATC clearance while in Class B, need to contain exceptions for sUAS and UAM low altitude flight. Defined service volumes, or a limited dynamic form of geofencing (such as provided by LAANC) could be used to protect the low altitude portion of arrivals and departures of UAM and conventionally piloted aircraft from sUAS. The evolution of low altitude separation services from the current airspace reservations system using LAANC, to smaller, dynamic airspace reservations following the sUAS vehicles, to true tactical airborne separation among vehicles using air-to-air surveillance and communication, could be accelerated through NASA research in this area.

There is another school of thought regarding air traffic management for large numbers of sUAS vehicles called "swarming." There are two kinds of swarming approaches. The technology used to produce airshows with drones forming coordinated shapes in the sky are controlled from a single ground controller. A second type of swarming sends directional commands to drones but the drones maintain safe distance from each other by use of cheap radar and LIDAR sensors on the drone and re-organize position cooperatively by nudging positions to maintain a safe distance. (Low power and short range on the sensors makes them less expensive.) This second kind of swarming behavior is cooperative and federated and is more like the approach needed for complex air movements of independent vehicles that we envision ruling separation under UML-6. As most UAM and sUAS flights will be to and from different origin and destination points, sUAS and UAM traffic will be traveling to different directions. The "swarm" appellation here refers to cooperative yielding and turning, much like walking through a crowd on a sidewalk, with just-in time sensing and avoiding of others to maintain distance.

Resolving this gap requires better definition of the UAM and sUAS integration ConOps, the ConOps for urban airspace under modified Class B, C, and D operating rules, and definition or the creation of standards for separation in urban airspace. As long as there are multiple service providers (USS) managing sUAS operations, there will be a need for a central organizer for AASP – an agreed entity that fulfills the AASP role.

4.6 Avionics Commonality Between UAM and sUAS

As the market size for sUAS is likely to grow much faster in the near term, the growing market will enable technological progression and economies of scope that will provide relatively inexpensive sensors on the avionics market, compared to traditional piloted aircraft avionics that undergo environmental and fatigue testing and become certified avionics in the eyes of the FAA. Present sUAS avionics function as well as consumer electronics can be expected to function over several years with minimal maintenance attention. Large UAS are pursuing certified electronics in order to be granted equal access to controlled airspace as manned aircraft and can be expected to have some level of avionics certification by UML-4. Regardless, the sheer number of UAS and sUAS using these avionics will drive prices down, and these lower priced avionics will be tempting to UAM air vehicle designers, bringing down unit cost. Avionics manufacturers may even pursue dual manufacturing lines, in which nearly the same avionics box is produced for two different markets (UAS vs UAM), with different price tags.

The UAM market is evolving independently, however, threatening to develop unique protocols and operations in each geographic market that emerges. Extension of common operating rules for UAM nationwide would provide some much needed certainty. If the U.S. does not enact airspace rules for UAM, rules enacted in other countries where UAM operations begin, will be seen as a de facto standard. The U.S. will be at a disadvantage due to the airspace differences; for instance, VFR is not widely available in other countries and so imported UAM operating rules may be incompatible with U.S. VFR traffic.

While technical alternatives for CNS technologies and services exist and may perform equally well, cost considerations among them become paramount in determining the way forward. For example, navigation precision may be achieved through a variety of GNSS augmentations. The function to be performed (e.g. autoland) may require something better than WAAS, but LAAS or machine vision may be cheaper than RTK. In another example, the USS provider may use a low cost RID to perform basic LAANC separation for system users but charge for the service. Alternatively, installing UAT2 on a sUAS may cost more in avionics but eliminate a continuing service charge and permit operations with far fewer delays and constraints. NASA could help define these tradeoffs.

4.6.1 Piloted vs. Unpiloted

In unpiloted UAM vehicles, the HMI display and control unit itself can be removed as the last major contributor to weight and power draw, as there is no human with whom to interface on the vehicle. Vehicles designed for SVO would still have a display for vehicle status and simplified control inputs, but it would be smaller, lighter, and draw less power than existing multi-function displays because it would support fewer functions. It is expected that technologies for SVO or "optionally piloted" vehicles will advance quickly during the next few years. At this time, however, there is a gap between the avionics used experimentally and what may be certified to perform SVO tasks seven to ten years from now. Similarly, the design of the CNS avionics for a "reconfigurable cockpit" to simplify the transition from SVO to UAV, will need to consider maintaining and adding to the CNS functionalities while removing the HMI from the vehicle.

4.6.2 Interoperability Protocols

There is a need for the establishment of standards for data exchange architecture and CNS services provided by the many separate USS providers. A competitive avionics marketplace would thrive if CNS avionics serve both on UAS and UAM. Similarly, data exchange protocols for both air-to-air and air-to-ground should be established and standardized sufficiently to accommodate the operations of a heterogeneous vehicle set.

sUAS protocols may lead the way to density of operations and interoperability, but first there needs to be a recognition of the projected density in urban operations. When LAANC was initially fielded, sUAS operators could reserve the airspace within one degree latitude and one degree longitude, covering a nearly 360-square nm area. Similarly, TSO C213 governs C2 radio use for sUAS but limits use to one ground antenna and one UAS per ground station and dictates that ground stations must not be within 10nm of each other. Use of this standard in a dense urban environment would mean that only one sUAS and one vendor could serve all of greater New York City. The standards in place today are being tried out for rural areas and the densities being codified today will not support dense urban operations. While such protocols are normally established by standards setting bodies, NASA can provide, through analysis and testing, the data required for those bodies to establish the needed standards.

The approach of open interoperability between UAM carrying passengers and sUAS met with resistance among many airspace and ATM professionals. There is a built-in preference in the existing NAS to favor vehicles with persons on board over cargo. In fact, we encountered resistance when speaking with advanced sUAS operators that seemed to originate in the forecast that UAM operations will relegate sUAS to lower priority, geo-fenced away from UAM, until they are squeezed out. This concern cannot be overstated. There is a history of preference for manned flight over all else in the NAS. As NASA forms research groups to study and recommend flight rules, the issues of equity must be remembered, and sUAS delivery priority preserved next to UAM flights.

4.7 Research Areas

4.7.1 Close UAM/sUAS CNS Gaps

UAM and sUAS vehicles and operating concepts are being developed separately and independently by different commercial interests. As a consequence, the systems and services being put forth by the two groups for CNS and air traffic management are different and mostly incompatible, as seen in Table 4-1. Both UAM and sUAS intend to operate simultaneously and side-by-side in the low altitude, urban airspace. There is, therefore, a need to harmonize the CNS services to enable dual use by the two types of operators, rather than field separate services and depend on an additional bridge service to interpret between them. In particular:

- Conduct comparative testing to determine the best technical means among the alternatives for cooperative surveillance to serve both constituents. This includes selection of a common frequency in the aviation protected spectrum.
- Investigate the feasibility of a data lake for cooperative surveillance using a dual stack with rebroadcast between UAS and UAM. Determine whether broadcast TIS is sufficient for UAS-UAM separation.
- Conduct research on new navigation capabilities to support vertical autoland navigation meeting the safety and affordability requirements of both constituents.
- Establish a process for data gathering and consolidation covering cityscape navigational and terrain information accuracy and upgrades for use in the new UAM/sUAS ecosystem for height keeping and vertical separation.
- Propose a U.S. standard for vertiport classes covering function, layout, and user classes. Consider allowing helicopters to land at vertiports as well.

4.7.2 Close Avionics Commonality Gaps

UAM and sUAS avionics, consisting of sensors, radios, flight control, and flight management computers are also being developed separately. For those functions that are unique to each type of vehicle, there is no harm in that. However, many functions are common between them and each can profit from re-using the breakthroughs made by the other. Additionally, those functions that require interoperability, such as the communications used in cooperative surveillance, must be established using jointly agreed standards. NASA can assist these processes by:

- Performing testing of all viable sensing and RF technologies proposed for UAM/sUAS avionics to provide the in situ performance and reliability data upon which rational choices can be made among competing alternatives.
- Provide the test results data to standards bodies that they will need to establish the industry standards for UAM/sUAS interoperability.
- Provide an operational test facility, either using an actual city or simulating one in a realistic manner, that will provide actual data on the integrity and reliability of the various proposed methods for:
  - Departing, navigating en route, and landing at vertiports and impromptu sites.
  - Safely maintaining separation from all other vehicles.
  - Autonomously organizing the sequence and spot assignments among vehicles using a common vertiport.

CHAPTER FIVE

5.0 RECOMMENDATIONS FOR UAM CNS

The primary task before the study team was to identify, assess, and recommend CNS alternatives for UAM use in UML-4, with consideration for the developmental roadmap to UML-4 and the technologies that would be needed to enable UML-6. These alternatives should encompass data services, wireless air-ground links, and ground architectures, navigation in denied environments, and the need for augmented navigation during take-off and landing. In addition, we were asked to also identify gaps in avionics certification and standards needed to enable UAM CNS, recommend practices for the efficient use of spectrum, exploit avionics commonality, study and recommend integration practices, and study and recommend measures for sUAS interoperability. To complete this task, we interviewed many experts, analyzed current practices, and reasoned through an undefined airspace and airspace rules, reporting many of these discoveries with the recommendations. To enable more forthright tracking of the accumulated recommendations, they are reproduced here in brief. To track the reasoning leading up to the recommendation, refer to the associated section of the report.

5.1 CNS Recommendations

For more information about the rationale behind these recommendations, see Chapter 1, Chapter 2 sections 2.1 and 2.2, and Appendices A and B.

1. ***Overall UAM Communications, Navigation, and Surveillance Technology Recommendations:*** In no particular order, the recommended technologies for ***all*** UAM communication functions are:

   - VHF data link (VDL) Mode 3, with digitized voice for piloted aircraft
   - 5G via satellite integration
   - Commercial low Earth orbit (LEO) satellites
   - C Band[42]
   - 5G Cellular

   Navigation technologies are depicted in Table 5-1. A check mark indicates that the identified technology is recommended for en route, approach, or landing navigation in the lateral or vertical dimension.

Table 5-1. Navigation Functions and Recommended Technologies

NAVIGATION TECHNOLOGIES*	EN ROUTE LATERAL	EN ROUTE VERTICAL	APPROACH LATERAL	APPROACH VERTICAL	LANDING LATERAL	LANDING VERTICAL
GNSS + PNT augmentation	✔	✔	✔	✔	✔	✔
GNSS + LAAS (GBAS)	✔	✔	✔	✔	✔	✔
GNSS + WAAS	✔	✔	✔	✔	✔	✔
GNSS + LEO	✔	✔	✔	✔		
GNSS + RF mapping	✔		✔			

[42] *Refers to the C band spectrum being considered by FAA for allocation to UAS for command and control (C2).*

NAVIGATION TECHNOLOGIES*	EN ROUTE LATERAL	EN ROUTE VERTICAL	APPROACH LATERAL	APPROACH VERTICAL	LANDING LATERAL	LANDING VERTICAL
GNSS + SAR/ISAR mapping	✓					
GNSS (only)	✓					
GNSS + INS/IRS (FOG /MEMS)	✓					
GNSS + RF Beacon			✓	✓	✓	
GNSS + LIDAR				✓	✓	✓
GNSS + K band radar					✓	✓
GNSS + FMCW in GHz					✓	✓
GNSS + Machine vision (optical)					✓	
Radio/Radar Altimeter		✓		✓		✓
Barometric Pressure Altitude		✓				
Barometric Pressure with References		✓				

** PNT = positioning, navigation and timing; LAAS = local area augmentation system; WAAS = wide area augmentation system; GBAS = ground-based augmentation system; RF = radio frequency; SAR = synthetic aperture radar ISAR = inverse SAR; INS = inertial navigation system; IRS = inertial reference system; FOG = fiber optic gyro; MEMS = microelectromechanical system; LIDAR = light detection and ranging; FMCW = frequency modulated continuous wave*

Table 5-2 summarizes recommended technologies for surveillance, both cooperative and non-cooperative techniques, for air and ground. UAM vehicles will separate cooperatively, using broadcast position and intent. They will also need a non-cooperative sensing system to avoid collisions with aircraft and obstacles; this non-cooperative sensing may do dual duty as a landing sensor. Ground cooperative surveillance provides data for dynamic density management and safety. Ground-based non-cooperative surveillance will become desirable to ensure public safety and security.

Table 5-2. Surveillance Functions and Recommended Technologies

SURVEILLANCE FUNCTION	RECOMMENDED TECHNOLOGIES
Air and Ground Cooperative Surveillance	• Universal Access Transceiver (UAT)-2 on 1104 MHz • Mode C Multilateration • Airborne Collision Avoidance System (ACAS-X) • 5G (passive listen)
Airborne Non-Cooperative Surveillance	• K-band RADAR • RF Detection • LIDAR • Infrared (IR) Sensing • Sensor fusion
Ground-Based Non-Cooperative Surveillance	• Advanced Doppler Range Gating Radar • Infrared (IR) Sensing • Bistatic Radar • Acoustic Detection

2. ***Cooperative Surveillance Architecture:*** Cooperative surveillance for vehicle-to-vehicle separation is a critical function for UAM, and UAT2 (on proposed 1104 MHz) is a highly superior alternative to satisfy that function, due to ab initio message set design and because it is ATC compliant but filterable. In addition to these recommendations, projected UML-4 traffic density cannot be supported under standard separation, even a modified version of standard separation that merely reduces the distances between vehicles. UML-6 density will be much more dense and dynamic than UML-4. Operating under UML-6 will be so complex and computationally intensive that a new system must be initiated before UML-4, to allow time for the evolution of increased system performance needed to accommodate UML-6. NASA should devote research to the separation rules, networking protocols, redundancy requirements, and hazard assessments for cooperative surveillance-based tactical vehicle separation for high density UAM. This research is far-ranging: it involves better definition of operating rules, the algorithms for cooperative separation, and the impact of signal loss on movement advisories. NASA should:
   - Lead by developing a cooperative surveillance concept for UAM airspace
   - Research the design of that concept
   - Integrate, by supporting FAA allocation of the frequency through demonstration of need, and support the creation of a message set by an industry group.
3. ***Emphasize Performance Based Requirements to Foster Development of Novel Solutions to UAM CNS Capabilities:*** Performance-based requirements allow applicants to propose new and novel techniques which might otherwise be dismissed because of the time it might take to request a legal interpretation or a rule change. However, there are times when a prescriptive rule requirement can aid the furtherance of industry and safety, such as in collaborative and flight safety-critical applications. Performance based requirements are recommended for UAM vehicle navigation and surveillance. In general, non-cooperative technologies are more amenable to performance based requirements while cooperative technologies need to be very specific to function and coding, and require MOPS. NASA should support development of novel navigation solutions through testing support to industry standards groups.
4. ***Research the Potential Application of 5G Cellular to Dispel Hype and Inform Choices:*** FAA has enforced a standard that the air-ground frequencies used for aviation communication must be able to prioritize aviation messaging, particularly during an emergency. Cellular infrastructure does not do this. Using 5G for airspace requires infrastructure changes at the carrier and cell tower level for this prioritization. In addition, current aviation-use 5G proposals use sidelobes, rather than pointing to the proper elevation. Beamforming for aviation would require retrofitting of cell towers. Even with such retrofit, the extent of signal die-off over range and elevation has not been properly quantified. The cellular providers so far have concluded the market for aviation use does not close, as aviation use causes dropping of terrestrial calls. There is evidence that implementing aviation prioritization would multiply terrestrial calldrops more than 1-for-1. [See the 5G entry in Appendix B.] Use of sidelink phone-to-phone communication holds much promise for ad hoc networking for cooperative surveillance. However, no U.S. cellular carriers have implemented sidelink in their infrastructure, and the operational 5G networks in the U.S. at present are closer to 4G in software capabilities. GHz frequency use promises very high capacity gains that would be useful; however, to explore this alternative requires:
   a. Fielding of 3GPP's Release 17 capabilities in software in 5G networks.
   b. Prioritization for aviation use or the further definition of this requirement with FAA relative to the communication needs in an AFR-guided UAM vehicle.

c. Testing of signal elevation die-off.
d. Testing of clear air die-off of GHz signals to define the suitable range for a signal and the ground network requirements (geography of cell towers to ensure coverage).
e. Fielding of antennas pointing at aviation elevations.
f. Use of secure network slices for aviation instead of reliance on geographical cells (beams) for security.
g. Assurance the business case for aviation allows for long term service, taking into account terrestrial call demand and call dropping.

NASA work in concert with 5G providers to test 5G, to provide clarity on the suitability of 5G for aircraft applications. 5G providers need to provide the infrastructure changes indicated above for such testing to be worthwhile; otherwise it would be a waste of time and funding.

5. ***Define and Research Ground-Based Non-Cooperative Target Surveillance:*** UAM ground-based non-cooperative surveillance needs are not adequately defined and should be addressed before they become a mandate, particularly from non-aviation sources. A future homeland security or defense implementation directive may be costlier and less informed than one developed by the aviation industry. Probable surveillance architectures include: defined route monitoring, perimeter security, and pervasive monitoring. At present understanding of future requirements, a distributed, low-cost system of sensors that respects privacy needs is recommended. NASA should lead a requirements study to determine what the future surveillance requirements will be, estimate when they will be needed, and develop technologies to fulfill identified requirements.

6. ***GNSS Independent Navigation: Research Impacts of the Urban Environment on GNSS WAAS Performance:*** GNSS WAAS is widely available and widely accepted but may suffer from signal degradation and jamming, particularly in the urban environment. While urban multi-pathing and blocking is known to occur, in practice, dealing with these impediments is done on an installation and experimentation basis. For UAM use in multiple cities, particularly to support required air-ground CNS functions, better understanding of the urban signal environment is needed. Testing experience flying drones that depend on continuous GNSS signals in the urban metal-rich, obstacle-heavy urban environment shows that dependence on GNSS alone is very problematic. Navigation that can operate without a continuous GNSS signal will be required. NASA should study signal degradation in the urban environment and identify the most effective means of mitigating loss of function, including losses from solar flares and urban obstructions. NASA should research alternatives to identify best market solution: given the fee-for-service UTM ecosystem, a solution that benefits other stakeholders such as automated cars and point of sale terminals may provide the most cost-effective solution. NASA should integrate providers and start-ups around the best alternative to promote its implementation.

7. ***Research Point-to-Point Laser-based Communications***: Laser communications are a strong alternative for UML-6 communications. Using a light beam between communicators and modulating the light beam with encoded data, laser communications cannot be eavesdropped upon in the air-ground (non-network) component. Laser communications have no capacity limit. Laser communications currently have limited deployments in corporate, industrial, and military aviation applications. We recommend development of air-ground and air-to-air laser communications technology for UML-6. An estimated minimum of 10 years will be needed to create the infrastructure, processes, and guidance needed to transition air-ground communications to a system that is channel agnostic, which would allow laser communications to complement and eventually replace radio frequency communications for air-ground links to UAM vehicles. NASA should engage in research to mature this technology.

8. ***Evolve the Separation Paradigm, with Cooperative Surveillance:*** 3 nm terminal separation will not yield any appreciable density in the urban environment. Below the roofline, separation will be not detectable – and thus enforceable - except linearly, meaning when vehicles are approaching head-on or following down a corridor. The closest points of separation will be in approach and departure traffic flows. These traffic flows also need definition, in terms of routes, procedures, and allowed separation. While an extension of today's RNP procedures could be used to get to UML-4, in UML-6, a better system based on dynamic separation will be required. Building a "good" system based on the legacy NAS and maturing it will delay the process of replacing it with a new method to meet UML-6. We recommend updating the AFR paradigm to UTN and UAM concepts, and working to promote and expand it. NASA should:
    - Research urban airspace rules under reduced separation
    - Conduct research to define vertiport approach and departure
    - Conduct research simulating vertiport arrivals and departures, en route flight, under alternative rules
    - Research a plan to reduce RNP to needed levels for near-term
    - Integrate: work with the FAA to establish urban flight rules under reduced self-separation
    - Research dynamic separation not based on standard distance, for UML-6.

9. ***Development of Reliable Urban Altitude Measurements:*** There will likely be a need for dual altitude sensors, such as a radar- or laser-based finite sensor for absolute ground level and pressure altitude to smooth across the urban roofline, once an urban flight altitude set of rules is developed. Strict adherence to AGL for flight level, such as used by drones today, will require repeated changes in altitude in the urban environment that consume more energy, make traffic deconfliction more difficult, and diminish passenger comfort. NASA research should inform, not only the sensors, but the operational rules of a common definition of urban altitude, and integrate that with other research defining UAM flight rules.

10. ***Independent, Redundant, and Reliable Communications and Navigation Equipment:*** In addition to sensor fusion, dual levels of equipment are required under Part 135 for communications and navigation equipment. Redundant and independent means of communications and navigation are needed, preferably two different radios on two different bands. Multiple alternatives from the list of recommended technologies need to be developed and matured to meet this requirement for commercial flight. NASA should avoid picking one technology to test and co-develop.

11. ***Development of Aviation Certifiable Software Defined Radios:*** The 1090 MHz frequency for cooperative surveillance, required of large commercial transport aircraft, has reached a capacity constraint fueled by high demand and exacerbated by a code assignment algorithm that did not, in any way, anticipate growth or the requirement for universal use. History threatens to repeat in the proposed assignment of frequency for UAS in the command and control use of C band (5030-5090 MHz). The proposed use of re-assignable frequencies by geography (regional assignment and use rather than national) and the use of concise command codes would use the bandwidth more efficiently. Reconfigurable software defined radio (SDR) will further extend a given band's use, both for C-band C2 for UAS and the frequencies selected for UAM. Use of re-assignable frequencies in a radio and the use of SDR must be designed at the hardware level. Unfortunately,

SDR and over-the-air (OTA)[43] updateable radios will require considerable work to get through the present certification process. NASA should support and encourage SDR for aviation as a design choice and work to create SDR certification toolsets. The demand for spectrum will continue to grow, and aviation will need to get more out of its assigned frequencies through SDR.

5.2 Integration Recommendations

For more information about the rationale behind these recommendations, see Chapter 2, Sections 2.4 – 2.6.

1. ***Develop an Integrated System Architecture to Enable UML-4:*** Complex systems such as aircraft or airspace systems require more than a simple design; they require a systems analysis to match requirements with system capabilities and operational modes, and to prevent post-production rework. A systems analysis of UAM includes:

    - Definition of the "baseline mission" at UML-4.
    - The CNS product architecture starting with a technology-independent solution (see Figure 2-3).
    - Feasibility assessment of the UAM operating environment, given the implementation and integration of viable CNS technology alternatives.
    - Identification of the operational requirements needing validation; validation relates back to the ConOps where the intended operating environment is defined – ultimately, UAM will need to be tested under realistic conditions in order to validate that both the vehicles and the entire system accomplish the intended purpose, i.e., safely moving passengers from point A to point B with the demonstrated time-savings and other conveniences as expected by the customer community.
    - Hardware and software certification requirements that flow down to the specific technologies.
    - Identification of advanced development required to ensure availability of the selected technologies for the UML-4 timeframe.
    - A strategy for managing technical risks.

    The challenge for UAM is that vehicles are being designed in the absence of a UAM traffic management system. Vehicles are being designed for the as-is NAS, in advance of definition of the UAM airspace system and rules. Without the transportation system in place, we are under-informing the UAM design and development community, thus preordaining a future UAM fleet with mixed equipage and capabilities, especially as we look ahead to UML-4. Mixed fleets will actively hinder achievement of UML-4. To achieve UML-4, NASA should define the elements of the systems analysis above. The longer such elements are delayed, the further UML-4 will be delayed.

2. ***Convergence Requires a Collaboratively Developed Common Architecture and Agreed-to Integration Plan:*** A key to advancement is to be mindful that the UAM community will not converge on its own. UAM is currently being advanced by multiple actors, in multiple locations. Without a common architecture and a common integration plan at the national level, the U.S. could find itself with architectures that are configured differently in every city or metropolitan area. This outcome would stunt U.S. business growth in this industry. Ceding the job of airspace definition to other nations also runs the risk that those systems, and thus the aircraft, would be able to be integrated into the U.S. airspace system, and will impose costs on vehicle developers as each tries

[43] *OTA updates refer to the communication of software updates through RF frequencies rather than updating the software while flying.*

to develop hardware solutions without collaboration and the efficiency savings of a common standard. NASA should lead the founding of a new US industry area through definition of common architectures. NASA should integrate the common architecture concept with FAA and industry.

3. ***UAM Ecosystem Needs to Support In-the-Field Software Updates:*** Plan for vehicle software upgrades through a secure data link ("over the air") and not through swapping out hardware boxes, thus ensuring no disruption to air vehicle availability for software upgrades. Implement over-the-air or loadable software capabilities – avoid taking a vehicle out of service for prolonged periods for the purpose of making software upgrades. NASA should research the protocols and constraints needed for FAA-certifiable OTA software updates, and integrate the research product with FAA and industry to bring certifiable OTA avionics software to fruition.

4. ***Modular, Upgradeable Vehicle Architectures will Speed Growth and Break Down Barriers to Progress:*** CNS avionics design must plan for upgradability of vehicle components in integrated units from their inception, to better position the industry for growth. Design engineers should plan for scenarios 10 years out. We foresee the need for communication channel agnostic systems, in which a modular change to an antenna and to SDR allows use of a different band, different message sets, and modulations. Designers need to plan for increasingly capable sensors on the aircraft skin, which will require different placements of sensors, and thus changes in wiring placement on vehicles. Increasingly simplified vehicle operations, decreasing human machine interfaces in the cockpit, and smaller and smaller avionics will increase available cabin size as the avionics bay shrinks. Cybersecurity of these new systems cannot be ignored. Manufacturers can increase the robustness of avionics systems through user and penetration testing as much as possible. NASA should conduct research with industry to develop modular means to incorporate rapid upgrades such as complete change out of communications systems on the aircraft.

5. ***Plan a Decadal Architecture:*** Long term integrated architectures for avionics are needed to encourage and mature the avionics market for UAM. Mixed fleets are a hindrance to achieving UML-4. The decadal plan will assist in avoiding retrofits. Retrofit implementations ripple through many subsystems, and the implications may or may not be caught prior to fielding. Some implications may arise in details as minute, but important, as the speed of the ARINC buses inside a flight simulator; if they are out of sync with the field units, pilots cannot be trained on a flight upgrade to the cockpit. NASA should research a roadmap to achieve the defined UAM airspace architecture.

6. ***Training and Deployment of New Procedures and Capabilities Needs to be Synchronized:*** Ground and avionics software should match - you cannot enable a procedure for which neither an air crew is trained or air vehicle is enabled to perform. Otherwise, you run the risk of a ground instruction asking the pilot to perform an action they cannot perform, due to equipment. Include as a key feature of the CNS architecture, the identification of the avionics/instrumentation that is on the vehicle and that which is on the ground. Avoid, as best possible, mismatches between technology maturation and aviation specific performance specifications and design guidelines. Mismatches also arise from misspecified generational avionics upgrades, and from accommodating older generations of technology with newer. Such mismatches require human intervention to manage and thus resist automation. Inclusion of human management over automation generally raises operating costs. NASA should continue the decadal roadmap research in subsequent years to encompass processes to integrate mixed fleets and the tools and automation needed and integrate such findings with the FAA.

7. ***Develop a Trusted Agent in the UAM Ecosystem to Address Mixed Equipage:*** For cooperative systems, since there is a regulator, but not a system manager, a service provider (trusted agent) of

some kind must be the keeper of the system configuration for every vehicle operating in the system. This helps to identify mixed equipage and is necessary to keep avionics and ground equipment synchronized. Standards are inadequate for managing mixed fleet configurations of the industry, and should not be used as substitutes to attempt to do so. At UML-4, some of the UAM fleet of vehicles will be equipped as needed, other older vehicles that are not equipped for UML-4 type operations will need to be accommodated through procedural workarounds. Knowing which vehicles are equipped to the UML-4 performance standards, along with vehicles that are not, is tantamount. In practice, a trusted agent is a superior method for dealing with mixed fleet equipage and differing aircraft capabilities in a performance-based airspace. NASA should research the attributes and roles of trusted agents that manage UAM airspace, to increase the efficiency of mixed fleet management.

8. ***High UAM Traffic Density Requires Higher Performance Position Determination, Reporting, and New Methods for Addressing Legacy Non-cooperative Users:*** UAM requires greater traffic density and will use automated or autonomous flight, requiring a new way of thinking for highly precise positioning. This will require a reset to the higher update rate of own-position navigation equipment, and an increased rate of reporting own-position to other aircraft. Other aircraft will include legacy NAS aircraft that will lack the updated reporting frequency. There are multiple gaps here. First, avionics manufacturers use rules of thumb derived from existing NAS procedures and certifiable engineering practices. For example, for accumulated positioning error, building positioning precision to a level above what the autopilot/flight control can do is considered wasted effort. New engineering and new rules of thumb need to be developed, and this is generally accomplished through prototyping research, which NASA should encourage or undertake. Second, the message and algorithm sets for UAM must be developed from concept to hardware. Third, the ability to integrate higher precision navigationally-equipped UAM aircraft with legacy aircraft and with sUAS will need to be defined as an industry standard. NASA should encourage the development of standards that plan for mixed equipage as part of higher precision positioning avionics.

9. ***Development of Low Weight and Power Solutions to Urban Electromagnetic Interference:*** UAM's unique operating environment, coupled with the high degree of autonomy, will require low weight and power engineering solutions to electromagnetic interference, communication of traffic information, and interoperability with the existing NAS. NASA should research and test operation of low-power sensors and comms, especially GNSS navigation and low power UAT2, on board an operating electric air vehicle to determine electromagnetic interference (EMI) pitfalls and electromagnetic field (EMF) engineering needs.

10. ***Establish an Industry-Government Body to Establish Standards and Rate Complex SVO/Automation Software as a Step in Software Certification:*** The complexity of code for SVO operations and sensor processing, which may include AI, will be time-consuming to certify. The sensing algorithms integrated with the flight management computers and the auto-pilot/auto-emergency software modules will be more complex than the software designs of today's airline cockpits. Over time, and by UML-4, the software modules will become even more complex as UAM transitions to autonomy of flight. The FAA of today is ill-equipped to respond quickly to increasingly complex code for certification. This points to the need for industry consensus bodies on modular design and software design, code, and implementation maturity for the programmers that write and maintain these codes. These bodies' deliberations should develop a maturity model and requirements for the requisite software capabilities. The FAA can then lean on these bodies for standards and guidelines for software validation, and to help facilitate the certification process. When industry standards and guidance already exist, then the applicant doesn't have to wait on an

FAA developed MOC. NASA should lead and integrate, working with industry and FAA to identify and establish an independent complex aviation software standards organization to advance complex software for avionics.

11. ***Develop a Common Flight Test/Simulation Environment for CNS Avionics in UAM Operations:*** The ability to perform simulations and flight testing will likely be required by the regulators, service providers, and municipalities/port authorities to assure that novel CNS technologies for UAM applications will have the required performance to meet safety-of-flight functions and regulations. A simulation could be used to test the navigation sensors' performance and capabilities, primarily, but not exclusively, to determine if the UAM vehicles can safely land under nominal and emergency conditions. It could also be used to test the required positional accuracy standards for sufficiency as well. The simulation would start with numerical models and could proceed to a combination of numerical and physical testing. NASA should develop a flight test environment for numerous safety of flight, signal strength, EMF, cooperative separation and other testing. A physical testing area available for use over multiple generations of UAM Maturity Levels – conceivably from UML-1 to UML-6 - would be most useful.

5.3 Certification and Standards Recommendations

For a complete discussion of the state of the as-is, how to, and the background behind these recommendations, see Chapter 3.

1. ***Support UAT2 for UAM Cooperative Surveillance:*** UAT2 can borrow from MOPS, TSOs, and ACs for UAT-1 for both installation and operation (See Chapter 3 for more information). Work is needed to allocate 1104 MHz for the UAM market, develop a message set, and upgrade ADS-B ground receivers in Class B and C airspace to receive the UAT2 frequency, integrated with an ATC-select ability to receive UAM aircraft in defined airspace, such as when on approach to a large airport. This alternative poses multiple advantages for UAM, including relief from carrying two ADS-B transceivers, and NASA should pursue it as an airspace solution for UAM. In mixed fleets, UAT2 ground retransmitters may provide solutions to sUAS-UAM interoperability. NASA should research cooperative surveillance CONOPS to ensure mutual separation and coordinate flight paths (e.g. landing), as recommended in CNS. NASA should also set in motion development of a message set to maximize use of this frequency.
2. ***Develop Minimum Performance Standards for Maturing Communications Technologies:*** Half of the recommended communications technologies lack even basic minimum performance standards documents. C-band has a MOPS (RTCA DO-362) for UAS data link. The only TSO to follow is TSO-213a for C band C2, which restricts one UAS to one ground station, and no ground station may be closer to another ground station than 10 nm. TSO 213a presents a barrier to urban UTM and will be a stumbling block for urban C-band C2. For UAS flight in the urban environment, modifications to TSO-213 should be pursued. NASA should work with industry standards groups for communications technologies for UAM, particularly supporting testing.
3. ***Reallocation of VDL-3 Frequencies for UAM Air-Ground Communications:*** VDL-3 is an available aero-reserved frequency for critical and operational air-ground communications that was developed for commercial air transport but not adopted. It has several existing standards and represents low hanging fruit from a standards viewpoint for UAM air ground communications. We recommend pursuing testing and allocation of this frequency for necessary air-ground UAM communications. NASA should work with FAA to reserve frequency, within the new architecture, and should research integrating UAM in traditional NAS using data communications over VDL-3.
4. ***Develop Minimum Performance Standards for Evolving Navigation Technologies:*** Multiple feasible navigation technologies - including RF mapping, LIDAR, machine vision, and short range

radar - that UAM vehicle manufacturers are investigating for sensor fusion - do not have corresponding industry standards such as MOPS. The experience of flying drones that depend on continuous GNSS signals in the urban metal-rich, obstacle-heavy urban environment shows dependence on a single sensor for navigation is very problematic. Multiple sensor fusion MOPS need to be developed for navigation, landing, and for non-cooperative collision avoidance. NASA can support development of MOPS standards, working with RTCA to support MOPS for fusion navigation, which will accelerate maturation of the UAM industry through the establishment of common standards.

5. ***Develop Requirements for Ground-Based Non-cooperative Surveillance:*** A CNS recommendation urged research to develop preferred ground based non-cooperative surveillance. Such research needs to encompass identification of the user of ground-based surveillance. NASA should lead development of the system architecture, and include the role of the consumer of ground-based surveillance; and integrate the solution with FAA, DHS, and other government organizations.

6. ***Develop Requirements and Simulations for Conflict Avoidance Between UAM and sUAS:*** NASA should take the lead in simulating various expected sUAS/UAM traffic encounter scenarios (head-on, crossing angles, overtake, etc.), so as to develop appropriate performance requirement targets for DAA equipment to be used by both sUAS and UAM vehicles. These simulation results would add credibility to both DAA standards development and equipment designs. One way to help mitigate this DAA performance requirement burden would be to establish more definitive conflict detection and resolution rules for both parties and then test, e.g. via simulation. Gaps that NASA could help fill include: rules of airspace access, operational guidelines for airspace coordination, and procedures surrounding shared use of vertiports. These test results should be shared with standards bodies writing DAA guidelines, such as RTCA S/C -228.

7. ***Emphasize Performance Based Requirements to Foster Development of Novel Solutions to UAM CNS Capabilities:*** Performance-based requirements allow applicants to propose new and novel techniques which might otherwise be dismissed because of the time it might take to request a legal interpretation or a rule change. However, there are times when a prescriptive rule requirement can aid the furtherance of industry and safety, such as in collaborative and flight safety-critical applications. Performance based requirements are recommended for UAM vehicle navigation and surveillance. In general, non-cooperative technologies are more amenable to performance based requirements while cooperative technologies need to be very specific to function and coding, and require MOPS. NASA research should work with several technologies in CNS areas to promote standards based on performance rather than point designs.

8. ***Establish a Design Assurance Level (DAL) for UAM Designs:*** A DAL level for the U.S. UAM market needs to be established in order for the industry to go forward. UAM designs will have to consider redundant battery buses, data/control buses, and avionics to assure continued safe flight and landing under various failure conditions (e.g., a bird strike takes out electric bus A). Whether it results in a target DAL of 10^{-7} or 10^{-9}, the UAM manufacturer will need to develop a very thorough safety assessment. At a minimum, Special Condition Issue Papers will be required for: the battery technology (charging and thermo runaway containment), flight path control, automated functions, fly-by-wire, flight performance under non-normal and emergency conditions, and cybersecurity. NASA can accelerate UAM achievement by tracking and participating in standards bodies (e.g., ASTM) to develop informed standards in these areas that will lead more efficiently to industry markets for common items. NASA research should work with several technologies in CNS areas to promote standards based on performance rather than point designs.

9. ***Ensure Appropriate Aviation Type Testing As Novel Solutions to UAM CNS Capabilities Mature:*** There are various new COTS technologies that, on first appearance, seem like they will

also be appropriate for use in UAM vehicles but have never been used (stressed) in an aviation environment. This includes environmental testing (i.e., shake and bake), as well as establishing a probability of reception/availability that meets the rigor necessary for the operation. This rigor is necessary for effective standards making. NASA can help dispel some of the unfounded optimism surrounding the ease of incorporating COTS technologies by conducting preliminary and progressively more thorough testing of these technologies. The use of the cellular network or other spectrum not assigned for aviation use for critical communications may present particularly challenging issues for certification. The road to aviation use of a promising potential technology will be paved with testing. NASA should support/integrate industry and FAA as they work toward a solution.

10. ***Define Minimum Performance Standards for Autonomy and Assistive Automation and Evaluate Impact on Existing Regulatory Frameworks***: Assistive and operational UAM aircraft automation rely on sensors to perceive the environment. Regulatory allowance for sensor-based perception to conduct flight operations is extremely limited. Expansion not only of the minimum performance standards and advisory circulars governing such technologies (often proprietary), but also the operating rules that allow use of automated flight and landing under Parts 91 and 135, is needed. NASA can evaluate the sensor technology performance for these functions, assisting standards, and rule-making activity. NASA should conduct research to assist in the extension of FARs permitting operational use of sensors in place of physical human eyes, working with industry standards bodies to integrate findings.
11. ***Research and Mature Digital Data Communications Architectures:*** Although an enhancement to communications efficiency, CPDLC is not sufficient as a means of compliance to voice communication[44] equipment requirements of 14 CFR parts 91, 121 and 135, and is not required by these rules. CPDLC functions are not yet consistently supported across the domestic U.S. To allow for SVO and increasingly autonomous operations, greater use of digital data communications in the FAA infrastructure should be accelerated as part of NAS evolution. NASA should conduct research to identify how CPDLC can be standardized for required UAM communications, especially when operating in traditional NAS. NASA should also conduct research to identify processes to reduce controller workload in mixed traffic, using CPDLC in the NAS, and conduct research to identify whether VDL-3 CPDLC could be used to coordinate vertiport operations.
12. ***Research and Define Appropriate Spacing Standards in Urban Airspace Procedures:*** An extension of RNP concepts for urban tolerances provides one way to achieve dense urban traffic for UAM and UAS. Given the multi-year timelines for developing new separation guidelines, work should start now on defining new vehicle separation procedures that allow for closer spacing than 3 nm. NASA should lead the effort to define reduced spacing for UAM operations.

5.4 Interoperability Recommendations

For more information about the gaps in interoperability between sUAS and UAM, see Chapter 4.

1. ***Research Collaborative Autonomous Operations for UAM and sUAS:*** Aircraft below rooftop level in an urban environment will not be able to operate on the basis of continuous contact with a remote operator. The command and control in urban aircraft will need to be designed to operate around these conditions, and sUAS and UAM will have to work cooperatively to both traverse the environment safely and maintain cooperative spacing, without the assistance of a human pilot in the loop. Research in this area of collision avoidance automation should be pursued, as it is custom software not available as COTS, and will need to become an industry standard. NASA should also

[44] FAA AC 90-117, Data Link Communications

research the alternatives in Table 4-1 to determine best alternatives for sharing situational awareness between UAM and sUAS.

2. ***Define Standards for Data Exchange Between UAS Service Suppliers (USS):*** There is a need for the establishment of standards for data exchange architecture and CNS services provided by the many separate USS providers. A competitive avionics marketplace would thrive if CNS avionics serve both on UAS and UAM. Similarly, data exchange protocols, both air-to-air and air-to-ground, should be established and standardized sufficiently to accommodate the operations of a heterogeneous vehicle set. The standards in place today are being tried out for rural areas and the densities being codified today will not support dense urban operations. While such protocols are normally established by standards setting bodies, NASA can provide, through analysis and testing, the data required for those bodies to establish the needed standards.
3. ***Define the Role of the Air Authority Service Provider (AASP):*** As long as there are multiple service providers (USS) managing sUAS operations, there will be a need for a central organizer for AASP – an agreed entity that fulfills the AASP role. NASA should seek to identify and advocate for such an entity during its participation in UAM industry activities.
4. ***Build Consensus on Equitable Access to Low Altitude Airspace Between sUAS and UAM:*** The issues of equity must be remembered, and sUAS delivery priority preserved next to UAM flights. NASA should advocate for equity in airspace access among operator classes.
5. ***Determine if a Cooperative Surveillance Model can be Shared Between sUAS and UAM:*** Conduct comparative testing to determine the best technical means among the alternatives for cooperative surveillance to serve both constituents. This includes selection of a common frequency in the aviation protected spectrum. NASA should lead/integrate to define the authority that provides the communication gateway between sUAS and UAM, in collaboration with industry, for the system architecture. NASA should test and support development of the means by which cooperative shared surveillance assures safety between sUAS and UAM.
6. Alternatively, ***Determine Whether a Dual Stack Cooperative Surveillance Solution with Rebroadcasting Meets the Performance Requirements:*** Investigate the feasibility of a data lake for cooperative surveillance using a dual stack with rebroadcast between UAS and UAM. Determine whether broadcast TIS is sufficient for UAS-UAM separation.
7. ***Research Common Navigational Solutions for Vertical Autoland for sUAS and UAM:*** NASA should determine the business case and operational rules behind shared sUAS and UAM vertiport use. Having established the scope of common airspace need, NASA should research whether UAM autoland capabilities and sUAS autoland capabilities are compatible. Do the navigation systems needed for low visibility operations work for both constituencies? NASA should research the safety and affordability requirements of both constituents, and determine compatibility for vertiport use.
8. ***Determine Requirements and Processes for Collecting Data on Urban Terrain and Cultural Features/Obstacles:*** Data on obstacles and terrain can be gathered by urban sUAS or by UAM and shared across both communities for greater safety and efficiency, given that there is an established process for data gathering and consolidation. Agreements and standards need to cover authentication and traceability of navigational and terrain information. Standards will be needed to ensure accuracy and upgrades for use in the new UAM/sUAS ecosystem for height keeping and vertical separation. NASA should work to integrate data set and CNS sharing between the UAM and sUAS communities.

9. ***Develop Standards for U.S. Vertiports:*** U.S. standards are needed to define vertiport classes covering function, layout, and user classes. Consider allowing helicopters to land at vertiports as well.
10. ***Conduct Real-World Testing for All Viable CNS Technologies:*** Perform testing of the recommended viable sensing and RF technologies proposed for UAM/sUAS avionics to provide the in situ performance and reliability data upon which rational choices can be made among competing alternatives.
11. ***Provide an Open Forum for Sharing Interoperability Test Results:*** Provide the test results data to standards bodies that they will need to establish the industry standards for UAM/sUAS interoperability.
12. ***Develop an Operational Test Facility to Examine Interoperability Integrity and Reliability:*** Provide an operational test facility, either using an actual city or simulating one in a realistic manner that will provide actual data on the integrity and reliability of the various proposed methods for shared operations at vertiports.

5.5 Summary

This report identifies the recommended CNS technologies needed to enable a new form of air transportation that is expected to mature into a popular urban alternative. It will operate in a physically challenging airspace where traditional CNS technologies will be unreliable or overwhelmed by the forecasted traffic. Existing and novel technologies to support UAM at UML-4 have been evaluated by the SAIC team and select alternatives recommended.

A significant challenge to realizing these solutions in an urban environment is the scarcity of appropriate RF spectrum and the highly competitive demands on spectrum already in use. In addition to identifying the most recommended technologies and their spectrum bands, this study also describes the industry and government contributions needed to bring new technologies into standards for certification and commercial use, and identifies stumbling blocks in integration and interoperability with sUAS that will be encountered in the path to implementation.

Because traditional NAS CNS technologies are not expected to support the densities of UML-4, they must be replaced with new airspace rules and processes that support independent collaborative decision making, to replace the existing command ATC structure. Since UAMs are designed to relieve urban congestion, they will require new spacing requirements, much closer than today's NAS. These requirements are the basis for the CNS technologies recommended in this report. UML-4 cannot be achieved until a selection of the recommended CNS technologies are described in aviation standards and available as avionics.

One recommendation rises above all else: in order to enable UML-4 and beyond, the development and maturation of the CNS technologies to achieve UML-4 is required. While this will be a collaborative effort of all the UAM stakeholders, a central organizer is needed to push these ideas to fruition or UML-4 will not be achieved. Industry self-interest dictates building air vehicles to operate in today's NAS, in order to generate a return on their investment as soon as possible. The FAA's first job is serving the traffic of today rather than tomorrow. Neither of these stakeholders, working alone, will develop and implement a safe, viable, and efficient UML-4. If UML-4 is to be achieved, NASA must lead the development and maturation of the CNS technologies that are necessary conditions of a UML-4 system.

Contract Number: GS00Q14OADU130 Delivery Order: 80GRC019D0017, Deliverable 5

Reliable, Secure, and Scalable Communications, Navigation, and Surveillance (CNS) Options for Urban Air Mobility (UAM)

Appendix A: UAM CNS Functional Specifications

12 August 2020

Prepared for:
NASA Glenn Research Center

Prepared by:
SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

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The material is based upon work supported by the National Aeronautics and Space Administration under Contract Number GS00Q14OADU130.

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APPENDIX A: UAM CNS FUNCTIONAL SPECIFICATIONS

1. Communications, C2, Air-Ground, Vehicle to AOC, Vehicle Position Reports, Downlink

Piloted and Non-Piloted

Definition: Vehicles need to be monitored by owner/operators to ensure compliance with flight plans

SPECIFICATIONS:

Availability/Reliability:	100% when airborne, downlink assurance 99.9%
Capacity/Demand:	100 bits per msg, 1 Hz per aircraft (continuous)
Precision:	Tenths of degree-minutes/NACp = 11
Update Rate:	Once per second
References:	FAA, "UAS C2/CNPC Regulatory Framework and Technical Evolution," Presented by Jain, R., FAA AIR-6B2, July 2019 [retrieved November 9, 2019] Rios, J., Smith I., Venkatesen P., Homola J., Johnson M, and Jung J., NASA "UAS Service Supplier Specification, Baseline requirements for providing USS services within the UAS Traffic Management System," NASA/TM-2019-220376, Oct 2019 Mark, R., "Five Years After MH 370, Aviation Industry Rolling Out Tech To Ensure No Plane Disappears Again," Forbes Magazine, May 4, 2019. https://www.forbes.com/sites/rmark/2019/03/04/five-years-malaysia-370-disappear/#7aa019832c7b [retrieved May 13, 2020]

2. Communications, C2, Air-Ground, Vehicle to AOC, Flight Plan, Uplink

Piloted & Non-Piloted

Definition: Like for-hire aircraft today, an aircraft owner/operator maintains an operational center (AOC) where flight plans are created, sent to the aircraft (& pilot) and filed with the FAA. When the aircraft needs to change its flight plan due to weather or other hazards, the AOC negotiates and plans the new flight plan and transmits it to the flight deck

SPECIFICATIONS:

Availability/Reliability:	Depends on ConOps: an air-ground link may not be needed if the flight plan and alternates are loaded to the aircraft at the vertiport; If an air-ground upload is needed, 10^-5, similar to aircraft health.
Capacity/Demand:	UML1-2: Less than or equal to 100KB at a time. UML 3-4, LT 2 MB/hr. UML 6, Less than or equal to 10 MB/hr. Assume flight plan is 1-2KB each, each flight includes primary and secondary plans. Number per city UML1-2, a dozen aircraft at a time max. UML3-4, 200 veh/hr; UML6, 5000 veh/hr.
Precision:	N/A
Update Rate:	Assume flight plans are 1-2 KB, communicated once or twice per flight.

3. Communications, C2, Air-Ground, Vehicle to AOC, Vehicle Health Reports, Downlink

Piloted and Non-Piloted

Definition: Like for-hire aircraft today, aircraft owners are required to maintain an independent communication with aircraft that monitors aircraft condition and issues

SPECIFICATIONS:

Availability/Reliability:	10^-5, (ACARS requirement)
Capacity/Demand:	Assume message size similar to flt plan.

Precision:	N/A
Update Rate:	On status change - after take off, start cruise, every 15 minutes during flight, begin ascent, on ground; may be continuous (recommended).

4. Communications, Vehicle Situational Awareness, Out-the-Window (OTW) Video, Downlink

Non-Piloted

Definition: OTW video, downlink. A great deal of weather expertise and judgment is incorporated in a human pilot. A vast suite of sensors would be required to fully replace the pilot's situational awareness of hazards, including weather, both before takeoff and en route. For instance, many airports do not have lightning sensors. Incorporating an OTW video to remote surveillance is an additional needed safety net.

SPECIFICATIONS:

Availability/Reliability:	100% when airborne, downlink assurance 99.9%
Capacity/Demand:	0.5GB/aircraft while on
Precision:	480p
Update Rate:	60Hz
Notes:	HD-quality video uses about 0.9GB (720p), 1.5GB (1080p) and 3GB (2K) per hour. UHD quality video uses a lot of data. A 4K stream uses about 7.2GB per hour. Service uses 562.5MB of data/hour at 480p resolution (standard definition). At 60 Hz and 720p 1.86GB/hour, 3.04GB/hour at 1080p, 15.98GB/hour in 4K.
References:	Android Central, "How much mobile data does streaming media use?" https://www.androidcentral.com/how-much-data-does-streaming-media-use [retrieved March 25, 2020] Price, D., "How Much Data Does Streaming Video Use?" MakeUseOf, December 13, 2019, https://www.makeuseof.com › tag › how-much-data-does-streaming-video-use [retrieved May 13, 2020]

5. Communications, FAA Voice Comm

Piloted and Non-Piloted

Definition: Required communications with ATC in Class A/B/C/D airspace.
Autonomous operations will require voice comm to either transition to datalink or have the capability for ATC-to-AOC transmission, such as over VOIP.

SPECIFICATIONS:

Availability/Reliability:	Per current FAA specifications.
Capacity/Demand:	64 kbps. 4KHz digital voice bounced via C2. Future: controller may have VOIP or may procedurally reduce the need.
Precision:	N/A
Update Rate:	In current NAS, every aircraft has a minimum of 4 comms per sector.
Notes:	1) For certain ConOps, may be needed only in case of emergency. 2) This communications function is currently addressed by VHF/UHF radios, or ACARS based datalink. VOIP is a possible technology alternative.

6. Communications, Broadcast Position and Intent

Piloted and Non-Piloted

Definition: Includes UAM-to-UAM and UAM to non-UAM cooperative aircraft Detection & Tracking. Supporting technologies include ADS-B, TCAS and DAA solutions. Specifications for this function are closely linked with related FAA requirements for "well clear", collision avoidance, and surveillance (transponder, Mode C, S, ADS-B out, etc., as applicable. Surveillance sensor specifications should be addressed within this line item, including DAA. Position is required under Mode C veil; intent is required for commercial aircraft with more than 30 passenger seats. Given the high density of urban airspace, and lack of ATC-provided separation, intent increases safety.

SPECIFICATIONS:

Availability/Reliability:	100%
Capacity/Demand:	116 bits per msg
Precision:	Relevant only to navigation precision.
Update Rate:	Own-aircraft positional awareness requirement of 10 Hz and 100m.
References:	ASTM F38 WK62668 Committee, Draft “Detect and Avoid Performance Requirements”, September 19, 2019 Thipphavong D., Cone A., Park C., Seung ML., and Santiago C. “SC-228 Defining the Collision Avoidance Region for DAA Systems” https://ntrs.nasa.gov/search.jsp?R=20160010603 [retrieved May 13, 2020]

7. Communications, Passenger Welfare, Passenger Emergency Communications

Non-Piloted

Definition: Passenger emergency communications: video and voice (PTT) to AOC, potentially to ANSP/USSs/police

SPECIFICATIONS:

Availability/Reliability:	5 second reliability (Latency).
Capacity/Demand:	4 KHz voice; intermittent use.
Precision:	N/A
Update Rate:	Infrequent use: emergencies only.

8. Communications, Vehicle Situational Awareness, Receive/Uplink (Wx, etc.)

Piloted

Definition: FAR 135.175 & 121.357 require approved wx radar equipment for a/c over 12,500 lbs. max gross takeoff weight. FAR 135.173 requires approved thunderstorm detection equipment for aircraft over 9 pax

SPECIFICATIONS:

Availability/Reliability:	No change to current requirement.
Capacity/Demand:	No change to current requirement.
Precision:	No change to current requirement.
Update Rate:	No change to current requirement.
Notes:	Pilots currently obtain weather from company briefs, from FIS-B, from UAT, from commercial service, etc.

9. Navigation, En Route (Lateral)

Piloted and Non-Piloted

Definition: The aircraft must know where it is and be able to self-locate in order to complete a flight to a destination and to avoid known obstacles and hazards. If autonomous or in low visibility, such location relies on sensors.

SPECIFICATIONS:

Availability/Reliability:	For autonomy, will need 99% and possibly higher availability, due to operating constraints, namely low range on battery. Based on ILS, which has 95-98% availability.
Capacity/Demand:	N/A
Precision:	Precision/Lateral Position Certainty: less than 100m. For example, lateral position certainty must be better than 100 m at UML-4 due to assumed density. NACp of 3 m seems advisable when flying past skyscrapers full of people. 5.1 m (10 Hz @ 100 kts).
Update Rate:	At 10 Hz and 100kts, minimum lateral position uncertainty = 5.1 m (before considering precision inertial navigation). UAM-UAM collision avoidance buffer: 4 seconds.

10. Navigation, En Route (Vertical/Altitude)

Piloted and Non-Piloted

Definition: The aircraft must be able to conform to an assigned or suitable altitude for its speed, phase of flight, vehicle size and potentially other considerations. Altitudinal separation is assumed to be used to prevent collisions and thus the aircraft must know its altitude.

SPECIFICATIONS:

Availability/Reliability:	For autonomy, will need 99% and possibly higher availability, due to operating constraints, namely low range on battery. Based on ILS, 95-98% availability.
Capacity/Demand:	N/A
Precision:	14 CFR Part 43 Appendix E alt calibration requirement is 125 ft (barometric altitude). RVSM altitude system error, the error between the displayed/system error and true altitude must be less than 245 ft.
Update Rate:	10Hz, assumed. Current D-GPS units capable of 5 Hz. Speed and closer approach of autonomous vehicles requires higher certainties. 10Hz achievable with current electronics.
Notes:	If vehicles are expected to operate below 400 ft, need precision near to 10 ft due to obstacle avoidance. If vehicles can operate much higher, can be closer to 100 ft.
References:	"Altimetry System Error," Skybrary, EASA Flight Safety, 18 July 2019.

11. Navigation, Approach, Low Precision (Lateral)

Piloted and Non-Piloted

Definition: –The aircraft must selflocate with greater precision in the x,y coordinate plane for approach (compared to the precision required in cruise or en route phase of flight)

SPECIFICATIONS:

Availability/Reliability:	For autonomy, will need 99% and possibly higher availability, due to operating constraints, namely low range on battery. Based on ILS, 95-98% availability.

Capacity/Demand:	N/A
Precision:	4.5 meters
Update Rate:	10Hz (by assumption). Current DGPS capable of 5 Hz. Speed and closer approach of autonomous vehicles requires higher certainties. 10Hz achievable with current electronics.
Notes:	1.) Assume vehicle slows speed during approach Speed level determined in part by allowable positioning error (0.76m, 4.5m). Ex: Assuming approach speed of 50 kts (example from helicopter approach plates), closure rate is 84 fps. Average human reaction time is 0.2 sec; 0.2 sec distance is 17ft. Average US urban building-to-buildlng (street) separation is 72'= 2*(8' sidewalk+8' parking)+4* (10') driving. If a vehicle is 50' then margin = 22', less 17' reaction time leaves 5 ft/2 so precision for 50 ft vehicle must be around 2.5 ft or 0.76m. If a vehicle is 25' wide then margin = 47', less 17' reaction leaves 30 ft precision, 15' on each side, precision must be 4.5 m. 2) Navigation accuracy (if separating from known obstacles) is only as accurate as the underlying database that supports it. McCutchan, S., PlannersWeb, September 24, 2013, "How Wide Should a Neighborhood Street Be?" http://plannersweb.com/2013/09/wide-neighborhood-street-part-1/ [retrieved May 13, 2020] "Uber Air Vehicle Requirements and Missions," undated, https://s3.amazonaws.com/uber-static/elevate/Summary+Mission+and+Requirements.pdf [retrieved May 18, 2020] EVTOL News, "A3 Vahana eVTOL Tiltwing," as linked from Vertiflite, March/April 2018. https://evtol.news/2018/02/26/a3-vahana-evtol-tiltwing/ [retrieved May 18, 2020]

12. Navigation, Approach, Low Precision (Vertical/Altitude)

Piloted and Non-Piloted

Definition: –The aircraft must selflocate with greater precision than in en route when on approach to a vertiport with uneven obstacles potentially in its flight path; unlike a public airport, the flight path may not be obstacle free.

SPECIFICATIONS:

Availability/Reliability:	For autonomy, will need 99% and possibly higher availability, due to operating constraints, namely low range available on battery. Based on ILS, 95-98% availability.
Capacity/Demand:	N/A
Precision:	Altitudinal position certainty under precision within 5 feet for rotorcraft gentle landings. 5 meters [GBAS]; 2 ft radar altimeter.
Update Rate:	At 10 Hz and 100kts, minimum lateral position uncertainty = 5.1 m (before considering precision inertial navigation).
Note:	Approach phase may be the final nm or may be the final 100 yards before touchdown; exact distance is an undefined part of ConOps.
References:	FAA, FAA Order 6750.24E, "Instrument Landing System and Ancillary Electronic Component Configuration and Performance Requirements" March 29, 2012,

	https://www.faa.gov/documentlibrary/media/order/6750.24e.pdf [retrieved May 18, 2020] Eltahier, M. M. A., Hamid K., "Review of Instrument Landing System" IOSR Journal of Electronics and Communication Engineering (IOSR-JECE) e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 12, Issue 2, Ver. III (Mar.-Apr. 2017), PP 106-113 www.iosrjournals.org

13. Navigation, Landing, High Precision (Lateral)

Piloted and Non-Piloted

Definition: The aircraft must be able to sense location in low visibility conditions and with sufficient update rates to land safely on a vertiport at a high degree of availability.

SPECIFICATIONS:

Availability/Reliability:	For autonomy, will need 99% and possibly higher availability, due to operating constraints, namely low range on battery. Based on ILS, 95-98% availability.
Capacity/Demand:	N/A
Precision:	Precision/Lateral Position Certainty: better than 1.5 meters (5 feet) in precision situations (landing) based on team analysis of standard helipad size.
Update Rate:	At 10 Hz and 100kts, minimum lateral position uncertainty = 5.1 m (before considering precision inertial navigation).
References:	FAA, FAA Order 6750.24E, "Instrument Landing System and Ancillary Electronic Component Configuration and Performance Requirements" March 29, 2012, https://www.faa.gov/documentlibrary/media/order/6750.24e.pdf [retrieved May 18, 2020] Eltahier, M. M. A., Hamid K., "Review of Instrument Landing System" IOSR Journal of Electronics and Communication Engineering (IOSR-JECE) e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 12, Issue 2, Ver. III (Mar.-Apr. 2017), PP 106-113 www.iosrjournals.org

14. Navigation, Landing, High Precision (Vertical/Altitude)

Piloted and Non-Piloted

Definition: The aircraft must be able to sense location in low visibility conditions and with sufficient update rates to land safely and without a "hard landing," on a vertiport, at a high degree of availability.

SPECIFICATIONS:

Availability/Reliability:	For autonomy, will need 99% and possibly higher availability, due to operating constraints, namely low range on battery. Based on ILS, 95-98% availability.
Capacity/Demand:	N/A
Precision:	Precision/Position Certainty: 0.3 meters in precision situations (landing) - for soft landing.
Update Rate:	At 10 Hz and 100kts, minimum lateral position uncertainty = 5.1 m (before considering precision inertial navigation).
References:	FAA, FAA Order 6750.24E, "Instrument Landing System and Ancillary Electronic Component Configuration and Performance Requirements" March 29, 2012,

	https://www.faa.gov/documentlibrary/media/order/6750.24e.pdf [retrieved May 18, 2020] Eltahier, M. M. A., Hamid K., "Review of Instrument Landing System" IOSR Journal of Electronics and Communication Engineering (IOSR-JECE) e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 12, Issue 2, Ver. III (Mar.-Apr. 2017), PP 106-113 www.iosrjournals.org

15. Surveillance, Ground Monitor of UAM, Aircraft Detection and Tracking

Piloted and Non-Piloted

Definition: AASP and/or USSs need to monitor the airspace to 1) verify that authorized aircraft are where they say they are and are operating normally and 2) monitor dynamic density

SPECIFICATIONS:

Availability/Reliability:	For UAM health, should be operational 99% of time during prevailing flight hours.
Capacity/Demand:	Depends on area area to be covered. Coverage area may be flight routes, core urban area, or perimeter. May eventually extend to greater regional areas such as the NY-BOS corridor, or greater LA area (33,000 sq mi) . For the purposes of alternatives analysis, lacking a defined area, we assumed surveillance of a 100 sq mi urban core.
Precision:	Must be able to detect a small UAM (2-3 sq m cross section) among clutter.
Update Rate:	Cooperative comm is at least 1/sec. Verification sensing must be more frequent than every 4 sec to confirm. (1,2) second frequency of sampling preferred.

16. Surveillance, Ground monitor of Non-UAM, Aircraft Detection and Tracking (non-cooperative aircraft)

Piloted and Non-Piloted

Definition: AASP and/or USSs need to monitor the airspace to detect noncooperative and unauthorized aircraft

SPECIFICATIONS:

Availability/Reliability:	For detecting unauthorized aircraft, availability should be based on urban requirements (which are currently not known). Assume 90% of time; unplanned outages limited to 1 hr continuous during operational hrs.
Capacity/Demand:	Depends on area area to be covered. Coverage area may be flight routes, core urban area, or perimeter. May eventually extend to greater regional areas such as the NY-BOS corridor, or greater LA area (33,000 sq mi) . For the purposes of alternatives analysis, lacking a defined area, we assumed surveillance of a 100 sq mi urban core.
Precision:	To detect aircraft, must be able to detect a small UAM (2-3 sq m cross section) among clutter. UAS detection may impose higher requirements.
Update Rate:	Every 1 or 2 seconds.

17. Surveillance, UAM to Non-UAM, Aircraft Detection and Tracking of Non-Cooperative Aircraft

Piloted & Non-Piloted

Definition: The UAM needs to be able to detect and avoid non-cooperative aircraft, whether they are cloaked police/security vehicles, UAS, or potentially unauthorized aircraft, that present a hazard.

SPECIFICATIONS:

Availability/Reliability:	Must be operative to fly the aircraft.
Capacity/Demand:	N/A
Precision:	Must be able to detect a 5-lb UAS or bird (enough to cause damage) at a distance sufficient to avoid collision. At low altitude, speed is slower but multipath is present. Need 1.5 second reaction time for humans, 0.2 reaction time for automatic pilot.
Update Rate:	10 Hz based on own-aircraft positional awareness requirement of 10 Hz and 100m.

18. Surveillance, UAM Non-Aircraft Detection

Piloted and Non-Piloted

Definition: UAM vehicle must avoid obstacles including cranes, flagpoles, wires, buildings, etc. Applies particularly to autonomous operations and operations in low visibility.

SPECIFICATIONS:

Availability/Reliability:	Must be operative to fly the aircraft. Can potentially be same sensor for landing system (dual use).
Capacity/Demand:	N/A
Precision:	Must be able to detect large obstacles that could cause substantial damage to UAM in a collision with sufficient time to avoid the collision. Detect 0.5m^2 at 150 ft range in crowded environment.
Update Rate:	10 Hz based on own-aircraft positional awareness requirement of 10 Hz and 100m.

Contract Number: GS00Q14OADU130 Delivery Order: 80GRC019D0017, Deliverable 5

Reliable, Secure, and Scalable Communications, Navigation, and Surveillance (CNS) Options for Urban Air Mobility (UAM)

Appendix B: Technology Attributes Worksheets

12 August 2020

Prepared for:
NASA Glenn Research Center

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SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

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The material is based upon work supported by the National Aeronautics and Space Administration under Contract Number GS00Q14OADU130.

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APPENDIX B: TECHNOLOGY ATTRIBUTES WORKSHEETS

5G, Cellular

Area and Functions: Comm, C2

Description: Next generation of cellular communications technology, frequency modulation techniques, and network capability/capacity/data update rates. 5G is the fifth generation set of protocols and technologies for cellular phones, and is being defined by the 3GPP group in sequential releases. Every release (Rel) adds features or refines previously outlined features, which the cellular providers can choose to implement on 5G devices. 5G's predominant characteristic is moving service definition to the maximum extent possible to software definition, "edge computing" and the 5G control plane. Edge computing extends the cloud into the core network to reduce latency. The 5G control plane turns the core into cloud services with entirely PKI-based security framework. All the 4G boxes become content workers translating for 5G. Some of the notable features for 5G include network slicing: the network is entirely virtual (software defined, not hardware defined) so you can apply a firewall inside the network functions. A network slice can be applied on anything: it could be a network slice for autonomous cars, or a network slice for Netflix, or a network slice for online access within a building; and it could be a network slice inside a network slice.

The FCC auctioned parts of spectrum from 35 GHz to 70 GHz for 5G in 2019. Operating cell phone service in these bands means very low propagation: it won't penetrate a fuselage; that the beam must be formed and focused on a point to deliver service, and that very high data rates with a very high number of channels are delivered. The band is not a required part of 5G, it is coincident; 5G software can be offered at MHz if the spectrum is available. In practice, the 5G being implemented in the U.S. in 2019-2020 does not contain most of the advertised features of 3GPP. 5G in 2020 does not contain sidelink and network slicing. New antennas are required for beamforming and will take investment to roll out.

1. Air or Ground Based? on vehicle?
- *Air based with ground-based network.*

2. Size
- *Airside: Less than 3" x 5" x 0.25." Possible fit on a quarter (see reference [1]).*
- *Groundside: Antenna size similar to airside.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)
- *Airside less than one pound.*
- *Groundside: Probably 0.2-5 lbs with cabling.*

4. Power
- *Airside: Less than one watt continuous.*
- *Ground side: Probably less than 60 W continuous.*

5. Frequency and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS
- *For 2020s, from 900 MHz up to 70 GHz. 5G is a comm protocol that can be used from KHz to 99 GHz.*
- *Capacity: Multi GB per second.*
- *In GHz range above 4GHz, highly obstructable, including by operator's fingers, leaves, aircraft skin.*
- *Range: 500 meters. Requires networked transmission.*

6. Cost

- *Probably $1000 per air-based unit.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Better at high levels when networked.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Less saturated at large sporting events than 4G.*
- *Night operations at low and high traffic levels: Works at night. Better in high traffic levels.*
- *VMC and IMC with high winds, low and high traffic levels: Signal can be blocked by leaves, other aircraft.*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: Better at high traffic levels due to networking. Provides beneficial location services in emergency.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: No prioritization for aviation planned for 5G in emergencies, may experience 5G black out in emergencies.*
- *Operator with ill intent: Will be on the front edge of cybersecurity warfare.*
- *Bird events: A heavy flock of birds can block signal, or one bird resting on the antenna.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. For communications, no impact from non-cooperative traffic/not detected.*

8. Advantages relative to other technologies serving this function

- *Significant infrastructure is already in place – the Internet of Things (IoT) is happening, and there is significant research and commercial development ongoing to leverage the technology for UTM and fleet management systems.*
- *The MU-MIMO processing does not permit cellular signals to be eavesdropped upon (per DD, MIMO protocol summary).*

9. Disadvantages relative to other technologies serving this function

- *Requires cellular carriers to prioritize aircraft comms to be used for C2; otherwise, not appropriate for safety critical systems (i.e. DAA or C2), per FAA.*
- *Market case for upward pointing antennas may be lacking. Carriers would have to implement upward-pointing antennas.*
- *Roaming. Switching from one network to the next is problematic and non-harmonized; causes call dropping which disproportionately affects ground users.*
- *Fee for use structure.*
- *GPS could be a single point of failure for cellular communications since towers use GPS for timing.*
- *Wireless carriers have not shown a willingness to prioritize air traffic for cellular use. This would make LTE ineligible for any CNS function. They could implement that change in their networks by 2035, but there does not seem to be a market case for it.*
    - *Range limits on GHz band would require ground antennas approximately every half-mile if used for flight-critical application.*
    - *Network slices could solve many of these concerns but is not currently being implemented.*
    - *Sidelink would need to be implemented on the network for cooperative surveillance function.*

10. Precision

Geopositioning technology of 5G good to one meter altitudinally and laterally.

11. **FAA Acceptance**

    None at present.

12. **Cybersecurity and Privacy**
    - *In 2020, the primary security for this medium consists of beamforming. Signal reception is limited to a small geographic area of half a degree of angle and less than a mile of range. For an aircraft, this would mean only devices onboard or attached to the aircraft could intercept signals, unless another aircraft (e.g., sUAS) were in the beamwidth within range.*
    - *Rel 17 includes network slices, which would provide "pretty good" security, akin to VPNs today. In 2020, network slices have not been implemented in the field by the cellular companies, even in cities where 5G service is available; but could be implemented by UML 4. This is a market decision by the carriers.*
    - *Forward looking security explorations include Quantum Key exchange for security, using AI/Machine Learning for security, and integration with satellite, high altitude relay platforms etc., especially for rural coverage and more edge capable networks. Forward looking discussions include use of the 70-300 GHz range, and use in rural and agricultural sectors. [2]*
13. **Maturity in time: use** at what UML levels?
    - *UML-2-6.*
    - *Offered COTS in UML-2 timeframe but without features needed for C2, such as prioritization, network slices.*
14. **Ground Architecture**
    - *For beamforming, new antennas need to erected. These can be placed on existing cell towers. To serve UAM, new antennas will need to point at altitudes of the UAM traffic. Sidelink is not presently enabled. Sidelink would enable networking among end users, where one signal is carried from one user to another until reaching a tower or the intended other party. Without sidelink, new towers or clusters of antennas will need to be installed in order to offer service over an urban area with decreased range of the signal. New antennas can be placed on existing structures with permission of the structure owner, but communication cabling and power are required up to the antennas, as well as maintenance access.*
    - *Since 5G networks are built for terrestrial mobile applications, the following reasons must be addressed in order to serve UAM or aviation applications:*
        - *For initial 5G deployments, mm-wave frequencies will not allow long-distance communications in rain conditions, around building, or through trees.*
        - *5G base stations will be positioned for optimal coverage of foot traffic in major cities, not for airborne traffic.*
        - *Terrestrial antennas are designed for "downtilt" to provide gain to mobile devices, while aviation applications will require "uptilt" (pointing at altitudes of the UAM traffic, as aforementioned).*
        - *Aviation applications cannot afford the loss of messages that may occur during mobile traffic overload conditions.*
        - *Terrestrial 5G networks will not accommodate the degree of Doppler shift that occurs with high-velocity aircraft.*
        - *Mobile spectrum licenses specifically prohibit ground-to-air applications.*

15. References

- *[1] O. Haraz, M. Mamdouh Ali, A. Elboushi, A.R. Sebak, "Four-Element Dual-Band Printed Slot Antenna Array for the Future 5G Mobile Communication Networks," The 2015 IEEE AP-S Symposium on Antennas and Propagaion and URSI CNC/USNC Joint Meeting,Vancouver, CAN. July 2015.https://ieeexplore.ieee.org/document/7304386*
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5G, Satellite Integration

Area and Functions: Comm, C2

Description: In December 2019, the 3rd Generation Partnership Project (3GPP) agreed to add the satellite-integration specification to Release 17 of its 5G technical standards. The latest development in the 3GPP Working Groups did not come as a surprise because the consensus was that satellite should and must be part of the 5G standards. According the Global Special Mobile Association forecast[1], 5G could account for over one billion connections by 2025. In order to meet the increasing global connectivity demand of the world's population, satellite-integration specifications must be defined and added to the 5G standards to provide worldwide 5G-capable Internet access. The basic function of satellite Internet is that it generally relies on a satellite (GEO) or a constellation of satellites (LEO), a number of ground stations or gateways that relay Internet data to and from the satellite, and a small antenna at the subscriber's location. Satellite integration into 5G[2], and related topics have been well researched[3] to support 5G network development based on 3GPP specifications and standards. Different schemes and computing framework have been proposed to reduce satellite delay and expand coverage[4].

Due to its low latency and high throughput, we will use Telesat LEO and Gilat Satellite Networks' modem as the baseline for this 5G over satellite technology assessment. Gilat modem was used in the first ever demonstration of 5G services over Telesat LEO satellite connected to the University of Surrey's 5G testbed network[5].

1. Air or Ground Based? on vehicle?

Air and ground.

2. Size

- *4.4 H x 48 W x 44 D cm (Gilat Model GLT1000 modem).*
- *A small antenna.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

4.5 kg (9.9 lbs.).

4. Power

- *50 W.*
- *300 W EIRP[6] (power to antenna).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *950 – 2150 MHz. Note that Gilat Satellite Networks claims that GLT1000 can support C, X, Ku, and Ka-bands.*
- *In general, Ka and Ku Satcom bands are used commercially to transmit low-quality video, MBps rate (U.S. Army ref).*

- *Note that Gilat also has a dual-band Ku/Ka airborne terminal designed inflight connectivity Model AeroEdge 6000 that includes a Ku/Ka antenna, SkyEdge II-c Taurus MODMAN, Ku/Ka Antenna Networking Data Unit (KANDU), and Wavestream's Ku/Ka Radio Frequency Units (KRFU). This Ku/Ka airborne terminal has never been tested for 5G over satellite.*
- *Not Aero-reserved; licensed.*

6. Cost

Cost is not available at this time.

7. Use Case Evaluation

- *Ka-band signals affected by atmosphere situations like rain[3], snow, and clouds.*
- *VMC at low traffic levels (nominal), and IMC at low traffic levels. No impact is expected; however, study should be conducted for UAM aircraft.*
- *VMC and IMC at high local traffic levels such as a large sporting event: No impact is expected.*
- *Night operations at low and high traffic levels. No impact is expected.*
- *VMC and IMC with high winds, low and high traffic levels. UAM vehicles should not fly in the condition of high wind; however, satellite signals are not affected by high wind in the urban environments, except high wind that brings in dust, rain, or snow.*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: No impact is expected.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: No impact.*
- *Operator with ill intent: TBD.*
- *Bird events: Not applicable.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Not applicable.*

8. Advantages relative to other technologies serving this function

- High system throughput and low latency (30 to 50 ms) for 5G over LEO satellites.
- Can support wide range of latency-critical applications.
- Wide coverage for 5G over GEO satellites.

9. Disadvantages relative to other technologies serving this function

- *Earth fade due to terrestrial obstructions or objects (mountains, towers, buildings, etc.) block the view to LEO satellites, which cross the sky at lower elevation below obstructed objects.*
- *Major challenge in using LEO satellites for 5G is the strong Doppler effect between ground terminals and satellites due to the rapid movement with respect to the Earth's surface.*
- *Latency may be a problem for 5G satellite integration for critical functions. The approximate latency of GEO Satcom is 270 milliseconds and for LEO 30 milliseconds.*

10. Precision

Not applicable.

11. FAA Acceptance

No FAA acceptance for Gila Modem GLT1000 (Note that AeroEdge 6000 Ku/Ka airborne terminal is compliant with ARINC-791 and RTCA/DO-160G).

12. Cybersecurity and Privacy

Advanced encryption standard (AES) 256 bits.

13. Maturity in time: Use at what UML levels?

- *UML-2-6.*

- *Although Telesat LEO service will not be available until 2023, Gila satellite modem GLT1000 and AeroEdge Ku/Ka airborne terminal have been in the market for several years.*

14. Ground Architecture

- *3GPP has agreed to add satellite-integration specifications to its 5G technical standards. Evolution in satellite ground network architectures are not well documented and implementations may not follow existing standards, as the functions are deployed on vendor-specific networks. A general reference model for a multi-gateway satellite ground network segment is currently structured in the following three main subsystems:*
  - *The access subsystem includes the satellite gateways (GWs) and satellite terminals, which are interconnected through the resource of one or several channels (transponders) of a communication satellite.*
  - *The core subsystem is an aggregation network that interconnects different GWs located in the same or different satellite hub or teleport facilities as well as the network nodes located in some points of presence (PoPs) to connect with other operators, corporations, and ISPs.*
  - *The control and management subsystem includes network elements such as the Network Control Center (NCC) and the Network Management Center (NMC).*

  Research is needed to provide a reliable and secure ground network architecture for satellite integration into 5G to support aviation in the urban environment, specifically in Software Defined Networking (SDN) and Network Function Virtualization (NFV).

15. References

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- *[2] Florian Volk et al., "Satellite Integration into 5G: Accent on First Over-The-Air Tests of an Edge Node Concept with Integrated Satellite Backhaul," Future Internet, 5 September 2019.*
- *[3] Beatriz Soret, Israel Leyva-Mayorga, Maik Roper, Dirk Wubben, Bho Matthiesen, Armin Dekorsy, Petar Popovski, "LEO Small-Satellite Constellation for 5G and Beyond-5G Communications," Department of Electronic Systems, Aalborg University, Denmark, arXiv: 1912.08110v1 [cs.NI], 17 December 2019.*
- *[4] Lei Yan, Suzhi Cao, Yongsheng Gong, Hao Han, Junyong Wei, Yi Zhao, Shuling Yang, "SatEC: A 5G Satellite Edge Computing Framework Based on Microservice Architecture," Sensors, 18 February 2019.*
- *[5] University of Surrey's 5G testbed network (https://www.surrey.ac.uk/5gic).*
- *[6] EIRP = Equivalent Isotropic Radiated Power*

ACAS X, TCAS

Area and Functions: Surv, ATC; V2V

Description: TCAS = Traffic collision avoidance system, uses Mode C or Mode S transponders (per TSO C118, RTCA DO-197) onboard aircraft to cooperatively avoid collisions. TCAS works by sending interrogations to another aircraft's transponders. The transponder will reply to the interrogation in a similar way it responds to radar. From the time difference between the interrogation and the reply, the distance to the other aircraft is calculated. The reply itself contains the altitude of the other aircraft.

The distance and the altitude difference with the other aircraft is tracked to identify a trend. From successive distance measurements the closure rate is determined. With the closure rate and the current distance (slant range) an approximation is made of the time to the closest point of approach (CPA). This is done by simply dividing the range by the closure rate, the result is called 'range tau'. The same is done in the vertical plane. Dividing the difference in altitude by the vertical speed difference leads to the vertical tau. If both taus are less than a certain threshold, a Traffic Alert (TA) is raised. When the taus are less than another (lower) threshold, a Resolution Advisory is given. The TA is a 'heads up' indication; the RA is an instruction that must be followed by the pilot to reduce the collision risk. The threshold times depend on the altitude, ranging from 20 seconds (<1000 ft AGL) to 48 seconds (> FL200) for TAs and from 15 seconds (<2350 ft) to 35 seconds (> FL200) for RAs. Below 1000 ft AGL, RAs are inhibited. TCAS I only provided alerts; TCAS II allows for RAs. Originally designed for large fixed wing aircraft, the advisories are limited to altitude and heading movements, not speed.

ACAS-X is the next generation of TCAS, with detection algorithm optimization. ACAS XA – The general purpose ACAS X that makes active interrogations to detect intruders. ACAS XA is the baseline system, the successor to TCAS II. ACAS XA /XO standards were published by RTCA DO-385 and EUROCAE ED-256 in September 2018. Amendments to ICAO provisions and regulatory approval for ACAS XA /XO are pending.

ACAS XO – ACAS XO is an extension to ACAS XA designed for particular operations, like closely spaced parallel approaches, for which ACAS XA is less suitable because it might generate a large number of nuisance alerts. ACAS XA /XO standards were published by RTCA DO-385 and EUROCAE ED-256 in September 2018. Amendments to ICAO provisions and regulatory approval for ACAS XA /XO are pending.

ACAS XU – Designed for Remotely Piloted Aircraft Systems (RPAS), incorporating horizontal resolution maneuvers. Work on Standards started in 2016 and is expected to be finished in 2020 (FAA Joint Resource Council (JRC) is not funding this activity at this time).

ACAS XP – A future version of ACAS X that relies solely on passive ADS-B to track intruders and does not make active interrogations. It is intended for general aviation aircraft (that are not currently required to equip with TCAS II).

1. Air or Ground Based?

- *Air.*

2. Size

- *Size of typical general aviation piece of equipment.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Estimated at less than two pounds.*

4. Power

- *Probably less than 20 watts.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Requires use of the 1030 MHz (for interrogation) and 1090 MHz.*

6. Cost

- *General aviation (GA) equipment is estimated to be around $10,000 to $12,000, per aircraft (transport category equipment could be > $60,000, and would likely be combined with a dual*

Mode S transponder procurement). If installed, it would likely be part of an OEMs avionics suite if allowed on UAM.

7. **Use Case Evaluation**
   - *Would provide intruder aircraft range/altitude (and trend) to the onboard surveillance processor (likely would require multiple sensor sources for a complete surveillance picture).*
8. **Advantages** relative to other technologies serving this function
   - *Equipment is commercial availability.*
   - *Would provide an input to the surveillance processor.*
9. **Disadvantages** relative to other technologies serving this function
   - *Cost of equipment.*
   - *1090MHz frequency congestion issue. FAA proposed prohibition on use of 1030/1090 MHz on UAS/UAM.*
10. **Precision**
    - *TCAS I/II are dependent on a valid intruder aircraft altitude reply for ranging. This has been improved with the increasing use of serial altitude encoders that can output at 25 foot accuracy. TCAS ranging via interrogation is very accurate (slant range like DME).*
11. **FAA Acceptance**
    - *MOPS and TSO currently exist. Advisory circulars are also available to support installation and testing.*
12. **Cybersecurity and Privacy**
    - *Would be difficult to spoof since must be in the interrogation receive/response view.*
13. **Maturity in time:** Use at what UML levels?
    - *UML-1-6.*
    - *Equipment currently exists.*
14. **Ground Architecture**
    - *Mode A, Mode C, and Mode S transponders respond on 1090 MHz to ground secondary surveillance radar (SSR) interrogations (on 1030 MHz) with the aircraft's transponder code, for radar identification. Mode C and Mode S transponders are the "radio" component to TCAS. SSRs are usually co-located with primary radar and provide identification of the radar targets in the datablock. The SSRs are connected to the ERAM or to terminal radar systems(ARTS/STARS) by ground wire, fiber, or FAA remote communications air-ground (RCAG) .*
15. **References**

"GTS 8000 TCAS/ACAS II," Garmin website, https://buy.garmin.com/en-US/US/p/106233.
Walter Bender, "ACAS-sXu Concept / Standards / Certification," 7 Nov 2019, FAA briefing charts.
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Wayne Rosenkrans, "ACAS X," AeroSafety World, Flight Safety Foundation, October 2014. https://flightsafety.org/asw-article/acas-x/.
"Introduction to TCAS II Version 7.1" FAA brochure, HQ-111358, February 28, 2011,
https://www.faa.gov/documentLibrary/media/Advisory_Circular/TCAS%20II%20V7.1%20Intro%20booklet.pdf

"Integration of ACAS-X into Sense and Avoid for Unmanned Aircraft Systems" FAA, https://www.faa.gov/uas/research_development/information_papers/media/Integration-of-ACAS-X-into-SAA-for-UAS.pdf.

16. Other Notes

- *Mode S radio also transmits other data in the unused data space of its transmissions, such as roll angle, selected altitude, barometric pressure setting, true track angle, ground speed, track angle rate, true airspeed, magnetic heading, indicated airspeed, mach, barometric altitude rate, and inertial vertical rate. Data transmitted in the extra bits is set by standards groups and can be updated and changed.*
- *It should be noted that MIT-Lincoln Labs studied the use of orthogonal waveforms in Mode S transmissions for datacomm and concluded that it could not be assured that such waveform datacomm would be invisible to the existing ATCRBS system without modification of the ground units.*

Acoustic Detection, Air and Ground

Area and Functions: Surv, Ground; V2X

Description: Acoustic sensor technologies have been studied for UAS BVLOS detection, and for aiding collision avoidance with cooperative and non-cooperative air traffic. The technology works by detecting the low-frequency sounds emitted by aircraft ranging from small ultralight aircraft to military transport aircraft. By simultaneously using a number of spatially separated microphones in an array configuration, the detection, localization, and tracking of an acoustic source such as an aircraft can be achieved. [1,2] Acoustic sensors do not typically have the capability to be a primary detection source. Acoustic technology might typically be considered validation tools or secondary sensors to primary detection systems (radar and RF). [5]

1. Air or Ground Based? on vehicle?

- *Air or Ground.*
- *May be on vehicle for the detection of other manned or unmanned aircraft for which a noise signature may be obtained.*

2. Size

- *Minimal. Varies. Circuit boards approximately 3" x 3", Microphones approx .5" x 1". Has been miniturized for small UAS (UAS under 55 pounds). [3]*
- *Ground: 415 mm x 54 mm x 475 mm. [6]*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *UAS: Minimal. Lightweight circuit boards and microphones as needed. Approx. < 1 lb. Has been miniturized for small UAS (UAS under 55 pounds).*
- *Ground: 6 kg. [6]*

4. Power

- *UAS: minimal. Has been miniaturized for small UAS (UAS under 55 pounds).*
- *Ground-based detection unit: 48 VDC (18 V to 75VDC), 600 mA 30 W. [6]*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Not in RF range.*

- *Acoustic range depends on background noise. In rural/farm environment reliable detection at 5-10km; not tested in urban environment. Estimate 100-1000m in urban environment, depending on background noise and UAS/UAM traffic density.*
- *Would function but be somewhat attenuated BVLOS.*

6. Cost

- *Estimated cost of ground and air systems from $5000 to $100,000.*
- *On an advanced drone (inlcuded with drone cost): $30,000.*

7. Use Case Evaluation

- *Night, VMC, and IMC at low traffic levels: Would work in both VMC and IMC.*
- *Night, VMC, and IMC at high local traffic levels such as a large sporting event: Testing required to determine capacity or scenario limits of acoustic-based detection technology.*
- *Gusty or high winds: Winds may produce noise across the microphone(s) reducing ability to detect.*
- *Emergencies: Works without operator input (emergencies); may not work in high winds or certain scenarios/traffic.*
- *Operator with ill intent: May be acoustically blinded by noise, noise jamming.*
- *Bird events: No impact or negative affects found.*
- *Would detect non-cooperative traffic.*

8. Advantages relative to other technologies serving this function

- *Can detect cooperative and non-cooperative aircraft.*
- *Would work in both VMC and IMC.*
- *Could be paired with complementing technology, such as optical, radar, or lidar.*
- *Does not rely on ground or air communications or data networks.*

9. Disadvantages relative to other technologies serving this function

May require acoustic tuning for the UAS on board noise and possibly environmental noise. May be impacted by wind. [1]

10. Precision

- *UAS: Test results from one test series/ConOps. For the FAA Pathfinder Program test ConOps located at the Gypsum test range, Salina Kansas, the system demonstrated the ability to reliably detect an incoming intruder at a range of 10 km (~5.4 NM) and 360 degree field of view with zero missed detections and no false alarms. This range is significantly longer than the visual detection distance (DEVLOS) of 2.37 NM and is nearly double the recommended minimum detection distance. [3]*
- *Ground Detection: Performance can be ConOps dependent. Example of ground drone detection system: the acoustic coverage of Discovair G2 is 105 degrees in azimuth and 105 degrees in elevation for a single Sensor Unit. Each Sensor Unit is typically capable of detecting drones at a range of up to 500m. Depending on drone size and sound, detections have been observed as far as 1km. Combining multiple Sensor Units into a single system can extend both range and coverage. [6]*

11. FAA Acceptance

Analysis completed of PrecisionHawk on-UAS solution as part of the FAA PathFinder Program. [3]

12. Cybersecurity and Privacy

Does not rely on ground or air communications or data networks.

13. Maturity in time: Use at what UML levels?

- *UML-2-6.*
- *Currently in use and shows promise. However, without acoustic tuning false detections can occur [4], so the technology may need further testing and development to be adapted to high traffic, noisy, urban environments.*

14. Ground Architecture

- *Air to air acoustic surveillance does not require ground infrastructure; any shared common operating picture would be shared over communication equipment.*
- *Ground surveillance of air vehicles in a university research used a rooftop-mounted tower with four 0.5" free field microphones with pre-amplifiers. Estimated cost less than $1000 per structure. University study recommends fusion detection of acoustic, visual, and RF with processing equipment for 1-km range. Each sensor requires a small amount of power. A real-world implementation would require one sensor suite every kilometer. A perimeter or area protected by such sensors would require ground communication from sensors to surveillance authority.[7]*

15. References

[1] Ismail Guvenc, Ozgur Ozdemir, Yavuz Yapici, Hani Mehrpouyan, and David Matolak, "Detection, Localization, and Tracking of Unauthorized UAS and Jammers, "ICNS 2017.

[2] Mohammad Mahdi Azari, Hazem Sallouha, Alessandro Chiumento, Sreeraj Rajendran, Evgenii Vinogradov, and Sofie Pollin, "Key Technologies and System Trade-Offs for Detection and Localization of Amateur Drones," Proceedings of the IEEE, arXiv:1710.08478v1 [cs.NI] 14 Oct 2017 [link 4]

[2] https://www.aopa.org/news-and-media/all-news/2018/may/03/acoustic-detection-and-avoidance

[3] Allison Ferguson, Pathfinder Focus Area 2 PHASE III REPORT by PrecisionHawk, 2018, https://www.faapathfinderreport.com/

*[4] Acoustic Detection of a Fixed-Wing UAV, Brendan Harvey * ID and Siu O'Young, 15 January 2018. https://www.mdpi.com/2504-446X/2/1/4/pdf*

[5] FAA, Unmanned Aircraft System Detection - Technical Considerations, Retrieved 2/13/2020, https://www.faa.gov/airports/airport_safety/media/Attachment-3-UAS-Detection-Technical-Considerations.pdf

[6] Squarehead technology. Retrieved 2.14.2020, https://www.sqhead.com/wp-content/uploads/2018/10/Drone-Detection-Discovair-G2-brochure.pdf and https://www.sqhead.com/drone-detection/ and https://www.sqhead.com/industrial-measurements/acoustic-camera/

Example on vehicle Acoustic Detection for UAS: Precision Hawk:
https://www.bing.com/videos/search?q=acoustic+Precision+Hawk+daa&view=detail&mid=DF02A012C450424C7EC3DF02A012C450424C7EC3&FORM=VIRE

[7] Xiufang Shi, Xie Weige, Chaoqun Yang, Zhiguo Shi, " Anti-Drone System with Multiple Surveillance Technologies: Architecture, Implementation, and Challenges," IEEE Communications Magazine, April 2018.

ADS-B Out, as Currently Mandated

Area and Functions: Surv, ATC; U2U

Description: Automatic Dependent Surveillance–Broadcast (ADS-B) is the satellite-based successor to radar.[1] It uses GPS with WAAS to determine an aircraft's location and broadcasts that information to a network of ground stations, and to nearby aircraft equipped to receive that information via ADS-B In. ADS-B broadcast services take advantage of ADS-B In to provide traffic, weather, and other flight information directly to the cockpit at no subscription cost. Two systems have been approved by the FAA for ADS-B: Mode S and UAT. FAR 14 CFR 91.225, 14 CFR 91.227 mandate that as of January 1, 2020, aircraft must be equipped with ADS-B Out to operate in Class A, B, and C airspace, above the Class C floor, and within 30 miles of any Class B airspace. ADS-B In hooked up to a display allows equipped aircraft to electronically see other aircraft around their aircraft, from air-to-air broadcasts received by own-aircraft or by displaying the traffic information broadcast from a gound station.

1. Air or Ground Based?

On vehicle.

2. Size

From size of a circuit card (integrated electronics) to hand-held (small brick) to avionics unit less than 10" x 8" x3."

3. Weight

From 500 g to 2 kg.

4. Power

Standard aircraft power (28v).

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *1090/1030 MHz using the mode-S extended squitter (downlink format 17) of the SSR transponder, with about 50 kHz of bandwidth; and*
- *978 MHz (UAT, Universal Access Transceiver), using a larger bandwidth of about 1.3 MHz for the optional display of aviation weather (FIS-B) as well as traffic (TIS-B).*
- *Aero-reserved.*

6. Cost

$1500 for parts up to tens of thousands range for certified avionics.

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal) and IMC at low traffic levels: Usable at low levels of traffic.*
- *VMC and IMC at high local traffic levels such as a large sporting event: High numbers of UAM users in a dense environment would overwhelm the available frequencies and ATC.*
- *Night operations at low and high traffic levels. Not affected by nighttime; see previous note about high traffic levels.*
- *VMC and IMC with high winds, low and high traffic levels. Not affected by weather and winds; see previous note about high traffic levels.*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: Useful if onboard ADS-B can squawk the appropriate code in emergencies*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Not useful in high traffic levels. Not affected by emergency situations.*

- *Operator with ill intent: ADS-B can be used to track a known operator if not disabled.*
- *Bird events: Bird strike may disable antenna but otherwise not a factor.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: ADS-B not useful in detecting non-cooperative traffic in any weather or at any time.*

8. Advantages relative to other technologies serving this function

- *Allows for ADS-B traffic, weather, and flight-information services.*
- *Aircraft location is easily detected with standard mandated avionics or with COTS low cost equipment.*
- *ADS-B improves safety and efficiency in the air and on runways, reduces costs, and lessens harmful effects on the environment.*
- *Supplement to ground-based radar for ATC surveillance. Deployment of ADS-B out receivers provide ATC coverage of areas not previously served by ground based radars (i.e., Gulf of Mexico), which has benefit of more efficient traffic spacing/handling.*

9. Disadvantages relative to other technologies serving this function

- *Privacy concerns due to the transmitted Mode S address being easily traceable to the registry number, thereby transmitting flight activity of the registered owner (public information). In 2020, FAA introduced a method of anonymizing Mode S addresses to mitigate these concerns.*
- *Can be spoofed with minimal hardware.*
- *Police helicopters can turn off ADS-B, so they are sensor-invisible.*
- *ADS-B out on the 1090 Mhz frequency is threatened with a frequency saturation issue, and as such has been discouraged for use by UAS, threatening interoperability of traditional aircraft, UAM and UAS.*

10. Precision

ADS-B provides position information, a Navigation Integrity Category (NIC) value based on the GPS Horizontal Protection Limit; and a Navigation Accuracy Category for position (NACp) based on the Estimated Position Uncertainty / Horizontal Figure of Merit. The ADS-B transmitter will encode the NIC/NAC as 0 (unknown) if the positioning system cannot provide integrity or accuracy. The aircraft's NIC must be less than 0.2nm (NIC≥7), NACp less than 0.05nm (NACp ≥ 8), and velocity NACv must be less than 10ms-1 (NACv ≥1). Per TSO-C129 (or later revision), TSO-C145a/C146a (or later revision), or TSO-C196 (or later revision).

11. FAA Acceptance

Mandated: FAR 14 CFR 91.225, 14 CFR 91.227. On January 1, 2020, aircraft must be equipped with ADS-B Out to fly in most controlled airspace.

12. Cybersecurity and Privacy

- *Privacy concerns due to the transmitted Mode S address being easily traceable to the registry number, thereby transmitting flight activity of the registered owner (public information)*
- *Can be easily spoofed.*
- *Police and law enforcement air vehicles can turn off ADS-B, so they are sensor-invisible.*

13. Maturity in time: Use at what UML levels?

- *UML-1 through UML 4.*
- *Currently mandated. May experience saturation and other limitations in airspace with UAM and other air traffic congestion. The allocation algorithm in ADS-B was not designed for any kind of*

density and is overwhelmed in dense airport environments by jet assignments; use for dense UAS and UAM operations would be highly impractical.

14. Ground Architecture

- *Air to air works with or without ground retransmission for aircraft equipped with ADS-B In. Blind spots are possible due to antenna placement on the aircraft.*
- *Mode S transponders transmit on 1090 MHz to ground secondary surveillance radar (SSR) interrogations (on 1030 MHz) with the aircraft's transponder code, for radar identification. ADS-B Out is also transmitted on a prescribed intermittent basis for air-to-air cooperative tracking. SSRs are usually co-located with primary radar and provide identification of the radar targets in the datablock. The SSRs provide the ADS-B information to UAT rebroadcast transmitters on the ground, which broadcast traffic information within range for a traffic situation display on UAT-display equipped aircraft. UAT antennas also provide received traffic information to the rebroadcast antennas.*

15. References

[1] FAA NextGen Office press release: "ADS-B Broadcast Services.")
"FAA Worried About ADS-B, 1090 MHz Interference " Aviation Week, May 12, 2016. https://aviationweek.com/commercial-aviation/faa-worried-about-ads-b-1090-mhz-interference
"Inert and Alert: Intelligent ADS-B for UAS NAS Integration Concept of Operations " Uavionix White Paper.
"Equip ADS-B PIA User Guide," FAA White paper, undated (2020.)

16. Other Notes

Potential mitigations for ADS-B out use for UAS/UAM: "The Battle for Drone Tracking Technology", UASVision, https://www.uasvision.com/2017/05/05/the-battle-for-drone-tracking-technology/
Three-step mitigation approach:
1. Reduce the number of drones with ADS-B. Only a mandate for drones that are conducting risky operations – flights over people, BVLOS, or even near airports or in controlled airspace.
2. Reduce the transmit power. The biggest impact to solving the potential spectral problem is by drastically lowering the power output of the transceivers – which directly correlates to the range of how far the signal can be "heard." The power standards that exist today were determined for manned aviation for the purpose of communicating with the ATC system over long distances (100-200 miles or more). If the primary focus for drones is to alert only nearby aircraft – this power can be significantly reduced. A recent study by MITRE's Center for Advanced Aviation System Development (CAASD) confirmed this hypothesis and found a power setting range that was compatible with the high-density predictions.
3. Reduce the number of transmissions. Through the "Inert and Alert" concept, operators and airspace users can monitor the drone and the airspace to only transmit if needed for safety reasons. These reasons may include the presence of a nearby aircraft, entering into controlled airspace, maneuvering above an altitude threshold, or a lost command link scenario.
Ground station network established in the U.S. Satellite based ADS-B surveillance now in NAT as of 2019 (Iridium based, provided by Aireon's Next Satellite constellation). ANSP requirement specifications for space based ADS-B may vary (e.g., update rates, antenna diversity, etc.).

http://interactive.aviationtoday.com/avionicsmagazine/march-2019/space-based-ads-b-going-live-in-the-north-atlantic-airspace/.

UAT ADS-B 2nd Frequency on 1104 MHz

Area and Functions: Surv, ATC; U2U

Description: A second UAT frequency at 1104 MHz (referred to as UAT2), presents an opportunity for UAM operations to solve multiple needs. This second UAT frequency (UAT2) could provide, (1) addressable data uplink communication; (2) surveillance (State Vector) broadcast messages to other vehicles; and (3) vehicle health information to support UAM operations. It is intended that this adaptation would be in compliance with the current RTCA DO-282 UAT modulation scheme and forward error correction (FEC) format.

1. Air or Ground Based? on vehicle?

- *Both, would require UAT2 ADS-B transmit and receive (often referred to as ADS-B "Out" and "In") equipment on the UAM vehicle, as well as UAT2 ground stations to transmit/receive UAT2 information. The required number of ground stations would be based on service volume and required probability of reception.*

2. Size

- *General aviation piece of avionics radio, potentially miniaturizable to a single board computer with antenna.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Estimated at less than two pounds.*

4. Power

- *Probably less than 15 watts.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Aero-reserved frequency at 1104 Mhz, with band mask and modulation scheme identical to 978 Mhz UAT.*
- *Subject to atmospheric bending, range can be 60 miles under appropriate circumstances.*

6. Cost

- *$1,500 to $6,000, but would likely require dual equipage for dispatch capability.*

7. Use Case Evaluation

- *VMC at low traffic levels (nominal), and IMC at low traffic levels: Usable at low levels of traffic.*
- *VMC and IMC at high local traffic levels such as a large sporting event: UAT2 capable of providing services at high local traffic levels, unlike 1090MHz. ATC can screen out non-controlled traffic by geography and frequency to reduce viewing clutter.*
- *Night operations at low and high traffic levels: Atmospheric carry sometimes greater at night but otherwise, see previous note about high traffic levels.*
- *VMC and IMC with high winds, low and high traffic levels. Not affected by weather and winds; see previous note about high traffic levels.*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: Useful if onboard ADS-B can squawk the appropriate code in emergencies.*

- *City emergency in VMC, IMC, high wind, and/or high traffic levels: UAT2 capable of handling large emergencies and could be configured to send fleet-wide alerts.*
- *Operator with ill intent: ADS-B can be used to track a known operator if not disabled.*
- *Bird events: bird strike may disable antenna but otherwise not a factor.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: ADS-B not useful in detecting non-cooperative traffic in any weather or at any time.*

8. Advantages relative to other technologies serving this function

- *Would have commercial availability.*
- *Solves multiple spectrum needs.*
- *As a new technology, can design in weather; other status messages such as alternate routes in the unused milliseconds of delivery.*

9. Disadvantages relative to other technologies serving this function

- *Cost of equipment.*
- *Would likely require redundant equipment.*

10. Precision

- *As output by NIC and NAC values of installed navigation equipment, but not a factor in this determination.*

11. FAA Acceptance

- *Need to develop MOPS standards for UAT2; installation guidance and testing criteria already available.*

12. Cybersecurity and Privacy

- *Encryption would be designed into the MOPS standards.*

13. Maturity in time: use at what UML levels?

- *UML-3-6.*
- *MOPS standards not currently available.*

14. Ground Architecture

- *Air to air works with or without ground retransmission for aircraft equipped with suitable displays for traffic information display. Blind spots are possible due to antenna placement on the aircraft.*
- *ADS-B Out via UAT can be transmitted on an intermittent basis for air-to-air cooperative tracking. The FAA does not publish information on the location of ground antennas for UAT, but they may be co-located with Seconday Surveillance Radars (SSRs) that receive 1090 MHz transmissions. ADS-B information from both 1090 and UAT frequencies is relayed via ground networks to UAT rebroadcast transmitters, which broadcast traffic information to aircraft within range.*

15. References

RTCA DO-282B document for the figure referenced in Footnote 1, may be purchased from RTCA, Inc. 1150 18th Street NW, Suite 910, Washington, DC, 20036, www.rtca.org.
See Section XVI of the NPRM on proposed restricted use of transponders and ADS-B out: https://www.federalregister.gov/documents/2019/12/31/2019-28100/remote-identification-of-unmanned-aircraft-systems.

16. Other Notes

- *The UAT one second frame is divided into a synchronous ground uplink segment and the non-synchronous ADS-B message broadcast segment, as shown in DO-282B Figure 1.The UAT one-second frame accommodates a synchronous ground uplink segment and the non-synchronous ADS-B message broadcast segment. The ground segment provides 32 message start opportunities (MSO slots) of 4000 bits each, that is currently being used to uplink Flight Information Service - Broadcast (FIS-B) (e.g., weather radar, winds aloft, temporary flight restrictions [TFR], etc.), for those aircraft that have ADS-B "In" capable equipment installed. The ADS-B segment makes a once per second pseudo-random broadcast from among 3,200 MSOs to output aircraft State Vector (SV) information (24-bit identification, position, velocity, altitude, etc.), as well as other aircraft information (i.e., emitter category, TCAS capability, etc.) which can either be in every one second message broadcast or "on-condition" (i.e., every Nth message or when a static parameter changes status, e.g., gear up or down). The pseudo-random MSO slot selection is used to improve the probability of message reception (i.e., to lessen the possibility of another aircraft stepping on your broadcast).*
- *On December 31, 2019, the Federal Aviation Administration (FAA) issued a Notice of Public Rule Making (NPRM) (Federal Register Document Citation 84 FR 72438, FAA Docket No.: FAA-2019-1100 – see references), for performance-based Remote Identification of Unmanned Aircraft Systems (UAS). In this NPRM, the FAA proposes to prohibit UAS vehicles from using transponder or ADS-B equipment , basically to prevent frequency congestion from an expected overwhelming amount of future UAS vehicle operations. This prohibition is expected to also apply to UAM vehicles.*
- *Second UAT Frequency Proposal – Given the above NPRM announced prohibition, and the FAA Spectrum Office's proposal for a second UAT frequency at 1104 MHz (referred to as UAT2), presents an opportunity for UAM operations to solve multiple needs. This second UAT frequency (UAT2) could provide: (1) addressable data uplink communication; (2) surveillance (State Vector) broadcast messages to other vehicles; and (3) vehicle health information to support UAM operations. It is intended that this adaptation would be in compliance with the current RTCA DO-282 UAT modulation scheme and forward error correction (FEC) format.*
- *Addressable Data uplink – It is proposed that the current UAT ground uplink segment be restructured to support UAM vehicle addressable uplink messages. Currently, this ground uplink is used for FIS-B weather information by identifying MSO slots to a specific ground station (e.g., slots 11, 12, 13) to prevent frequency interference with an adjacent ground station uplink broadcast. If the UAM has a pilot, then the uplink message to a specific vehicle might be "Proceed to the alternate Vertaport," but in autonomous mode, there is no human to receive a textual message, so an uplink message might be as simple as "EX(ecute) 41"). The important aspect of this proposal is that a "close-loop" confirmation to the uplink message could be made through the ADS-B message broadcast format. These addressable uplink messages would be via "private" encryption to provide proprietary security to the UAM Operation Center (UOC).*
- *State Vector (SV) Message – The SV message would be the same format as with the 978 MHz UAT message. The vehicle identification, position, velocity, and altitude information would be in a "public" encryption format to allow other UAM vehicles to receive/share the SV position report to support surveillance monitoring. However, to get a complete picture, the on-board*

surveillance monitor may need to receive civil ADS-B and remote ID input to form a complete surveillance picture.

- *Health Monitoring Messages – The optimal use of a second UAT message format would be to output UAM vehicle health information that is important to the UOC operator, such as:*
  - *Fan No X amperage high.*
  - *Fan No X RPM low.*
  - *Battery temperature high, etc.*
- *These messages (and others important to safe UAM operation) would be via a "private" encryption format for the specific UOC operator; in addition, the ADS-B segment could be used to provide a downlink message to the UOC to acknowledge reception of an addressable up-link (ground segment) message (e.g.," EX 41 acknowledged").*
- *Standards Development – Much of the UAT2 MOPS development can be taken directly from RTCA DO-282 MOPS, just relocating the center frequency to 1104 MHz as opposed to 978 MHz. Modulations, FEC, spectrum masking will still apply. The UAT2 can provide the same SV messages as UAT (and with UAT2 ADS-B "in" would be one input to the onboard UAM surveillance processor. Standardized UAM health messages in the ADS-B Segment could be developed, or it could be OEM specified. The main effort will be defining how the Uplink Segment can be restructured to provide addressable uplink messages, and how the ground station will format, sequence, and broadcast these messages. It is anticipated that this effort would take 18-24 months to accomplish. It is also anticipated that this would include time to determine probability of uplink message reception and a ground station deployment investigation/scheme.*
- *Bottom Line – The establishment of a second UAT (UAT2) function on protected spectrum frequency (1104 MHz) has the potential to address three areas of concern to UAM operations; communication, part of the total surveillance picture from SV messages (augmented with civil ADS-B "In" receive capability), and vehicle health monitoring to the vehicle's urban operation center (UOC).*

Advanced Doppler Range Gating Radar, Ground

Area and Functions: Surv, Ground

Description: Pulse Doppler and Range gated radar are radars fitted with advanced processing techniques specifically designed to reject clutter from ground, birds, rain, ground water (sea) and ground. Filtering techniques have improved year after year over the past few decades and processor improvements make them easier to accomplish. The algorithms cited here are assumed applied to a standard airport surveillance type radar, as in the cited sources, but these algorithms could also be applied to smaller planar array radar, for smaller size and greater cost.

1. Air or Ground Based? on vehicle?

- *Ground: Advanced radar with moving target detection with Doppler range-gating and background decluttering.*

2. Size

- *Antenna width: 17.5 ft. Rotation rate 13 rpm.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Compare to airport radar: Several tons, possibly 10 meters high.*

4. Power

- *High power, over 1KW continuous.*
- *PRF 1000Hz. C/N =40 dB.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Wavelength S-band, 10.7 cm wavelength; 1.55 to 5.2 GHz spectrum; need to avoid 2.4GHz cellular. 2.4-2.283 is unlicensed band. 3.55 to 3.7 is shared spectrum.*
- *Range – 60 nmi.*

6. Cost

- *Between $2 and $9M each.*

7. Use Case Evaluation

- *S-band resistant to rain and snow attenuation*
- *Handling of obstructions and BVLOS: Need to 8 to 10 pulses per sec to reject birds, rain, ground clutter in pulse Doppler filtering. Also use spatial clutter map memory as a software add to de-clutter displays.*

8. Advantages relative to other technologies serving this function

- *Proven technology.*

9. Disadvantages relative to other technologies serving this function

- *Relatively expensive and would require multiple ground stations to surveill an urban environment.*
- *Availability is below 90%; generally around 87% availability.*

10. Precision

- *Resolves aircraft 360 degree rotation.*
- *At cited wavelengths, will resolve small aircraft and many sUAS easily.*

11. FAA Acceptance

- *Would want to avoid i/f with nearby airport radar.*
- *Has weather radar applications so FAA approval likely.*

12. Cybersecurity and Privacy

- *No privacy implications.*
- *No cybersecurity implications other than industrial hacking vulnerability and potential loss of service. Relies on physical security for protection.*

13. Maturity in time: use at what UML levels?

- *Available on market now. UML 1-6.*

14. Ground Architecture

- *This radar would comprise a large piece of ground architecture for ground-based surveillance. If utilized, each radar would require a free-standing base capable of supporting its weight and significant power, likely DC to the unit and conditioned at the radar. It may require an equipment shed or locker. Power hookups, physical base, and communication of the radar returns to the surveillance authority via communication lines would be required. The radar signal is blocked by buildings and physical structures so use of a Doppler-range gate radar would require multiple stations in order to resolve UAM traffic from buildings. If UAM traffic flew straight down streets, radar could be pointed down street views to resolve traffic, but there would need to be multiple* *radar to resolve all the traffic, which is unlikely to be cost effective compared to other alternatives.*

15. References

Dr. Robert M. O'Donnell (MIT Lincoln Labs), IEEE Guest Lecture (New Hampshire section), "Radar Systems Engineering – Clutter Rejection," Nov. 2009. and

L. Cartledge, R.M. O'Donnell, "Description and Performance Evaluation of the Moving Target Detector," FAA and MIT-Lincoln Laboratory, NTIS, June 1977.

J. Herd, S. Duffy, D. Carlson, M. Weber, G. Brigham, C. Weigand, D. Cursio, "Low Cost Multifunction Phased Array Radar Concept," FAA Contractor Report, IEEE Proceedings, DOI: 978-1-4244-5128-9, 2010.

Cost information based on Airport surveillance radar cost range. www.prnewswire.com/news-releases/telephonics-awarded-airport-surveillance-radar-8-asr-8-secondary-surveillance-radar-ssr-systems-upgrade-contract-from-nasa-300755100.html

Altimetry, Barometric Pressure Altitude

Area and Functions: Nav, Appr; EnRt; Land

Description: Traditional barometric pressure altitude measurement from aneroid wafers and their associated indicator gauges and displays. A variant of the aneroid wafers on a micro scale is used inside cell phones.

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *4" x 4" x 8" and plumbing for static port.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *1.5 pounds.*

4. Power

- *Can function without power; power for instruments and communication equipment only.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Not applicable.*

6. Cost

- *Varies per avionics installation.*

7. Use Case Evaluation

- *VMC at low traffic levels (nominal), and IMC at low traffic levels: Usable at low levels of traffic.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Not affected by high traffic.*
- *Night operations at low and high traffic levels. Not affected by nighttime use; illumination and power would be required*
- *VMC and IMC with high winds, low and high traffic levels. Registers increase in pressure in accordance with ambient conditions including high wind pressure, turbulence, leeward pressure differentials. Leeward/windward pressure differentials can throw a pressure barometer off by hundreds of feet.*

- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: Electrically powered instrument would be affected by a power out situation.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Not affected by ground emergencies.*
- *Operator with ill intent: Not affected by operator with ill intent.*
- *Bird events: Not affected.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Not affected.*

8. **Advantages** relative to other technologies serving this function
    - *Existing commercial aircraft use pressure altitude and fly on same barometric settings to avoid collisions, at 1000 ft of separation in low altitudes.*
    - *Barometric pressure altitude would not be sensitive to ground structures, advantage over a radar altimeter.*
9. **Disadvantages** relative to other technologies serving this function
    - *Rapidly changing atmospheric conditions require frequent updates to achieve accurate mean street level altitudes (i.e. may vary due to city canyon effect).*
    - *Not sufficient precision for urban canyon use in IMC, when urban canyons cause errors in altitude of several hundred feet and flight is several hundred feet from buildings, people.*
10. **Precision**
    - *Insufficient precision for precision landing operations.*
11. **FAA Acceptance**
    - *Accepted: traditional aviation altimetry method.*
12. **Cybersecurity and Privacy**
    - *Not applicable.*
13. **Maturity in time: use** at what UML levels?
    - *UML-1 -3.*
    - *Currently in use. Accuracy not sufficient for UAM urban vertiport use under automation or in precision operations under IMC.*
14. **Ground Architecture**
    - *Relies upon traditional aviation weather reporting infrastructure of recording and reporting barometric pressure at every airport.*
15. **References**

"Wind Pressure around Buildings: Ventilation & Wind load," Rheologic website, https://rheologic.net/en/wind-induced-pressure-around-buildings, accessed 11-30-19.

16. **Other Notes**
    - *Pressure altitude is relative to MSL not AGL. NAS low altitude operating rules: Use pressure altitude and fly on same barometric settings to avoid collisions, at 1000 ft of separation. Eastbound = odd thousands +500 ft [Pilot Manual].*
    - *A 28 mph wind can create 100 Pa pressure differential = 1 mB, which is also a standard building pressure rating. 100 mB of pressure differential can create an inaccuracy in pressure altitude of 533 ft.*

Altimetry, Vertical, Barometric Sensing with References

Area and Functions: Nav, Appr; EnRt; Land

Description: Traditional barometric pressure altitude measurement and indication, augmented by a network of reference barometers to attune airborne barometers for the pressure variations in urban areas, with high precision. The reference is provided by miniature barometric sensors placed on structures at the altitudes that UAM would fly through. The miniature reference barometers are outfitted with local Wi-Fi transmitters to transmit actual barometric pressure and own altitude. The signals would be received on aircraft and used by an on-board sensor that would constantly update pressure altitude, for use in close-in operations in the urban environment.

1. Air or Ground Based? on vehicle?

- *Ground-based sensor for reference. Broadcast via internet, bluetooth, Wi-Fi, RF to enable precision manuevers. Re-set in aircraft prior to flight and often thereafter.*

2. Size

- *A chip inside a cell phone: Total unit with recharging battery could be the size of a small flip-phone and could be placed on accessible rooftops or balconies of urban buildings.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Less than 250 grams.*

4. Power

- *Aneroidic barometers need no power; they operate on pressure and a screw mechanism.*
- *Chipset: Micro watts (10^-6).*
- *Broadcast signal power not included.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *This utility is pre-market and so several transmission methods are possible: Local unreserved Wi-Fi or bluetooth or as a commercial service, including webpage delivery.*
- *The information could be available locally on Wi-Fi or bluetooth, or alternatively a network of sensors could transmit to a web utility that aircraft or operators would reference. The web utility could be accessed via internet or via cell phone app, and would be commercially provided.*
- *A reference file could be transmitted to aircraft instruments before flight at vertiport over C2 link.*
- *Envisioned as local short range (bluetooth or Wi-Fi) or internet, carried over C2 or phone app (network).*
- *Wi-Fi or bluetooth will not have reliable BVLOS over long distances.*

6. Cost

- *Less than $100 for parts[1] for the building reference sensor and transmitter. Low cost.*

7. Use Case Evaluation

- *Works in low traffic and high traffic, since this is a measurement broadcast.*
- *Works in all-weather conditions.*
- *Will be affected by high winds and the temperature differentials on the sides of buildings will be a problem. Even if the ground sensors are sited so that they are not affected by building pressure differentials, the airborne vehicle sensor would be affected by the leeward or windward side of buidlings, rendering a comparison with a known good less useful.*

- *Works in citywide emergency, may work on harvested power (solar, wind, kinetic).*

8. Advantages relative to other technologies serving this function

- *Cost and availability.*

9. Disadvantages relative to other technologies serving this function

- *Not tested for aviation applications.*
- *No aviation standards apply for novel technology.*
- *Does not solve the problem of pressure differentials throwing off altitude measurements on opposite sides of buildings, unless both sides of the building are instrumented.*

10. Precision

- *Chip barometer detects changes in altitude with near 100% confidence to 10-ft precision and are observed to track 1-ft increments. [2, 3] This is precision, not accuracy. A reference measurement is needed for accuracy, and the reference pressure altitude (real life) changes, so accuracy depends on timeliness of update. Must update pressure reading at a minimum every 30 minutes; temperature changes throughout day cause pressure altitude changes. Research needed to determine whether pressure needs to be updated more often; gusts of wind happen on a second-by-second basis so required update could be 1 second.*

11. FAA Acceptance

- *Chip-barometers are not covered by TSO. Recommend 3 chip barometers with 2-of-3 voting if using them for precision altitude.*

12. Cybersecurity and Privacy

- *Attached to a board thus provenance is required to ensure live and accurate (not gray chips). Operates with on-chip firmware.*
- *Use of FPGA or SWR is a cyber weakness as it could be re-written to do harm. Chip neither contains nor uses PII.*

13. Maturity in time: use at what UML levels?

- *COTS. UML 2-6.*

14. Ground Architecture

- *Reference barometers would be composed of small modules for placement on a building in person-accessible spots, such as rooftops. The unit would require either regular battery replacement, or a small amount of power (on the order of a light bulb), or reliable solar/wind power to power the wireless transmissions. Standard Wi-Fi would carry for nearby aircraft. Since Wi-Fi travels short distances, the barometers would need to be placed where needed, e.g., landing spots and high buildings, or would need to be placed densely, such as every 1-5km along flight routes.*

15. References

[1] " Digital Barometer Module for Arduino (BMP180), $13.59, Part #VUPN6601," Internet catalog webpage, https://vetco.net/products/digital-barometer-module-for-arduino-bmp180?gclid=Cj0KCQiAtrnuBRDXARIsABiN-7C8TjPUz1Eq1VsDwio4RFK4UBDD0LE85WAWurq1neBrOgtxlFtRyJ8aAvmlEALw_wcB, accessed 3-18-20.

[2] Brian Knitter, " Accuracy of barometric pressure sensor in mobile devices?" Stormtrack.org community FAQ, https://stormtrack.org/community/threads/accuracy-of-barometric-pressure-sensor-in-mobile-devices.26556/, accessed 3-18-20.

[3] "Tiny barometers in cell phones could tell you how high you are," ArsTechnica Open Forums, https://arstechnica.com/civis/viewtopic.php?p=25517067, accessed 3-18-20.

16. Other Notes

- *A 28 mph wind can create 100 Pa pressure differential = 1 mB, which is also a standard building pressure rating. 100 mB of pressure differential can create an inaccuracy in pressure altitude of 533 feet.*

Altimetry, Vertical, Radar Altimeter

Area and Functions: Nav, Appr; EnRt; Land

Description: Radar altimeters, also known as radio altimeters, transmit radio frequency signals toward the ground and measures how long it takes them to be reflected back to the aircraft receiver to determine the aircraft's distance from the surface. Radio altimeters are used in the NAS today as integral and essential for flight navigation. Because of the precision and accuracy of radio altimeters at altitudes of 1000 feet or less, they are used as a height controlling sensor in many aircraft automatic approach and landing systems. In many aircraft, the radio altimeter is directly connected to the Ground Proximity Warning System which is designed to warn the pilot if the aircraft is flying too low or descending too quickly.

1. Air or Ground Based? on vehicle?

- *Air-based. Radar or radio altimeter measures distance from ground with radio wave bounce.*

2. Size

- *Example Garmin GRA-55. [1]*
  - *Unit Height (with mounting rack): 3.99" (101.3 mm).*
  - *Unit Width (with or without mounting rack): 3.02" (76.7 mm).*
  - *Unit Depth (with mounting rack and connector): 11.62" (295.2 mm).*
  - *Unit Depth (with mounting rack, connector and configuration module): 12.08" (306.9 mm).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *3.5 lbs (1.6 kg) with mounting rack.*

4. Power

- *Power Consumption: 13.75 W maximum (0.5 A at 27.5 VDC, 1.0 A at 13.75 VDC).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *4200-4400 MHz.*
- *Aero reserved frequency, not shared. [3]*
- *Range more than sufficient for low altitude vehicles.*

6. Cost

- *Varies depending upon avionics suite and system certification level (standalone vs integrated avionics for CAT II/III ops).*
- *Example Garmin GRA-55 https://sarasotaavionics.com/avionics/gra55. $11,600; probably lower cost per unit for a manufacturer.*

7. Use Case Evaluation

- *Radio altimeters are common for CAT II/III IFR landings, space shuttle landings, unmanned air vehicles, tactical weapons (missiles), and drone targets.*

- *In many aircraft the radio altimeter is directly connected to the Ground Proximity Warning System.*
- *Radar altimeters are indifferent to adverse weather conditions, traffic density, and emergencies on the ground or in the aircraft.*

8. Advantages relative to other technologies serving this function

- *Currently mature technology, FAA approval for intended use and industry standards (to include human factors display and symbology).*
- *Mature technology accounts for height variations in surface.*
- *Already constructed to avoid problems from overlapping transmissions.*

9. Disadvantages relative to other technologies serving this function

- *None.*

10. Precision

- *Varies. Approx 2' accuracy. Currently used in CAT II/III approaches by aircraft and helicopters.[2]*
- *CAT II minimum performance requirements per Part 91, Appendix A:*

  (c) Radio altimeter. A radio altimeter must meet the performance criteria of this paragraph for original approval and after each subsequent alteration.

  (1) It must display to the flight crew clearly and positively the wheel height of the main landing gear above the terrain.

  (2) It must display wheel height above the terrain to an accuracy of plus or minus 5 feet or 5 percent, whichever is greater, under the following conditions:

  (i)Pitch angles of zero to plus or minus 5 degrees about the mean approach attitude.
  (ii) Roll angles of zero to 20 degrees in either direction.
  (iii) Forward velocities from minimum approach speed up to 200 knots.
  (iv) Sink rates from zero to 15 feet per second at altitudes from 100 to 200 feet.

  (3) Over level ground, it must track the actual altitude of the aircraft without significant lag or oscillation.

  (4) With the aircraft at an altitude of 200 feet or less, any abrupt change in terrain representing no more than 10 percent of the aircraft's altitude must not cause the altimeter to unlock, and indicator response to such changes must not exceed 0.1 seconds and, in addition, if the system unlocks for greater changes, it must reacquire the signal in less than 1 second.

  -See FAA AC 120-28D for CAT III system requirements (more restrictive, attached)
  -Example Garmin GRA-55 https://sarasotaavionics.com/avionics/gra55 Performance Specifications
  -Altitude Accuracy: ± 1.5 ft (3 - 100 ft AGL); ± 2 % (> 100 - 2500 ft AGL)
  -Altitude Range: -20 - 2550 ft AGL
  -Altitude Alert Outputs Range: 0 - 2500 ft AGL
  -Altitude Output Time Constant: 0.1 second maximum
  -Transmitter Output: Frequency: 4.25 - 4.35 GHz "Gated" FMCW; Power: 1.0 W nominal
  -Horizontal Velocity: 0 - 200 knots maximum
  -Vertical Velocity: 20 ft/sec maximum (up to 100 ft AGL); 25 ft/sec maximum (above 100 ft AGL)
  -Pitch Angle: ± 20° maximum

-Roll Angle: ± 20° maximum (with published altitude accuracy limits); ± 20° to ± 30° (with ± 20 % altitude accuracy limits throughout entire altitude range

11. FAA Acceptance

- *Currently used in CAT II/III approaches by aircraft and helicopters.*

12. Cybersecurity and Privacy

- *Code base of radar altimeter represents a point of potential entry and/or corruption and strict manufacturing protocols to prevent such corruption must continue.*

13. Maturity in time: use at what UML levels?

- *UML-1-5.*
- *Currently mature technology, FAA approval for intended use and industry standards.*

14. Ground Architecture

- *No ground architecture required for this unit.*

15. References

[1] Garmin GRA-55 https://sarasotaavionics.com/avionics/gra55

[2] Federal Register, "Helicopter Air Ambulance, Commercial Helicopter, and Part 91 Helicopter Operations,"National Archives. https://www.federalregister.gov/documents/2014/02/21/2014-03689/helicopter-air-ambulance-commercial-helicopter-and-part-91-helicopter-operations

[3] United States Frequency Allocations: The Radio Spectrum, U.S. Department Of Commerce National Telecommunications and Information Administration Office of Spectrum Management, October 2003.

Jim Sparks, "Radio Altitude: The instrument of choice," Aviation Pros, July 1, 2003. https://www.aviationpros.com/home/article/10387134/radio-altitude-the-instrument-of-choice

16. Other Notes

- *135 Operators: Requires each rotorcraft to be equipped with a radio altimeter (§ 135.160). Radio altimeters can greatly improve a pilot's awareness of height above the ground during hover, landing in unimproved landing zones, and landings in confined areas where a more vertical approach may be required. Additionally, radio altimeters help increase situational awareness during inadvertent flight into instrument meteorological conditions (IMC), night operations, and flat-light, whiteout, and brownout conditions.*

Bistatic Radar – Short Range Radar

Area and Functions: Surv, Ground

Description: Bistatic radar places the transmitter and receiving antenna in different locations. Obtuse angles between antenna, relative to the target, are ideal. Both antenna may illuminate the target, but the waveform is received at the other station. Decoding of pulse width and Doppler shift provides information about the size of the target and its direction of travel. When more than two stations are used, this is called multistatic radar. Multiple illuminators may provide relief from an obstacle-rich environment such as urban canyons. This technology alternative does not include passive bistatic radar (PBR), a radar that makes use of emissions from broadcast, communications, or radionavigation transmitters rather than a dedicated, co-operative radar transmitter. PBR is detailed in the RF detection technology assessment.

1. Air or Ground Based? on vehicle?

- *Ground.*

2. Size

- *Antenna between 1'x1' and 2'x2'; mounted on tripod like a camera or laser surveying device.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Less than 50 lbs per mounted antenna/receiver.*

4. Power

- *GHz radar can be powered from a standard U.S. electric line or a car battery. X-band requires 220V line.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Bandwidth – Can operate in virtually any spectra: Choose the spectra desired for the RCS of the targets you want to detect.*
- *Handling of obstructions and BVLOS.*
- *Decluttering is much more difficult in bistatic, so you would probably want to null out reflective obstruction returns on setup.*
- *Can be very low frequency for BVLOS, waves would bend but also would have very long range, undesired in urban environment. Higher frequency wavelengths suitable for urban environment and smaller targets will not work BVLOS.*
- *Range depends on power and antenna. UHF and GHz ranges are possible. En route radar is used for up to 450 km (L-band, 1 to 2 GHz), airport radar up to 150 km (S-band, 2.7 to 2.9 GHz). S-band may be interfered with by Wi-Fi. X-band (8 to 12 GHz) is probably the most suitable band for the desired wavelength. Neither Aero-reserved nor licensed; it is used for many radar applications including marine radar and interplanetary coms.*

6. Cost

- *NetRAD radar used to detect intruders incoming over waves using multiple networked receivers at 2.4 GHz (S-band) three-node system was $6000.00.*

7. Use Case Evaluation

- *VMC at low traffic levels (nominal), and IMC at low traffic levels: Can detect low traffic levels if in an unobstructed environment. Good for detecting incoming aircraft. Receivers must be stationary.*
- *VMC and IMC at high local traffic levels such as a large sporting event: At present development, difficult to define individual targets at higher levels of traffic. At suitable wavelengths, not bothered by humidity or rain.*
- *Night operations at low and high traffic levels: Suitable for night operations. Will work on, and detect, multiple targets; individual identification of multiple targets, particularly in a multipath environment, is not ready to go at the present time but could be accomplished (20 years?) with research.*
- *VMC and IMC with high winds, low and high traffic levels: Will function in adverse weather. See above comments about low/high traffic levels.*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: Will function at low traffic levels to help identify errant flight paths.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Requires transmitter and receiver to be stable (nonmoving) and receiving power and a timing signal to operate.*
- *Operator with ill intent: Good at detecting entry to airspace.*

- *Bird events: At suitable wavelengths will detect birds. Can be used to detect insects.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. Good at detecting non-cooperative traffic, can be tuned to detect small UAS.*

8. **Advantages** relative to other technologies serving this function
   - *Choice of spectra; choose to suit desired target, e.g., small UAS.*
   - *Cheap for the short range anticipated for urban environment. May be a good candidate for occasional surveillance of non-cooperative or unauthorized aircraft; available rapidly and cheaply. Can also use the interruption of the signals from the local airport as the source signal.*
   - *May receive stronger signal from stealthy targets than monostatic radar due to angle of refraction.*
9. **Disadvantages** relative to other technologies serving this function
   - *Decluttering is more complex than monostatic radar and aspects of null Doppler returns on foci of return are not fully understood.*
   - *At present level of technology, must know location of transmitter, therefore transmitter should be fixed and not another aircraft. It is possible to set up a return based on moving transmitters but this is trickier, requires more setup and possibly some years of research.*
   - *At present, obstacles complicate the clutter environment.*
10. **Precision**
    - *Synchronized with RTK or GNSS to achieve precision.*
    - *Range gating is accomplished using distance to transmitter, which is known; exact position determined from Doppler shift from target.*
    - *When used over audible frequencies (10-100 Hz), the radar can detect very small targets, such as insects.*
    - *Clutter has less spiky return than monostatic, easing filter requirements.*
11. **FAA Acceptance**
    - *No record of FAA use or standards for this technology.*
12. **Cybersecurity and Privacy**
    - *Bistatic radar is by nature using an independent emitter to detect targets. A third party could also do so and detect targets. The radar itself does not contain any identifying information. It has not been used by the FAA in cooperation with secondary surveillance radar, so there is no personal or identifying data to be hijacked.*
13. **Maturity in time:** use at what UML levels?
    - *UML-3-6.*
    - *For detection of intruders or entry to airspace, the technology is mature now.*
    - *For tracking of multiple targets in an obstacle-rich environment, would require development and perhaps be mature in UML 4 or later.*
    - *Some bistatic radar (more advanced models) are ITAR-regulated, but bistatic radar is developed in multiple countries, so it is unlikely the ITAR restriction would remain onerous as for less common technologies.*
14. **Ground Architecture**
    - *Bistatic or multistatic radar could be employed in a networked fashion to detect numerous urban aircraft. Ideally, the emitters would be placed near the ground to illuminate a wide horizon of the sky, and multiple receivers would be employed to receive returns, decoding the range and*

direction of traffic. Multiple aircraft across an urban environment could be imaged and potentially tracked on such a network. Any aircraft with a building between the aircraft and the receiver would not generate a return, so lower altitude operations would be more invisible. This potential network would require acquisition of ground siting stations with power and telecom available, and the returns would need to be mosaicked into a situational awareness picture for the local air authority. If the effective range is 5 km, then a single emitter would need to be placed approximately every three miles to provide dense surveillance coverage.

15. References

Griffiths, H. "Chapter 16 - Passive Bistatic Radar" Academic Press Library in Signal Processing Volume 2, Edited by Sergios Theodoridis and Rama Chellappa, ScienceDirect, Waltham, MA, , 2014, Pages 813-855.

"Professor Hugh Griffiths' Inaugural Lecture on Radar," March 28, 2012, University College of London, https://www.youtube.com/watch?v=whG6v6OBwB4

Range: O'Hagan, D.W., Doughty, S.R., and Inggs, M.R.,"Multistatic Radar Systems," Academic Press Library in Signal Processing, Volume 7: Array, Radar, and Communications Engineering, Edited by Rama Chellappa and Sergios Theodoridis, Academic Press, San Diego, CA, 2017. p 253-273.

Doughty, S. "Development and Performance evaluation of a multistatic radar system," Ph.D. thesis, University College London, U.K. 2008. https://discovery.ucl.ac.uk/id/eprint/14634/1/14634.pdf

Bluetooth 5, Aircraft U2U

Area and Functions: Comm, U2U

Description: The FAA UAS Remote ID Notice of Proposed Rulemaking released on December 31, 2019, requires the UAS to transmit identification and location information to an FAA-contracted UAS Service Supplier (USS) and locally broadcast that information over unlicensed spectrum such as Bluetooth. On the ground, several technologies have emerged to provide communications for vehicles or vehicle-to-vehicle, including Infrared, Bluetooth, ZigBee, and DSRC. Bluetooth is one of the most popular short-range wireless communication standard known as IEEE 802.15.1 currently being maintained by the Bluetooth Special Interest Group (SIG). Version 5.2 of the Bluetooth Core Specification released January 2020, has added several new features and enhancement, including a long-range mode. Since Version 4.0, Bluetooth specification has been split into three categories: classic, high-speed, and low energy. Bluetooth Low Energy (BLE or Smart Bluetooth) is not backward compatible to the Classic Bluetooth Basic Rate/Enhanced Rate (BR/EDR) protocol; however, devices can be implemented on either or both of the LE and BR/EDR systems. Both BLE and classic Bluetooth use the same 2.4 GHz RF, which allows dual-mode devices to share a single radio antenna. BLE or Smart Bluetooth are being considered for V2V communications. [1]

1. Air or Ground Based? on vehicle?

- *Airborne.*
- *Note that Bluetooth 5.0 has a long-range over one km, and Intel has successfully demonstrated drone identification by Bluetooth. [2]*

2. Size

- *2 to 5 cm.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *50 – 100 g.*

4. Power

- *100 mW.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *2.4 GHz.*
- *Range: 100 m (330 ft). Bluetooth SIG claims Bluetooth 5.0 range can go up to 1 km (3,281 ft).*
- *Not aero-reserved, unlicensed.*

6. Cost

- *$100 to $200 (for existing Bluetooth devices in the market for ground vehicles.*

7. Use Case Evaluation

- *VMC at low traffic levels (nominal), and IMC at low traffic levels: Water droplets from rain may have an impact on the 2.4 GHz signal strength.*
- *VMC and IMC at high local traffic levels such as a large sporting event: High traffic levels will have an impact due limited devices can be actively connected in master/slave configuration.*
- *Night operations at low and high traffic levels: No impact.*
- *VMC and IMC with high winds, low and high traffic levels: No impact.*
- *On-board emergency in VMC, IMC, high winds; and/or high traffic levels: No impact.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: May be problem due to unprotected, unlicensed spectrum.*
- *Operator with ill intent: Bluetooth link manager provides mechanism used by devices at either end of a link for negotiating encryption mode and coordinating encryption keys.*
- *Bird events: No impact.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: No impact.*

8. Advantages relative to other technologies serving this function

- *2.4 GHz ISM band spread spectrum is free and open to everyone worldwide.*
- *Low power consumption.*
- *Low cost.*
- *Incorporates Error Detection and Error Correction.*

9. Disadvantages relative to other technologies serving this function

- *Frequency may be noisy from other sources such as microwaves, cordless phone, garage door openers.*
- *Not currently adapted for aviation.*
- *Range may limit applications.*
- *May be limited to non-critical communications due to lack of reliability.*

10. Precision

- *Not applicable.*

11. FAA Acceptance

- *Industry proposed using Bluetooth for Drone Remote ID.*

- *FAA does not approve of using this technology for flight critical functions (e.g., carrying people or collision avoidance); disallowed that use in drones.*

12. Cybersecurity and Privacy

- *Using encryption mode and keys.*
- *Adaptive Frequency Hopping in a pseudo-random sequence.*

13. Maturity in time: use at what UML levels?

- *UML-1 -6.*

14. Ground Architecture

- *Airborne V2V communication does not require a ground infrastructure.*
- *If used for air to ground (operator center to vehicle), a network of broadcasting points would be required on the ground approximately every 1000m of route.*

16. Other Notes

[1] C. Poellabauer, P. Mitra, "Using Bluetooth Low Energy for Dynamic Information-Sharing in Vehicle-to-Vehicle Communication," SAE International Journal of Passenger Cars – Electronic and Electrical Systems, March 2017.
[2] Unmanned Airspace, August 20, 2018, "Intel demonstrates drone identification by Bluetooth," https://www.unmannedairspace.info/uncategorized/intel-demonstrates-drone-identification-bluetooth/
[3] Bluetooth SIG, "Bluetooth 5: Go Faster. Go Further," https://www.bluetooth.com/wp-content/uploads/2019/03/Bluetooth_5-FINAL.pdf.
Bluetooth SIG, "Bluetooth 5 Core Specification," https://www.bluetooth.com/specifications/bluetooth-core-specification
Martin Woolley, Bluetooth 5 High Level Overview, Bluetooth SIG, UK, 2020.

C-Band Use for C2

Area and Functions: Comm, C2

Description: the 5030-5091 MHz (C-band) may be utilized for UAS command and control; it is presently (Spring 2020) being studied by the FAA for allocation for this use. C2 payloads include: position information and telemetry, vehicle health, flight plans and contingent flight plans, execution commands (controlling the flight of the airborne vehicle); may also include voice-bounced ATC communications; may include streaming video from the airborne vehicle to its operational control center.

1. Air or Ground Based? on vehicle?

- *Air (UAS) and Ground (AOC) based. Units must be in sync with each other.*

2. Size

- *Skylinx is 50 grams, about size of Raspberry Pi. Integrated processors.*
- *To be used in urban environment for C2, two-way ground transceivers will be needed. The ground unit would be composed of a similar size radio, but probably outfitted with multiple radios, multiple directions.*
- *Roughly 2.5" x 3" x 0.75" today (uAvionix example).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Skylinx is 50 grams (comparable unit).*

4. Power

- *Skylinx is 10 W; probably 1-10W would work for the airborne unit in the urban environment.*
- *The ground unit would be composed of multiple antennas with power boosters; each may operate at 10W level. Standard supply power at 120VAC would suffice.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *C-band, 5030-5091 megahertz (MHz) (5 GHZ). Currently Aero-reserved (MLS). All C-band operates with low side downlink, high side uplink.*
- *Under Section 374, FAA is considering allocating 1 KHz channels (max of 60,000 channels).*
- *Skylinx is taken as representative but Skylinx operates at ISM band, 2.4 GHz; range 40 mi.*
- *Obstructions and BVLOS: This band will be obstructed by buildings, trees, obstacles. Does not perform in BVLOS or over distances greater than 5 mi.*

6. Cost

- *If the airborne unit is certified as flight critical, the radio will be on the order of $50,000 (order of magnitude). The unit would be flight critical if there is no pilot on board, as remote connectivity with a ground AOC would likely be required. However, it looks like UAS and UAM would share the band. If UAS are also in the market for the radio, then the market is larger than a typical large commercial transport aircraft and the cost would come down, perhaps as low as $5000 - $10,000 per unit.*
- *If a ground station is also certified flight critical, then it will also cost on the order of five to seven figures. A "mega" ground station would be able to handle all the given frequencies in C-band and could cost around $1M.*
- *The ground units would be located on the tops of tall buildings to reach a large section of city. Four well-placed mega units could cover a 10 mi x 10 mi dense urban area, though more units may be required if the best placement cannot be acquired, or if lakes, military installations, etc., are in the way. Placing "smaller" (fewer frequencies, lower range, lower power) ground units near vertiports for landing and take-off operations might be needed in low-UML steps.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Works well, signal may degrade with large-sized precipitation.*
- *VMC and IMC at high local traffic levels such as a large sporting event: The signal will work at high density. Partitioning parts of the frequency to UAS vs UAM and different parts of an urban environment could create congestion problems if done badly (see Mode S).*
- *Night operations at low and high traffic levels: Night will not affect operation.*
- *VMC and IMC with high winds, low and high traffic levels: Winds will not affect operation.*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: Dedicated C-band supports prioritization*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Dedicated C-band will support aero-prioritized events and emergency communications better than virtually any other alternative for this function.*
- *Operator with ill intent: Operator with ill intent could potentially jam large portions of the C-band and cause havoc. A backup frequency would be advisable.*
- *Bird events: Birds will obstruct signal somewhat but not obscure it.*

- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Non-cooperative traffic unlikely to affect signal.*

8. Advantages relative to other technologies serving this function

- *Would be an FAA accepted band for C2, and Aero-reserved.*

9. Disadvantages relative to other technologies serving this function

- *Some industry comments on the proposed rule say that C-band will not be enough spectrum to manage all the UAS that want to use it for all the C2, especially if video streaming is needed.*
- *An existing TSO (TSO213) is in place for C-band for C2, but it is a deterrent rather than an advantage for urban C-band UAS/UAM use, as it mandates a single ground station for a single airborne unit, and mandates that ground stations be no closer than 10 nm from each other.*
- *FAA is still far from embracing dense urban UAS operations.*

10. Precision

- *Not applicable.*

11. FAA Acceptance

- *TSO 213 is a non-starter for UAM, as it restricts one ground station to one band for one operator every 10 miles. This TSO would have to be scrapped for UAM to go forward. FAA would have to accept very dense UAS operations in urban environment.*
- *UAvionix and Collins have similar radios. Collins has a limited C-band radio under a very limiting TSO.*
- *The allocation of C-band for telemetry, command, and required C2 uses needs to be allocated, presumably via a RTCA S/C-228 working group.*

12. Cybersecurity and Privacy

- *Certified units unlikely to be encoded except with COTS algorithms such as PKI, RSA.*
- *Format of the instructions carried over the waveform may be proprietary to protect intellectual property of the UAM operators, similar to the way that Tesla over-the-air updates have a proprietary (and as yet unbroken) encoding.*

13. Maturity in time: use at what UML levels?

- *UML-2-6*
- *Market units probably available 18 months after publication of a RTCA C2 standard.*

14. Ground Architecture

- *The major elements of a typical control and non-payload communications (CNPC) for command and control in C-band consists of two or more identical Ground Stations (GS), which have network connections, likely over a secure Internet connection, for remote control, monitoring, configuration programming and operations (For example, UAM Operator/RPIC). These Ground Stations may have automatic fail-over switching allowing them to use an alternate independent connection, should the Internet service at the GS site is interrupted.*

15. References

[1] "Petition To Adopt Service Rules for Unmanned Aircraft Systems (UAS) Command and Control in the 5030-5091 MHz Band," AIA Petition for Rulemaking on UAS before the Federal Communications Commission, Washington DC, February 9, 2018. https://www.aia-aerospace.org/aia-petitions-fcc-spectrum-control-uas/aia-petition-for-rulemaking-on-uas-2018-02-08-filed/.

[2] TSO C-213, "Unmmaned Aircraft Systems Control and Non-Payload Communications (CNPC) Terrestrial Link System Radios," Department of Transportation Federal Aviation Administration Technical Standard Order, March 9, 2018. https://ecfsapi.fcc.gov/file/10529188164500/FAA%20TSO-C213.pdf.
*[3] TSO C-213 Public Comments, "*Comment Matrix Form for TSO-CNPC Unmanned Aircraft Systems Control and Non-Payload Communications Terrestrial Link System Radios," Federal Aviation Administration Technical Standard Order, March 9, 2018. https://rgl.faa.gov/Regulatory_and_Guidance_Library/rgTSO.nsf/0/BDEFA726EA8CDD8086258250005F071E?OpenDocument.

16. Other Notes

- *Assume no FAA hardware would be involved in the administration or transmission of the signal, and FAA would not regulate, define, nor certify waveforms, only requiring appropriate frequency filters by the user to avoid interference with adjacent bands.*
- *Note that FAA TSO-C213, "Unmanned Aircraft Systems Control and Non-Payload Communications Terrestrial Link System Radios" and RTCA/DO-362. The supported functions are one or more of the following:*
  1) *Allow pilot to safely control, monitor and manage the UA,*
  2) *ATC voice and data relay,*
  3) *Detect and avoid,*
  4) *Weather radar*
  5) *Video, and*
  6) *CNPC link system management, frequency assignment and CNPC link system monitoring and alerting.*
- *Note also that there are two POTL (pilot on the loop) control categories. In a basic POTL control, the pilot provides flight plan, manual setting of control targets and operation monitoring, and assumes control to the extent required if the UA deviates from the planned flight path or autopilot control targets. In the other POTL control capability to fly a programmed flight path, the pilot monitors the operation and assumes control to the extent required if the UA deviates from its programmed flight path. Loss of this function (1) above) is a hazardous/severe major failure condition. RTCA/DO-254 governs electronic hardware qualification of the airborne and ground system radios and includes these conditions: (i) No ground receiving station (GRS) can operate within 10 NM of another GRS and (ii) One GRS is limited to support one airborne receiving system (ARS). When the ARS is 9.5 NM or more from its GRS, the CNPC ARS must be operated at or above 3,000 ft AGL.*

DME Whitespace

Area and Functions: Comm, C2

Description: The FAA is considering enabling UAS use of L-band "DME Whitespace" where it does not conflict with existing users (DMEs and Link 16) for UAS operators command and control. Non-conflicting areas are delimited geographic areas, and require aircraft to remain low altitude, below obstructions to the DME, e.g., below 400 ft AGL. Use of this bandwidth, or "service volumes," would likely be administered by a commercial frequency manager. FAA is proposing "field it and they will come," meaning UAS operators would supply own broadcast hardware, own coding, own transceivers, etc. No FAA hardware would be involved in the administration or transmission of the signal, and FAA would not regulate, define, nor certify waveforms, only requiring appropriate frequency filters by the user to avoid interference with adjacent bands.

1. Air or Ground Based? on vehicle?

- *Air to Ground communications.*

2. Size

- *Avionics Control Panel Dimensions: 3.53" (89.7mm) x 1.80" (45.7mm) x 1.27" (32.4mm), available in vertical and horizontal versions.*
- *RF Module (antenna) Dimensions: 7.34" (186.6mm) x 2.38" (60.45mm) x 1.51" (38.23mm).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Control Panel Weight: 5.6 oz (159 g).*
- *RF Module Weight: 12 oz (390 g).*

4. Power

- *Power Input: 10-30 VDC for a standard DME radio. UAS radio would be less powerful.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Aero-reserved VHF Frequencies: 118.000 to 136.975 kHz.*
- *Channels of 1 kHz proposed.*
- *Goes BVLOS and is reasonably tolerant of obstructions.*
- *Range of a DME is up to 300 miles. For a UAS, the power on the frequency would be limited to a geographic cell that may less than 10 miles.*

6. Cost

- *GA certified DME radio is between $1200-2000 (not including install cost).*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: No problems.*
- *VMC and IMC at high local traffic levels such as a large sporting event: DME receivers are actually interrogation units and become saturated at high traffic levels. While the L-band use of the DME whitespace would not be interrogating DME receivers, one could see there being a saturation problem at high traffic levels due to limited frequencies and sensitivity to not overloading nearby DMEs.*
- *Night operations at low and high traffic levels: DME receivers are actually interrogation units and become saturated at high traffic levels. While the L-band use of the DME whitespace would not be interrogating DME receivers, one could see there being a saturation problem at high traffic levels due to limited frequencies and sensitivity to not overloading nearby DMEs. May not be enough frequencies at high demand levels. Signal may carry farther at night and make the problem worse.*
- *VMC and IMC with high winds, low and high traffic levels: Wind not a factor.*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: May saturate at high demand levels. May not be enough frequencies at high demand levels.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Jammable; may saturate at high demand levels. May not be enough frequencies at high demand levels.*

- *Operator with ill intent: Operator not observing the imposed constraints of the frequency manager could cause unusability of the frequency for others.*
- *Bird events: Not applicable.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. May saturate at high demand levels. May not be enough frequencies at high demand levels. Jammable by operator with ill intent.*

8. Advantages relative to other technologies serving this function

- *None.*

9. Disadvantages relative to other technologies serving this function

- *Map of available frequencies shows very few frequencies available in dense urban environments. Unlikely to be a viable solution for UAM in dense urban environments.*

10. Precision

- *Not applicable.*

11. FAA Acceptance

- *Yes; would be FAA- provided aero-reserved frequency.*

12. Cybersecurity and Privacy

- *Security and privacy would be up to the operator to secure; encoding would be vitally important.*

13. Maturity in time: use at what UML levels?

- *UML-3-4*
- *In May/summer 2020, FAA will prepare a report to go back to Congress petitioning for more study. More study will take at least three years to study UAS operating on this frequency near a DME at various altitudes (per FAA). Given that the frequency is in use, the studies might only happen at night and might take five years. After study, the FAA would have to draft a rule. Predict this might be at market 2028-2030.*

14. Ground Architecture

- *With the assumption that this L-band DME Whitespace is used for command and control of UAM operations in the urban enviroments, a high-level notional architecture of the L-band system supporting Air/Ground communication is consisted of two or more Ground Stations (GS), each providing a cell-like coverage service volume, and which are geographically situated to provide overlapping coverage to achieve seamless service volume handovers. Each GS would be connected to a Ground/Ground network through a ground network interface (for example, Gateway) to an end system (such as Air Traffic Service Provider or UAM Operator).*

15. References

Ian Atkins, "Memorandum Requesting Stakeholder Feedback on FAA discussion on the Use of Radio Frequency Bands for Unmanned Aircraft Systems (UAS) Command and Control frequencies for input to the FAA Reauthorization section 374 report", FAA, October 18, 2019.

DSRC - Dedicated Short Range Communications

Area and Functions: Surv, UTU

Description: DSRC is a dedicated band at 5.9 GHz reserved for vehicle-to-vehicle and vehicle-to-infrastructure communications for ground traffic. It was intended to allow ground vehicles to improve collision avoidance, to the point of harmonizing vehicle movements for better fuel usage, efficient traffic spacing, and maximize efficient road use. Originally designed in 1999 for quick download/upload of data as vehicle whizzed by at speed. Designed for LOS communications. Currently using 802.11p. Implemented up by some automakers (Toyota, Mercedes Benz, Volkswager-Eur). Europe was also attempting to standardize its own version in ITS. Used in Japan for congestion tolling. Not being used in U.S. and automakers are shelving plans to implement it. Lack of a standard for V2V message sets has caused vehicle-based roll-outs to be delayed, and mutliple parties have petitioned the FCC for the band to re-allocated for cell phones, W-Fi, and other uses. Considered for use here for air based vehicle-to-vehicle communications, cooperative position, and intent information exchange.

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *Estimated less than 3 cm per side, excluding antenna; smaller as time progresses.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Estimated less than 100g excluding antenna.*

4. Power

- *Estimated less than 1 W.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *75 MHz in 5.9 GHz allocated by FCC in 1999.*
- *Line of sight; short range; less than 1000 meters.*
- *Obstructed by buildings and structures.*

6. Cost

- *Sensor estimated $100; software, antenna, mounting may add a few hundred dollars. Automobile grade electronics.*

7. Use Case Evaluation

- *Night operations at low and high traffic levels: Good.*
- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: No problems.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Should be adequate for high vehicle concentration if similar protocols are used as in ground vehicles (research may be needed).*
- *Night operations at low and high traffic levels: Not affected by nightfall.*
- *VMC and IMC with high winds, low and high traffic levels: Wind and IMC not a factor; heavy rain may impede signals at long distances (greater than 0.5 mile).*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: Range limited but otherwise not a factor.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: May not be enough frequencies at high demand levels.*
- *Operator with ill intent: Operator not observing the imposed constraints of the frequency manager could cause unusability of the frequency for others.*
- *Bird events: Not applicable.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Does not work against non-cooperative traffic. No situational awareness common operating picture provided.*

8. **Advantages** relative to other technologies serving this function
   - *Tight beam control. If steerable, frequency is high enough for reasonably sized planar arrays or path antennas.*
   - *High density per second per square kilometer.*
   - *Innovative use of spectrum: broadcast plus peer-to-peer modes.*
   - *Trust and Authentication.*
   - *No subscription fee.*
   - *Privacy, Security.*
   - *Aligns with regulatory constraints.*
   - *Co-existence with other primary users.*
9. **Disadvantages** relative to other technologies serving this function
   - *May be picked up for ground V2V or other uses.*
   - *Originally designed for LOS communications.*
   - *Range limited to less than a half-mile.*
   - *Message sets undefined.*
   - *High uncertainty regarding future use.*
10. **Precision**
    - *Not applicable.*
11. **FAA Acceptance**
    - *None today; reserved for automobile use.*
12. **Cybersecurity and Privacy**
    - *802.11 claims high security but depends on Encryption Keys. (TEK and KEK)*
13. **Maturity in time:** use at what UML levels?
    - *UML-2.*
    - *Message set not defined and may push possible implementation later than UML-2.*
    - *Presently not implemented commercially for V2X communications in the U.S.*
    - *Commercially available for cars.*
    - *Uncertain future.*
14. **Ground Architecture**
    - *For V2V, no ground infrastructure is needed, other than message set definition. However, the V2I component could be activated for a shared common situational traffic awareness. Like UAT or ADS-B, this would require ground receivers to receive aircraft transmissions, and then the information would be rebroadcast, as well as shared to the airspace authority service provider. At 5.9 GHz, the receivers would be small and not require much power but would have to be located on line of sight; thus there would have to a receiver approximately every kilometer.*
15. **References**

J. Harding, G.R. Powell, R. Yoon, J. Fikentscher, C. Doyle, D. Sade, M. Lukuc, J. Simons, and J. Wang, "Vehicle-to-vehicle communications: Readiness of V2V technology for application." (Report No. DOT HS 812 014). Washington, DC: National Highway Traffic Safety Administration. August 2014. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwiN2dLYxanmAhVMnFkKHQfBBEYQFjAAegQIBBAC&url=https%3A%2F%2Fwww.nhtsa.gov%2Fstaticfiles%2

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Ken Leonard, "Dedicated Short-Range Communications (DSRC) and Spectrum Policy," ITS World Congress, Brisbane, Australia, October 2016.
https://www.its.dot.gov/presentations/world_congress2016/Leonard_DSRC_Spectrum2016.pdf
"Dedicated Short Range Communications (DSRC) Service", FCC webpage, updated April 22, 2019. https://www.fcc.gov/wireless/bureau-divisions/mobility-division/dedicated-short-range-communications-dsrc-service. Accessed April 22, 2020.

16. Other Notes

- *Low latency medium adapted for a highly mobile vehicle environment. Data can be distributed in a broadcast mode (300m range – line of sight). Peer-to-peer data exchanges engineered to work well in a moving vehicle environment. Packet-based medium based on IEEE 802.11 specifications for lower-layer definition. Additional network layer definitions and a cryptographic process for establishing trust and protecting confidentiality given in IEEE 1609 family of standards. Payload definitions and performance requirements for common data units established in SAE standards. General IP transport available with certain priority requirements and packet size limitations. Physical Medium (802.11p-wireless local wide area network (LAN) Standards.*
  - IEEE Standards for Wireless Access in Vehicular Environments (WAVE)—Architecture, Security and Management Standards for V2V and V2I
  - SAE Data Standards—Dictionary, Message Sets
  - SAE Performance Standards
- *Appropriate research into noise/interference allow applications to account for noise above and below the band needed. Modeling to define spectrum and channel usage will have to account for: 1. Message size and frequency; 2. Geographic layout and coverage that supports both broadcast and peer-to-peer exchanges without interference; 3. noise, interference, and multi-path.*
- *Note FCC is thinking of reselling some of the spectrum, which will further reduce attractiveness for DSRC, especially if spectrum is to be shared and/or in unlicensed use.*
- *Bandwidth could be reduced somewhat with modern communications technologies for a given high bit rate, like MIMO; but acquisition and channel prediction will become harder. Channel state will also change rapidly as vehicle moves, at the higher frequencies. Note 4G today is capable of 100s of Mb/sec at 10 MHz bandwidth with MIMO processing in lower bands. MIMO is not defined for DSRC.*
- *Due to short access and transmission times, 802.11p does not implement cybersecurity; it would need to be provided by higher layers.*
- *GM tried to implement V2V in the DSRC bands by 2021 in high-end cars. Toyota has abandoned implementing V2V in 2022 while waiting for CV2V standard in 3GPP Rel 16.*
- *DSRC was originally designed for V2X communications. Now attempting to use it for V2V. Also note that W-Fi V6 is changing air interface from the older 802.11 on which 802.11p is based, and uses OFDMA to improve access and grant times and latency. So 802.11p longevity is questionable.*
- *3GPP release 16 (July 3, 2020) (https://www.3gpp.org/release-16) technical reports defined Airborne base stations. It is expected that if reliability is proven, C-V2X and C-V2V will become*

the dominant standard for V2X and V2V. Rel 16 would also be able to support many of the ancillary services originally proposed for DSRC, like Mobile Bill Pay and Mobile Advertisements, possibly to replace DSRC.

FLARM (commercial solution used in EU)

Area and Functions: Surv, UTU

Description: Proprietary anti-collision warning avionics for low power aircraft and gliders, licensed and used primarily in Europe. FLARM obtains its own-aircraft position from an internal Global Positioning System (GPS) unit and a barometric sensor, updated each second. Position and projected flight path are broadcast over a low power RF transmitter (868.2 MHz). Its receiver searches for other FLARM devices within 3-5 km (early versions) up to 10 km range and processes the information received. Only aircraft equipped with FLARM are provided other-aircraft position information due to the proprietary data formats. Introduced for aircraft that could not afford or install a TCAS, FLARM now comes in many upgraded variants including ADS-B Out extensions.

1. Air or Ground Based? on vehicle?

- *Air, on aircraft.*

2. Size

- *Aircraft: Approximately 4" x 2" x 6". (Powermouse example: 84mm x 55mm x 25mm).*
- *sUAS solution: 70x32x8mm, (Powerflarm) 90mm wire antenna, GPS antenna, total weight 28g with antenna.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Approximately 2 lbs total.*

4. Power

- *Example: Powermouse, input voltage 8-36 VDC, consumption 0.8 W.*
- *sUAS solution: 4-36VDC on DF-13 or 5VDC via USB, selectable by switch.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Basic FLARM uses an ISM/SRD (experimental/short range device) band transceiver, e.g., NRF905 (Europe: 868 MHz). Licensed by ONERA.*
- *EU frequency use not compatible with U.S. frequencies.*
- *Illegal to use ISM band in U.S. for commercial products; ISM is for research only.*

6. Cost

- *Thousands of dollars.*

7. Use Case Evaluation

- *Ideal for a segregated airspace area of participating aircraft (e.g., gliders).*
- *ADS-B Out interoperability is available, allowing for separation and collision avoidance functions between cooperative aircraft.*

8. Advantages relative to other technologies serving this function

- *Already a mature technology in the EU for participating aircraft.*
- *Unique model of licensing a standard for minimum specifications and interoperability allows for a wide array of suppliers, capabilities, and price points; also drives innovation.*

9. Disadvantages relative to other technologies serving this function

- *Fee for use.*
- *Non-participating pilots cannot see FLARM pilots. Only FLARM pilots can see each other.*
- *Solution would still not solve a non-cooperative problem.*

10. Precision

- *Depends on the GPS onboard the aircraft; most often plain GPS or GPS-WAAS.*

11. FAA Acceptance

- *Traffic awareness beacon system covered in TSO-C199 for gliders and balloon operating outside of 14 CFR 91.225 airspace.*

12. Cybersecurity and Privacy

- *Encrypted. You are only able to enjoy the situational awareness picture if you'd paid for the proprietary box. Licensed by ONERA.*

13. Maturity in time: use at what UML levels?

- *UML-2-3.*
- *COTS product now in Europe but has never been sold in the U.S., even for gliders, and the low-power setting does not meet FAA requirements for collision avoidance. Because it is not sold in the U.S. now, UML-1 not included.*

14. Ground Architecture

- *No ground infrastructure; this is an air-to-air technology.*

15. References

https://flarm.com/products/powerflarm/uav/
https://gliding.lxnav.com/products/powermouse/
https://flarm.com/nasa-starts-using-flarm-for-drone-utm/

16. Other Notes

- *FLARM calculates own-aircraft path based on speed, acceleration, track, turn radius, wind, altitude, vertical speed, aircraft type, and other parameters. Position is based on a GPS receiver onboard. The flight path, together with additional information such as a unique identification number, is encoded before being broadcast over an encrypted radio channel twice per second. At the same time, it receives the future flight path from surrounding aircraft. A prediction algorithm calculates a collision risk for each aircraft based on an integrated risk model. When a collision is imminent, the pilots are alerted with the relative position of the other aircraft, enabling them to take action.*
- *Newer FLARM devices which are based on the improved PowerFLARM technology optionally incorporate an ADS-B and transponder (SSR) Mode-C/S receiver. This enables additional aircraft to be included in the collision prediction algorithm. Besides issuing collision warnings, many FLARM systems also show nearby aircraft on screen. This helps pilots to "see and avoid," before a collision warning becomes necessary.*
- *Over 40,000 manned aircraft and many UAVs are equipped with FLARM. FLARM systems are available from several manufacturers for powered airplanes, helicopters, gliders, and UAVs. FLARM is approved by EASA for fixed installation in certified aircraft. EASA supports FLARM as it significantly decreases the risk of a mid-air collision between participating aircraft. FLARM has been referenced in several EASA publications, including being approved as a Standard Change. FLARM is available to OEMs for integration into other avionics.*

GBSAA - Army Ground-Based Sense and Avoid

Area and Functions: Surv, Ground

Description: Ground-based radar designed to aid in UAS "Sense and Avoid." The GBSAA System uses ground radars to locate nearby aircraft. Data gained from the radars are processed to locate and prioritize the risk from all aircraft, issue alerts to the remote pilots of the UAS at risk, and compute the optimal avoidance maneuvers. This arrangement allows the GBSAA System to provide sense-and-avoid services to unmanned vehicles. Allows UAS to operate like manned aircraft in dense airspace, ATC procedures are not impacted. The system provides health and integrity monitoring, fault tolerance with failover architecture. System supports up to six simultaneous UAS operations.

1. Air or Ground Based? on vehicle?

- *Ground.*

2. Size

- *AN/TPQ-50 Radar and equipment: 40 in/102 cm diameter by 85 in/216 cm high.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *AN/TPQ-50 Radar and equipment < 227 kg / 500 lb.*
- *LSTAR system software and computers: ~100 lbs. Processing is done in the cloud.*

4. Power

- *1,200 W, 110/240 VAC 50/60 Hz (can be powered by AC grid, generator, or 24 VDC vehicle battery).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *L-band (1-2 GHz).*
- *Obstructions: configured-out or compensated-for with additional radars.*
- *BVLOS: No.*
- *Range: 15 km (for each radar).*
- *Not Aero-reserved.*

6. Cost

- *Estimated between $10M - $100M.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Probably impractical for urban canyons.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Does not support dense traffic. Radar returns would be obstructed by obstacles.*
- *Night operations at low and high traffic levels: no degradation at night.*
- *VMC and IMC with high winds, low and high traffic levels: No degradation due weather. L-band enables utility in night, fog, rain, snow.*
- *On-board emergency in VMC, IMC, high winds and/or high traffic levels: Not impacted.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Not impacted.*
- *Would detect non-cooperative traffic.*
- *Bird events – tunable radar may be able to filter out birds; may show dense flocks of large birds.*

8. Advantages relative to other technologies serving this function

- *Low risk, extant operational system.*

- *Designed to interface with extant radar.*

9. **Disadvantages** relative to other technologies serving this function
   - *Probably not practical for urban canyon environments.*
   - *Technology is developed under contract to U.S. Army.*
   - *Some aspects of LCMR AN/TPQ-50 Radar or LSTAR software might be sensitive or classified.*
10. **Precision**
    - *Position and track accuracy undisclosed; however, it calculates ballistic trajectories and resolves point of origin to 50 m at 10 km.*
    - *Provides separation of 1 nautical mile horizontal, +/-1000' vertical, verified to be safe/adequate via MIT simulations.*
11. **FAA Acceptance**
    - *FAA UAS Integration Office reviewing a proposed Letter of Acceptance for impacts. In cases of public agency use, the FAA generally accepts a certificate from the operator to functionality. Operator assumes liability of operation.*
    - *Some of the software which was deemed critical was certified IAW DO-178 (level unknown, suspected to be level DAL-B).*
    - *This system was part of the basis of a Letter Of Agreement (LOA) with FAA for airspace use; also being used as part of an ATC-like function for UAS transiting controlled airspace to get to UAS-designated airspace/COA.*
12. **Cybersecurity and Privacy**
    - *Vendor hardened for cybersecurity.*
13. **Maturity in time:** use at what UML levels?
    - *UML-2-3.*
    - *TRL 9 – Operational with 6000+ hours and upgrades scheduled.*
14. **Ground Architecture**
    - *Urban canyon surveillance requires a distributed collection of radars (count is city-specific) and a "control room" configuration consisting of a rack of computers and several LCD monitors. Upgraded version in near future will have cloud-deployment and minimization of required information displays to ANSP traffic managers. Most SAA/DAA information would be distributed automatically to operating UAM vehicles, reducing humans in the loop.*
15. **References**

"Army GBSAA" Presentation to RTCA S/C-228. August 5, 2019.

GNSS (unaugmented)

Area and Functions: Nav, EnRt

Description: Global Navigation Positioning Satellite Constellation(s): U.S. GPS and other constellations are included in the term GNSS, unaugmented satellite positioning. The U.S. GPS satellite constellation was purpose-built to provide a global positioning, navigation, and timing resource. The GPS satellites transmit an omnidirectional message of the current time based on their accurate atomic clocks. The GPS satellite clock time is maintained by the U.S. Naval Observatory (USNO) Master Clock to be accurate within 10 nanoseconds. A receiver on earth (or slightly above the surface) receives timing messages from several satellites. The receiver computes signal travel time from the timing message and from that the receiver's exact distance from the satellite. With three signals, the receiver knows it is at a point where the spherical distances from three satellites intersect. With four signals, the receiver aligns its own clock. The satellites broadcast all GPS satellite positions in the almanac, which is carried in subframes 4 and 5 in sequential transmissions such that a complete almanac is transmitted every 12.5 minutes. Positions are accurate to one meter. Other countries have launched their own GNSS constellations, including GLONASS (Russia), BeiDou (China), IRNSS (India), and Galileo (Europe). The various countries have an agreement in principle to align clocks; however, between constellations the clocks can differ by 50 ns.

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *When integrated into other electronics, the receiver is smaller than a watch; is chip size. For professional use, includes a small antenna the size of a fist.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Ounces when integrated into other electronics; up to less than 5-lbs standalone.*

4. Power

- *Tenths of watts.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Upper L-band (1 559 - 1 610 MHz), having the GPS L1, Galileo E1 and GLONASS G1, and to the bottom of the Lower L-band (1 151 - 1 214 MHz) where GPS L5 and Galileo E5 are located, with E5a and L5 coexisting in the same frequencies.*
- *Range: Line of sight extending hundreds of miles.*
- *BVLOS/clutter: Obscured by buildings if receiver is under a bridge or near a building.*
- *Reserved and protected frequencies.*

6. Cost

- *GNSS receivers for aircraft range from handhelds for low hundreds of dollars to $10K professional units but most GNSS are integrated with other avionics and sold in bundles, like Mode S with WAAS.*

7. Use Case Evaluation

- *GPS is easily spoofed/jammed. Buildings and obstructions can cause signal degradation and loss of service. [2]*

8. Advantages relative to other technologies serving this function

- *May be augmented with WAAS or other GNSS constellations.*
- *Industry standard, with global coverage and receiver autonomous integrity monitoring (RAIM) prediction tools.*

9. Disadvantages relative to other technologies serving this function

- *GPS vertical accuracy may not be sufficient for certain UAM Urban Operations such as landing.*
- *GPS does solve need for accurate AGL data (needs terrain and obstacle database).*

10. Precision

- *The government provides the GPS signal in space with a global average user range rate error (URRE) of ≤0.006 m/sec over any 3-second interval, with 95% probability. This measure must be* *combined with other factors outside the government's control, including satellite geometry, signal blockage, atmospheric conditions, and receiver design features/quality. [1]*

11. FAA Acceptance

- *GNSS Navigation is currently widely accepted and used for all phases of flight, domestically and internationally.*
- *WAAS enabled GPS approaches (LP or LPV) number in the thousands and commonly have 200' minima.*
- *GNSS/GPS is NOT typically approved as the ONLY source of navigation for IFR approach operations. Further restrictions apply for commercial operations. [2,3]*

12. Cybersecurity and Privacy

- *GPS may be spoofed/jammed by an operator with ill intent. [4,5]*

13. Maturity in time: use at what UML levels?

- *UML-1-4.*
- *Currently used and will be used in the foreseeable future.*

14. Ground Architecture

- *GNSS constellations rely on ground corrections provided from stable nuclear clocks and the satellite positional updates contained in the almanac.*

15. References

[1] Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report, Submitted by William J. Hughes Technical Center WAAS T&E Team to the FAA GPS Product Team, FAA, January 31, 2017.
[2] FAA, "Satellite Navigation - WAAS -Benefits", December 23, 2016. ww.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/
[3] "GPS Accuracy:The Official US Government Information Site about GPS Accuracy," NOAA, Dec 5, 2017. https://www.gps.gov/systems/gps/performance/accuracy/. Accessed January 9, 2020.
[4] Ignacio Fernández-Hernández,Todd Walter, Ken Alexander, Barbara Clark, Eric Châtre, Chris Hegarty, Manuel Appel, Michael Meurer, "Increasing International Civil Aviation Resilience: A Proposal for
Nomenclature, Categorization and Treatment of New Interference Threats,"FAA Whitepaper, 2019.
[5] Joseph C. Grabowski, "Personal Privacy Jammers: Locating Jersey PPDs Jamming GBAS Safety-of-Life Signals," GPSWorld, April 1, 2012. https://www.gpsworld.com/personal-privacy-jammers-12837/ Accessed October 22, 2019.

GNSS + Inertial Navigation/Reference Systems (includes FOG/MEMS)

Area and Functions: Nav, Appr; EnRt

Description: Augmentation to GNSS with INS or IRS: Both the INS and IRS can provide attitude, heading, and acceleration data, and are capable of providing present position information to an external flight management system (FMS), much like a GPS does. However, only the INS has an integrated navigation system that can be used independently of an FMS. Fiber optic gyroscopes (FOG), ring laser gyroscopes (RLG), and microelectromechanical system (MEMS) gyroscopes contain multiple sensing inputs including dual or triaxial accelerometers, barometers, and pressure comparators to determine attitude, pitch, direction, and distance of travel. INS and IRUs are not a means to provide augmentation for UAM augmentation. They should be considered as part of a navigation suite involving GNSS navigation because it will be necessary for UAM to "coast" for short periods when GNSS signals are lost in the urban environment.

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *Varies; roughly 1 sq. ft. for transport RLG and FOG systems, down to 1 ½ in sq for a MEMS/GPS coupled device for experimental aircraft or UAV.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Estimated <10 lbs. for transport aircraft version, MEMS version would be < 2 lbs.*

4. Power

- *Varies, ROM estimated 10W peak (some small packaged systems can operate at 0.5W).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Does not radiate; internal filter rates seem to vary between 400 Hz and 1000 Hz.*

6. Cost

- *High-end (transport category aircraft) variety RLG- or FOG-based INS cost between $60,000 to $120,000; some MEMS/GPS units can be as low as $3,000, but not sure if civil certified.*

7. Use Case Evaluation

- *Probably not acceptable as precision navigation source without GNSS updates.*
- *En route application needs to be evaluated, especially when coasting (i.e., without GPS aiding): Current air transport can coast for long time periods that would be inappropriate for UAM.*

8. Advantages relative to other technologies serving this function

- *Commercially available, low-end MEMS units being marketed for experimental aircraft and UAV use (but these vehicles are not expected to operate under 14 CFR Part 135).*
- *Can provide attitude and heading information as well as position.*

9. Disadvantages relative to other technologies serving this function

- *Cost of RLG and FOG INS equipment is very high.*
- *Position coasting errors likely to be too great for urban environment autonomous application as a navigation augmentation, especially with MEMS sensors.*
- *INSs for civil aviation were developed to mainly support cruise altitude (Class A airspace) long-range navigation in areas where ground-based navigation aids were not available and where reasonable position drift over time could be accepted without compromising aircraft separation. In an urban environment, without GNSS or other means of aiding, perhaps an RLG or FOG based INSs might be acceptable as an en route navigation backup, for very short-term GNSS outages, but would not be acceptable for UAM approach and landing guidance. Current MEMS-based INS systems tend to have large angular/position drift error, but might be acceptable to provide an attitude and heading reference.*

10. Precision

- *Varies with inertial technology used (from 0.001 degrees/hour to 10+ degrees/hour drift).*

11. FAA Acceptance

- *Need to demonstrate Part 23/27.1301 for intended function, and Part 23/27.1309 for safety assurance if to be used in 14 CFR part 135 operations.*
- *Appendix G to Part 121 is still the only policy pertaining to the drift accuracy that an INS system must demonstrate.*
- *RTCA SC-159, WG2c, is currently working on a MOPS for tightly-coupled GNSS/INS systems. They plan three categories (subject to change):*
    - *Category A - When no GNSS is available, Category A is compliant with 14 CFR Part 121 Appendix G, i.e., unaided by GNSS; Category A provides inertial coasting for positioning and velocity according to Appendix G.*
    - *Category B - Is not compliant with 14 CFR Part 121 Appendix G. When no GNSS is available, Category B can coast for horizontal position and velocity over a period specified by the manufacturer.*
    - *Category C - Is also not compliant with 14 CFR Part 121 Appendix G. When GNSS is available, Category C is capable of providing positioning, velocity, and enhanced attitude/heading as specified by the manufacturer. Category C cannot provide horizontal position or velocity coasting for extended GNSS disruptions.*
- *The MOPS is intended to be performance based and will accommodate RLG, FOG, MEMS, or other inertial technologies as appropriate. It will be the responsibility of the manufacturer to categorize and demonstrate the intended performance of its equipment. The SC-159 committee is expecting to have this MOPS ready for approval by mid-year 2020. It is expected that the FAA will, in turn, recognize this standard by issuing a Technical Standard Order (TSO), with Advisory Circular (AC) guidance.*

  See background information in notes below.

12. Cybersecurity and Privacy

- *Secure, no external interface to INS, can coast if GPS outage/jamming/spoofing is detected. Anti-spoofing GPS technology is available but increases costs and is not readily exportable.*

13. Maturity in time: use at what UML levels?

- *TRL 7/8/9 depending on inertial technology selected.*

14. Ground Architecture

- *No specific ground infrastructure is required for operation of INS and IRUs.*

15. References

Frank Van Graas, "Workshop on GNSS Data Application to Low Latitude Ionospheric Researc," International Centre for Theoretical Physics, Trieste, Italty, 7 May 2013. http://indico.ictp.it/event/a12180/session/23/contribution/14/material/0/0.pdf

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14 CFR Part 121, Appendix G. https://www.ecfr.gov/cgi-bin/text-idx?pitd=20170725&node=ap14.3.121_11500.g&rgn=div9
Rockwell Collins Athena 411
https://www.rockwellcollins.com/~/media/Files/Unsecure/Products/Product%20Brochures/Controls/Flight%20Controls/Athena%20411/Athena%20411%20data%20sheet.aspx

16. Other Notes

- *Short description: All inertial navigation systems suffer from integration drift: small errors in the measurement of acceleration and velocity are integrated into progressively larger errors in velocity, which are compounded into still greater errors in position. Since the new position is calculated from the previous calculated position and the measured acceleration and angular velocity, these errors accumulate roughly proportionally to the time since the initial position was input. Gyroscope technologies used in current civil INS systems include Ring Laser Gyroscopes (RLG), Fiber Optic Gyroscopes (FOG), and Micro-Electro-Mechanical-System (MEMS) technology. RLG include a bi-directional laser beam around a closed path with mirrors and FOG uses a bi-directional laser beam through optical fibers. MEMS technologies, which are used in many consumer goods (such as phones, cars, robots, etc.) to sense/detect motion, have recently moved into the experimental aircraft, general aviation, and UAV markets. The RLG and FOG systems make use of the Sagnac/ring interferometer effect, whereas MEMS makes use of the Coriolis force.*
- *Background: Initial uses of inertial systems were in rocket/missile guidance in the 1950s. In the 1960s, the U.S. Air Force added dual inertial systems to the Lockheed C-141 transport aircraft, and triple inertial systems on the Lockheed C-5 transport aircraft. Both aircraft types used the Delco Carousel with Ring Laser Gyro (RLG) technology. In the mid- to late-1960s, the Boeing Company added triple inertial navigation systems to its Boeing 747 commercial transport aircraft, to support long-range navigation, in addition to providing attitude and heading information. In early civil aviation applications, the INS was primarily used to provide navigation guidance in remote areas, e.g., oceanic, polar, beyond the service area of ground-based navigation aids and before the Global Positioning Satellite (GPS) navigation system was made available.*
- *In March of 1970, the Federal Aviation Administration (FAA) published, in the Federal Register, Appendix G to Title 14 Code of Federal Regulation (CFR) Part 121. Appendix G defined the requirements for an operator to certify its long-range navigation system, which at the time covered INS and Doppler radar navigation capabilities. As of today, Appendix G to Part 121 is still the only policy pertaining to the drift accuracy that an INS system must demonstrate. As stated in Section 6 of Appendix G, the allowable drift (i.e., without external alignment) is:*
  - For flights up to 10 hours' duration, no greater than 2 nautical miles per hour of circular error on 95 percent of system flights completed is permitted.
  - For flights over 10 hours' duration, a tolerance of ±20 miles cross-track and ±25 miles along-track on 95 percent of system flights completed is permitted.
- *These allowable drift values may seem large, but in long-range, remote/oceanic operations, the procedural separation of aircraft along-track and cross-track is usually 50 miles or greater. Gyroscopes are classified into three different categories (short-term devices, tactical grade, and navigation-grade) based on their performance in degrees of angular drift (bias)/hour when not*

updated by a known navigation position (e.g., GPS, DME/DME). A drift error of 0.01 degrees of longitude/hour is approximately equal to 1 nautical mile/hour of position error.

- Short-Term: > 10 degrees/hour.
- Tactical Grade: between 0.01 and 10 degrees/hour.
- Navigation (or Inertial) Grade: between .001 and 0.01 degrees/hour.

- *RLGs are currently the angular rate sensors with highest performance available in the market, and exhibit navigation grade performances. They are used in the most demanding applications, especially those requiring extremely high scale-factor stability. FOGs normally achieve tactical grade performance, while typical MEMS seldom exceed the short-term grade performance level, which is generally satisfactory for most of the automotive and consumer electronics applications. More recent MEMS-based INSs are being developed with GPS updating to improve positioning accuracy.*

GNSS + PNT Augmentation

Area and Functions: Nav, Appr; Land

Description: Example commercial solution for UAM landing site navigation augmentation designed for the challenges of an urban environment. PNT is a bucket term we used to encompass several ground-based commercial GNSS enhancement services, whether the ground beacons provide carrier-phase corrections, or kinematic corrections, or independent timing sources, all distributed over a local area. Often these enhancements are networked together with ground wire and transmit short range (1 km) RF signals. Commercially, NextNav, Metro Beacon, and RTK are some well-known examples. LAAS is a government-sponsored version of these commercial services; this category looked specifically at the idea that an urban environment might choose to self-equip with a GNSS enhancement service that UAM could use, in PNT. SmartCities were looking at, and investing in, city-wide PNT to provide enhancement to locational precision for emergency services and ground traffic, but the signal would also assist urban UAS, and UAM, and would also provide a backup timing source for systems like cell phones and point-of-sale terminals, among other services.

1. Air or Ground Based? on vehicle?

- *Ground units provide a known reference and broadcast a position correction to aircraft.*
- *Aircraft receive on aero radios.*

2. Size

- *Ground: Electrical cabinet - estimated 1m x 0.3m x 0.6m, plus stand, antennas, and cabling.*
- *Air: 1U standard aeronautical radio. May be implemented via subscription; signal may be integrated with GPS receiver.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Ground unit estimated 40-50 lbs.*
- *Air unit less than 10 lbs.*

4. Power

- *Transmit Power: 30W EIRP.*
- *Ground: 120VAC standard.*
- *Air: Aero radio, standard a/c power.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *M-LMS bands, 920 MHz. Digital signal (licensed user).*
- *Handling of obstructions and BVLOS: Denser network required for in-building penetration. Uses low signal power, partially offset by high processing gain. Signal available BVLOS.*
- *Range: Create a network of ground transmitters with site spacing dependent upon local clutter (if any).*
- *Altitude range unknown.*
- *NextNav has licensed bandwidth for this service.*

6. Cost

- *Service fee based. Unknown.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Good. Possibly good to IMC-2?*
- *VMC and IMC at high local traffic levels such as a large sporting event: Signal is a broadcast, not an interrogation. At this time, licensing handshakes in-air do not seem limiting.*
- *Night operations at low and high traffic levels: Good.*
- *VMC and IMC with high winds, low and high traffic levels: Precision unaffected by wind.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Augmentation suitable for CAT II landing at new locations.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Jamming may be a factor in an emergency/threat situation.*
- *Operator with ill intent: No obvious weakness except hacking.*
- *Bird events: Birds not likely to obscure signal.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Non-cooperative traffic not a factor in receiving augmented position signal.*

8. Advantages relative to other technologies serving this function

- *Nanosecond specific synchronization among transmitters.*
  - *Uses GPS signal format, for ease of legacy adoption.*
- *Broadcast-only infrastructure; no tracking of users.*
- *Architecture optimized for location (minimized GDOP).*
- *Scales to large shared network.*

9. Disadvantages relative to other technologies serving this function

- *Fee structure.*

10. Precision

- *Altitudinal: In-building reception on mass-market cell phones using NextNav service resulted in 94% of fixes within 3 meters and a max excursion of 5 meters. 80th percentile was 1.8 meters. Outside, approx. 1m precision at 80% given correct placement and install. CTIA tested.*

11. FAA Acceptance

- *Not started. May partner with an avionics company. Needs MOPS and TSO. Minimum of three years away.*

12. Cybersecurity and Privacy

- *Resilient if not immune to GPS outages. GPS independence planned.*

- *Signal is encrypted, available via subscription or prepaid service with infrequent license queries (less frequent than per-flight).*
- *Signal relatively low power – near to GPS signal power; signal is encrypted and spoofing mitigation techniques are available.*

13. **Maturity in time: use** at what UML levels?
    - *UML-2-6*
    - *Demo at Langley late 2019.*
    - *Lateral and altitude capabilities: ready for market.*
14. **Ground Architecture**
    - *Ground-based PNT relies on ground sensors to provide augmentation to GNSS positioning or wholly alternative positioning to GNSS. In the case of a local beacon, most available frequency for commercial systems is in the GHz range and so the antennas would need to be positioned within 1 km of the areas where precision positioning is needed, whether needed for landing operations or city wide. Although offerings vary widely, ground systems include single-line power to an equipment cabinet, an antenna, and sometimes a wired ground communication line for networking. This alternative considers specifically commercial services where the equipment would be commercially provided as part of a service-fee arrangement.*
15. **References**

NextNav website. http://www.nextnav.com/network.
Ganesh Pattabiraman, "NextNav, LLC: High Precision Urban and Indoor Positioning Services," PNT seminar, November 14, 2013, https://web.stanford.edu/group/scpnt/pnt/PNT13/2013_Presentation_Files/4-Pattabiraman-PNT13.pdf.

16. **Other Notes**
    - *"The NextNav network uses licensed spectrum designated for location services. To compute a position, multiple transmitters, arranged with a specific architecture, must be in view of the receiver. This results in transmitter spacing and site selection criteria that are very different than those used in a traditional cellular grid. NextNav precisely surveys every transmitter antenna location, and even takes into account timing variances introduced to its system from cabling runs. The specific location from which the transmission was made is not important in cellular networks but is critical to providing an accurate location. NextNav takes into account numerous other subtle factors (for which it has generated significant IP) to ensure the precision of its location information, and has perfected this capability over the last four years." (NextNav website).*

GNSS + eLoran

Area and Functions: Nav, EnRt

Description: Potential augmentation to GNSS in civil critical infrastructure for Aviation, Maritime, Timing. Loran-C was a series of hyperbolic arrays spaced far apart to provide positioning services over RF signals before GPS was fielded. Waveforms followed the curvature of the earth and traveled hundreds of miles, making it a valuable navigation service at sea prior to the advent of GPS. Loran-C accuracy is inferior to GPS, and was discontinued by Presidential order. At this time, funding support for Loran-C has been discontinued. Enhanced Loran, or eLoran, makes better use of signal processing techniques to increase the accuracy of navigation by Loran to plus-or-minus 8 meters, which is better than GPS with selective availability, but worse than augmented GNSS, including WAAS.

1. Air or Ground Based? on vehicle?

- *Ground.*

2. Size

- *Navigation receiver box: 11 cm x 9 cm x 3 cm, with spherical antenna approx 10 in diameter, 5 inches high.*
- *Timing receiver box: 11 in x 20 in x 3 in (server size).*
- *Ground transmitter: Several server racks, plus a 625-foot high antenna.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Receiver probably 5-10 lbs, antenna likely the same.*
- *Transmitter is very large and server rack takes a room.*

4. Power

- *Ground transmitter, 400 kW.*
- *Mobile receiver: Probably as much as a desktop computer.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *90-110 KHz.*
- *Long range signal with ionospheric bounce.*
- *Valid in BVLOS and around obstacles.*

6. Cost

- *Was discontinued because it was more expensive than newer technologies. Requires more than $38 million to restart.*

7. Use Case Evaluation

- *Not evaluated.*

8. Advantages relative to other technologies serving this function

- *Failure modes independent from GNSS.*
- *Can serve as back-up timing source.*
- *Ability to penetrate into urban canyons and buildings can assist service providers in meeting the evolving PNT performance requirements including those for E-911(US) or E-112 (Europe) response systems.*

  Useful as a backup system to GNSS but not as a superior alternative.

9. Disadvantages relative to other technologies serving this function

- *e Loran requires Loran to operate.*
- *Expensive towers requiring high power that interfere with themselves.*
- *Like GPS, denied by large metal objects (e.g., bridges and buildings) and EMC emitters like buildings.*

10. Precision

- *Accuracy 0.004 – 0.01 nautical mile (8 – 20 meters) (see attached eLoran Definition Document, 2007).*
- *eLoran has been shown to meet the Required Navigation Performance 0.3 (RNP 0.3) aviation specification.*

11. FAA Acceptance

- *Has no budget, therefore unsupportable, therefore unavailable.*

12. Cybersecurity and Privacy

- *Loran is difficult, but not impossible to spoof/jam.*
- *eLoran employs high-powered transmitters, so the signals reaching receivers are of much greater strength than those of GNSS and require much more power to jam. Given that radiating significant power efficiently at the low frequency and long wavelength of Loran requires large antenna structures, it is extremely difficult to produce a signal that could jam an eLoran signal over more than a very small local area.*

13. Maturity in time: use at what UML levels?

- *Past mature; a technology that has been surpassed by leaner alternatives. No longer available.*

14. Ground Architecture

- *Loran-C was a hyperbolic navigation system. Receivers measured the difference in times of arrival of pulses transmitted from chains of stations spaced hundreds of miles apart. The U.S. defunded Loran-C in 2010 and began dismantling stations. eLoran is based on Loran-C with improvements in the signals and in the information carried on the signals. Pulsed signals provide better time of arrival measurment, for better precision. eLoran signals can take advantage of GPS corrections and can carry messages.*

15. References

Loran and eLoran, Stanford Engineering GPS Lab Research, https://gps.stanford.edu/research/early-research/loran-and-eloran
Sherman Lo and Benjamin Peterson, "Enhanced Loran" Stanford GPS Lab, June 2009.

GNSS + GBAS (aka LAAS), Precision GPS Augmentation

Area and Functions: Nav, Appr; EnRt; Land

Description: Ground-Based Augmentation System (GBAS) is a system that provides differential corrections and integrity monitoring of Global Navigation Satellite Systems (GNSS). GBAS provides a navigation and precision approach service in the vicinity of the host airport (approximately a 23-nautical mile radius), broadcasting its differential correction message via a very high frequency (VHF) radio data link from a ground-based transmitter. GBAS yields the extremely high accuracy, availability, and integrity necessary for Category I, and eventually Category II- III precision approaches.

1. Air or Ground Based? on vehicle?

- *Ground and air.*
- *Ground unit is for sale from Honeywell (model SLS-4000). Available at 14 airports; two public airports in U.S. Consists of multiple ground GPS antenna, VHF antenna, two equipment cabinets.*
- *Avionics box – commercial. 1 GPS antenna + 2 cockpit displays + 1 interface unit + multimode receiver (MMR) LRU integrated to autopilot + pilot interface keyboard, VHF data interface.*

2. Size

- *Ground – need a large shed with power, environmental controls, antennas more than 6-ft high.*
- *Avionics box – avionics bay size boxes.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Air box probably 20-50 lbs, not including the autopilot.*

4. Power

- *Standard aircraft power; not high power.*
- *Ground antennas require power, supports.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Current GBAS systems approved by the FAA only monitor and augment the Global Positioning System (GPS) L1 C/A broadcast.*
- *GPS: L1, with corrections broadcast in VHF.*
- *Handling of obstructions and BVLOS – view should be unobstructed for signal*
- *Range – 23 nmi.*
- *Aero-reserved.*

6. Cost

- *Ground installation about $2M; commercially available.*
- *Ground installation far cheaper than ILS; France considered removing all its ILS for GBAS, to save money, but concluded 90% air equipage would be needed and could not afford to replace air boxes.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Under automation, may need onboard landing sensor for 0.3m accuracy.*
- *VMC and IMC at high local traffic levels such as a large sporting event: No capacity constraint on using for landing. Under automation may need onboard sensor for 0.3m accuracy.*
- *Night operations at low and high traffic levels: Some areas experience GPS interference at night and the combination will not function if GPS signal contains corruptions or errors.*
- *VMC and IMC with high winds, low and high traffic levels: Wind will not affect the accuracy of the signal.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Does not support precision landing at unprepared emergency landing spots.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Unaffected by high usage, unlike cell-based systems.*
- *Operator with ill intent: Would not affect.*
- *Bird events: Would not affect.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Does not detect non-cooperative traffic.*

8. Advantages relative to other technologies serving this function

- *Far cheaper than ILS.*
- *Better accuracy than WAAS.*
- *Does not require straight-in siting.*
- *Provides "bad signal" information on GPS.*
- *One VHF correction antenna may serve multiple airports within 20 nm.*

9. Disadvantages relative to other technologies serving this function

- *Multiple GPS antennas presents a siting problem in the urban environment.*

10. Precision

- *GBAS demonstrated accuracy is less than one meter in both the horizontal and vertical axis.*

11. **FAA Acceptance**
    - *FAA and internationally certified.*
    - *TSO C161a, Ground Based Augmentation System Positioning and Navigation Equipment, provides approval criteria for the GBAS avionics navigation function.*
    - *Manufactured: Rockwell Collins (the Multi-Mode Receivers [MMR] GNLU 925 and GNLU 930) and Honeywell International (Integrated Navigation Receiver [INR]).*
    - *TSO-C162a, Ground Based Augmentation System Very High Frequency Data Broadcast Equipment provides the approval criteria for the data link equipment.*
    - *The Honeywell International Satellite Landing System (SLS) 4000 series (SLS-4000) received System Design Approval (SDA) from the FAA on September 3, 2009, with a follow-on approval of an enhanced SLS-4000 (SLS-4000 Block 1) in September 2012. The Port Authority of New York/New Jersey (PANYNJ) purchased and operates the first public use system to receive FAA operational approval for Newark Liberty International Airport (EWR). Houston Airport System (HAS) owns and operates the second GBAS to receive FAA operational approval for Houston's George Bush Intercontinental Airport (IAH).*
12. **Cybersecurity and Privacy**
    - *Jammable with modest equipment. Spoofable with modest equipment.*
    - *No privacy concerns; does not receive, store, or transmit private data.*
13. **Maturity in time: use** at what UML levels?
    - *UML-1 -6.*
    - *In use since 2012.*
14. **Ground Architecture**
    - *Current GBAS systems consist of three or more VHF antennas connected to a system ground facility, located at an airport. The ground facility equipment computes precision navigational differentials and broadcasts them with an approximately 23-mile range around a subject airport. The locations of the VHF antennas tend to be spaced at least a half-nmi apart and their locations are precisely surveyed, so that timing differences in receiving satellite signals can be calculated. The ground facility compares the measured distance to the satellite with the actual distance based on the broadcast satellite position and the true GPS reference receiver position, and determines the error in the measurement. The average error measured by all operational reference receivers represents the correction term the GBAS avionics needs to apply to the satellite ranges measured by the GBAS avionics. Applied in an urban environment, several precisely surveyed antenna would be placed to potentially serve multiple vertiports. Receiving antenna would likely require ground communication links and power. The ground facility processor requires environmental protection (e.g., shed), power lines, and a VHF data broadcast antenna.*

16. **Other Notes**

"Satellite Navigation — Ground Based Augmentation System (GBAS)" Department of Transportation, FAA website www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/laas/. Accessed 11-30-19

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Pierre Ladoux and Benoit Roturier, "GBAS implementation status: international context and situation in France ," Rabat, 7 – 9 November 2017. https://www.icao.int/MID/Documents/2017/ACAC-ICAO%20GNSS%20Workshop/GBAS%20status%20ACAC.pdf; accessed April 7, 2020.
Joseph C. Grabowski, "Personal Privacy Jammers: Locating Jersey PPDs Jamming GBAS Safety-of-Life Signals," GPSWorld, April 1, 2012. https://www.gpsworld.com/personal-privacy-jammers-12837/ Accessed October 22, 2019.

GNSS + RF Mapping

Area and Functions: Nav, Appr; EnRt

Description: Augmentation to GNSS: An aircraft uses passive receipt of local RF transmitters such as radio/TV towers or cell towers to geolocate its own position. Many coding schemes are available to do this: top contenders are Frequency Difference of Arrival (FDOA) or Multilateration, aka, TDOA, because they do not require prior mapping (like fingerprinting or RSS) and do not depend on the referential RF sources to broadcast particular signals with known TDMA or FDMA; and do not rely on cell identity from cell base stations. Cell assignation algorithms change from LTE to 5G and may shift again in other releases. FDOA measures the Doppler shift from the known RF tower to compute change in position. Multilateration uses relative signal strength or Doppler of overlapping signals to triangulate position.

1. Air or Ground Based? on vehicle?

- *Aircraft based.*

2. Size

- *Dual avionics radios are currently about 6" x 8" x 2"; this radio if purpose-built, could be made without a user interface and occupy a much smaller space, e.g., 2"x3"x2" (e.g., 2 RPI) with present technology.*
- *Antennas on skin of aircraft.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Current technology of 2"x3"x2" = 300g.*
- *Antenna less than 0.5 lb each.*

4. Power

- *Power: Each processor radio running tenths of watts; each antenna consuming around 1-2W; with six antennas could be 10-20 W continuous.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Use emitters from TV and radio (KHz), LTE (MHz), and 5G (GHz).*
- *Line of sight with a minimum number of emitters needed.*
- *Range dependent on emitters. KHz more than 100 miles; LTE line of sight (at altitude potentially 10-20 mi); 5G 1 mi or less.*

6. Cost

- *Similar to Aero radios, but assume multiple (>=6) antennas/radios. About $5K. Compare to 4-radio $3285 MICHEL MX170C NAV/COM RADIO.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: No problems.*

- *VMC and IMC at high local traffic levels such as a large sporting event: No problems. Electricity (close by lightning) will temporarily disrupt signals, but only for a microsecond and re-acquisition of signal would not be difficult.*
- *Night operations at low and high traffic levels: Better reception at night. No problems.*
- *VMC and IMC with high winds, low and high traffic levels: No problems.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Will not work if physical radios are knocked out, or there is no power.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Will not work if there are substantial power outages in city; may be impaired if the cell networks are grounded for EMS services (would then rely on FM radio and television signals).*
- *Operator with ill intent: Unlikely to be jammable from a single person. Could be jammed with multiple jammers, but is more robust than GPS.*
- *Bird events: No problems.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: This technology won't work on non-cooperative traffic.*

8. Advantages relative to other technologies serving this function

- *This concept is not cutting edge but the novel invention is harvesting non-avionics emitters; as a result, no one needs to pay for the upkeep of the emitters; from a cost standpoint for a new network this may be highly desireable.*

9. Disadvantages relative to other technologies serving this function

- *Achievable precision not known; would be at least as good as airport surface multilateration (3 meters).*
- *W-Fi in close buildings/emitters may obscure 5G signals, reducing the number of signals on which to triangulate.*

10. Precision

- *Achievable precision not known; would be at least as good as airport surface multilateration (3 meters).*

11. FAA Acceptance

- *The multilateration concept is the same concept as triangulating on VOR radios, except that here the emitters are not giving any directional indication*.
- *Would need to build a test radio and demonstrate it; radio would need software like a GPS to indicate when it is not receiving proper number of emitters*.

12. Cybersecurity and Privacy

- *Relies on sensing RF signals, regardless of the encoding or encryption of those signals, so does not pose much of a threat to privacy or cybersecurity while "listening" to RF signals*.
- *This technology is not intended to decode the signal, only Doppler sense the frequency or signal strength, so it would not be a carrier for incoming threats (Trojan horses, viruses, etc.)*.

13. Maturity in time: use at what UML levels?

- *UML-3-6.*
- *This technology has been around for decades. Need to add software for automatic geolocation configuration on aircraft, develop package, go through certification. At least seven years off. Could be mature for UML 4.*

14. Ground Architecture

- *Passive use of environmental RF signals for navigation requires only a signal-rich urban environment with some stability of RF signals, such as radio stations, tv stations, RTK, wifi-equipped buildings, and non-moving cell towers. Additions and deletions from the signal environment would need to be added or subtracted from the air unit's positioning database and processes over time.*

15. References

Ashraf Tahat, Georges Kaddoum, Siamak Yousefi, Shahrokh Valaee, Francois Gagnon, "A Look at the Recent Wireless Positioning Techniques With a Focus on Algorithms for Moving Receivers", IEEE Access, September 7, 2016, (DOI 10.1109/ACCESS.2016.2606486).
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GNSS + SAR/ISAR Mapping

Area and Functions: Nav, Appr; EnRt; Land

Description: Synthetic Aperture Radar is used to map a path along the surface. Inferometry SAR sweeps a range across or to the side. Several range gates are used forward, underneath, and back, and a 3-dimensional picture of the objects in the path is formed using processing of the Doppler shift of the returns, rather than range-gating the returns. Thus, SAR is not effective at distance measurement, but is very effective in mapping the topology of the path underneath. This 3D mapping is like a fingerprint; specific objects can then be matched against a database of the city or the path, and location is verified. This allows air vehicles to know where they are with precision down to IMC3b conditions, in clouds, fog, and at night [1]. Corner cubes are placed when a precision path to a landing point is desired, to create a unique pattern for the SAR to capture and to which it can locate.

1. Air or Ground Based? on vehicle?

- *Air, on vehicle.*

2. Size

- *Standard size for aircraft is about 6 cu ft, about the size of snack-size refrigerator. Prototype built by Boeing and IMSAR, referenced below, was the size of a shoebox (12" x6" x6"). [2]*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *The smallest standard synthetic aperture radars weigh about 30 pounds. Most weigh between 50 and 200 pounds. Boeing and IMSAR developed and flew a prototype weighing 3 lbs, developed for sUAS. [1]*

4. Power

- *Prototype was 15 watts. Standard size uses 240VAC, large amounts of power. (Same note: will need power for processors.)*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *X-band [3]; a range of X-band is reserved for aeronautic radar.*
- *Not easily obstructed. At wrong wavelength, can be obstructed by airborne water vapor of same size.*
- *X-band suggested, would saturate in heavy rain over a long range.*

6. Cost

- *Antenna and reader $10,000 - $1,000,000 per unit.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: No restrictions on use for navigability. Works in rain, snow, fog.*
- *VMC and IMC at high local traffic levels such as a large sporting event: No restrictions on use for navigability.*
- *Night operations at low and high traffic levels: No restrictions on use for navigability; works in darkness.*
- *VMC and IMC with high winds, low and high traffic levels: Saturates in heavy rain.*
- *On-board emergency in VMC: No restrictions on use for navigability.*
- *IMC, high winds, and/or high traffic levels: No restrictions on use for navigability.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: No restrictions on use for navigability.*
- *Operator with ill intent: No restrictions on use for navigability.*
- *Bird events: Works even with heavy bird flocks.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: No restrictions on use for navigability.*

8. Advantages relative to other technologies serving this function

- *Works in all weather conditions, save heavy rain (X-band). The SAR sweeps an area in multiple samples and is robust to changes.*

9. Disadvantages relative to other technologies serving this function

- *Expensive, heavy, and requires commercialization.*
- *Not useful for altitudinal measurement.*
- *Among the heavier of the differential positioning systems available to augment GNSS.*

10. Precision

- *To the centimeter in lateral plane. Not useful for resolving height of the vehicle to precision.*
- *Practically unlimited range (used from orbit).*

11. FAA Acceptance

- *X-band radars are presently used for onboard weather radar, so the hardware can be certified with some adaptation (antenna size); but the rest would require start from zero.*

12. Cybersecurity and Privacy

- *Unlike visual matching, there are no PII concerns with these images, as a single pass cannot resolve names, plates, etc.*
- *The matching database would require security protocols for storing and updating.*

13. Maturity in time: use at what UML levels?

- *UML-2-4.*

- *NASA website characterizes Boeing IMSAR as TRL 6; other vendors are selling SAR systems on military aircraft with TRL closer to 8.*

14. Ground Architecture

- *No ground architecture required.*

15. References

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[2] William Matthews, "Miniature Radar Developed for Lightweight Unmanned Aircraft" originally printed in www.defensenews.com, 18 March 2008; reproduced in Barnard Microsystems, "Synthetic Aperture Radar," https://barnardmicrosystems.com/UAV/features/synthetic_aperture_radar.html(09/16/19)
[3] Alberto Moreira, "Synthetic Aperture Radar Principles and Applications, 4th Advanced Course In Land Remote Sensing," Harokopio University, Athens Greece, July 2013. https://earth.esa.int/documents/10174/642943/6-LTC2013-SAR-Moreira.pdf

GNSS + WAAS, Precision GPS Augmentation

Area and Functions: Nav, Appr; EnRt; Land

Description: Satellite based GPS augmentation. Signals from GPS satellites are received by 38 widely-spaced Wide Area Reference Stations (WRS). Information from the WRS is transmitted to three WAAS Master Stations (WMS). WMS generates a WAAS User Message every second with information enabling GPS/WAAS receivers to remove errors in the GPS signal. The messages are uplinked from the WMS to three geostationary satellites. The message is rebroadcast in GPS format. GPS/WAAS avionics receivers process the WAAS augmentation message as part of position estimation.

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *Many GA aircraft already have a radio-sized GPS unit and fist-sized antenna. The WAAS augmentation is a small peripheral less than 4"x4"x4."*
- *Can also be integrated into an ADS-B unit as a card inside the box.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *WAAS augmentation unit less than 5 lbs.*
- *Cabling from antenna to unit.*
- *Can be an integral part of the ADS-B+GPS+WAAS box; the entire radio weighs 1 lb.*

4. Power

- *Standard aircraft power. The GPS is not the big draw; the ADS-B xmitter is bigger.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *L1-band.*
- *Handling of obstructions and BVLOS: Line of sight, not obstructed by mountains.*
- *Obstructable by buildings and concrete.*
- *Available across the NAS when not obstructed.*

- *Aero-reserved frequency.*

6. Cost

- *For GA, can add WAAS for less than $1000.*
- *Commercial tend to use LAAS.*
- *Without localizer, no ground equipment to acquire and maintain.*
- *For CAT I, need to buy and maintain localizer RF signal, which is cheaper than ILS.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Under automation, would still need a localizer or an onboard landing sensor for 0.3m accuracy*.
- *VMC and IMC at high local traffic levels such as a large sporting event: No capacity constraint on using for landing. Under automation would need onboard sensor for 0.3m accuracy*.
- *Night operations at low and high traffic levels: Some areas experience GPS interference at night and the combination will not function if GPS signal contains corruptions or errors.*
- *VMC and IMC with high winds, low and high traffic levels: Wind will not affect the accuracy of the signal*.
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Does not support precision landing at unprepared emergency landing spots*.
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Unaffected by high usage, unlike cell-based systems*.
- *Operator with ill intent: Would not affect*.
- *Bird events: Would not affect*.
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Does not detect non-cooperative traffic.*

8. Advantages relative to other technologies serving this function

- *Certified for helicopter approaches*.
- *Compared to GPS-LAAS, can execute low altitude non precision approaches with no ground equipment*.
- *For CAT I, this technology requires LPV at the ground site, still cheaper than ILS*.
- *Less cost and maintenance for ground equipment*.

9. Disadvantages relative to other technologies serving this function

- *Localizer requires obstruction-free straight in path. Difficult to obtain in some urban environments.*

10. Precision

- *FAA-GPS-WAAS Office rated performance is 2.9 m horizontal at 95%; 4.3 m vertical at 95%.*
- *Without any ground equipment, enables decision height of 350-400 ft AGL, using onboard WAAS+GPS (NPA).*
- *When coupled with a ground-based Localizer Performance with Vertical Guidance (LPV) at an airport, enables CAT I landings (ceiling 200'); WAAS-LPV horizontal accuracy is 0.7m and vertical is 1.2m (both at 95%). A localizer is a runway-centerline RF signal.*

11. FAA Acceptance

- *TSO'd.*

12. Cybersecurity and Privacy

- *No personal information is transmitted.*

- *WAAS indicates if the GPS signal has errors and does not permit landing if the general GPS signal is bad.*

13. Maturity in time: use at what UML levels?

- *UML-1-3.*
- *In use since early 2000s.*

14. Ground Architecture

- *WAAS positioning errors are measured by 38 Wide Area Reference ground Stations (WRS) in the U.S. (including Alaska, Puerto Rico, and Hawaii), which are transmitted via ground communications to three Wide Area Master Stations (WMS). The WMS compute fast and slow differential corrections and transmit those to the geo-synchronous GPS satellites for transmission with the GPS signals. This ground architecture is maintained by the FAA for all U.S. aviation.*

15. References

"WAAS Wide Area Augmentation System," FAA, www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/library/factsheets/media/WAAS_QFSheet.pdf. Accessed 040820.

Dave Hirschman, "How It Works: WAAS Approaches Comfortingly Familiar, Incredibly Accurate," AOPA Flight Training Magazine, August 1, 2018. https://www.aopa.org/news-and-media/all-news/2018/august/flight-training-magazine/how-it-works-waas-approaches. Accessed 121819.

Infrared (IR) Sensing, Ground

Area and Functions: Surv, Ground

Description: An infrared sensor is augmented with differential processing to serve as a surveillance instrument. Such instruments only exist in DoD technologies now, so much of the processing capability in this assessment is based on similar technologies and is slightly speculative or forward looking.

1. Air or Ground Based? on vehicle?

- *Ground: Could potentially also be used for air-based machine vision navigation, but the most promising and near-to-market solution is ground surveillance of airborne targets.*

2. Size

- *Processor/display/control unit, approximately 10" x 10" x 14" (unit described here is an experimental Army vision system).*
- *Lenses approximately 1-5 inch diameter rounds with small 1-2" hoods for mounting.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Approximately 25 lbs.*

4. Power

- *28 VDC.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *400-700 nanometers (near infrared), unlicensed and free spectrum.*
- *Visual line of sight.*
- *Range approximately one half mile.*

6. Cost

- *Between $10,000 - $100,000 each.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Works in all weather conditions*.
- *VMC and IMC at high local traffic levels such as a large sporting event: Works in all weather conditions and can track multiple targets. Resolution of humans versus machines would require developmental processing*.
- *Night operations at low and high traffic levels: Works at night*.
- *VMC and IMC with high winds, low and high traffic levels: Works in high winds*.
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Works in all weather conditions. Senses things on fire very well.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Works in all weather conditions. Will detect and track emergency vehicles, even if non-cooperative*.
- *Operator with ill intent: Operator with ill intent would find it difficult to evade thermal detection.*
- *Bird events: Would be able to filter out bird level returns if desired*.
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Detects non-cooperative traffic of sufficient size*.

8. Advantages relative to other technologies serving this function

- *IR coupled with Machine Vision would provide a superior surveillance option to either Machine Vision or IR alone. Together would work in all weather environments, day and night.*
- *This technology is available in the military market now and would be made cheaper if a commercial option resulted in large scale production.*
- *An IR + Machine Vision sensing system could potentially be both an airborne vehicle sensing system and a precision landing aid.*

9. Disadvantages relative to other technologies serving this function

- *This technology is currently military based and elements of the IR are ITAR-protected. It is not commercially available at present.*

10. Precision

- *Gigpixel picture precision; resolves print at 1000-2000 feet away.*

11. FAA Acceptance

- *FAA acceptance: As a ground based technology, there is no FAA use at this time but limited standards apply to ground surveillance technologies.*

12. Cybersecurity and Privacy

- *The resolution of digital cameras is significant and poses a privacy threat that would need to be managed. Identification of persons, reading text, and possibly through-the-window spying would be enabled by such a technology.*
- *The protected status of image resolution hardware in IR would pose a cyber target that would be difficult to protect.*

13. Maturity in time: use at what UML levels?

- *UML-3-6.*
- *Maturity in time depends on resolution required. Versions of this technology are available commercially now, but with degraded precision and limited range (less than half-mile), and no processing. The military system described here is tested and capable but is not on-market.*

14. Ground Architecture

- *Current airborne systems are mounted in UAS: If equipped with airborne processors, would not require ground equipment. Current ground systems are mounted in vehicles. A ground system used for surveillance would require sensors to cover required field of view on line of sight; potentially every two to three miles on an urban perimeter subject to haze or smog. Such sensors would require ground communications to an airspace surveillance authority and power to the sensors.*

15. References

John Keller, "Army surveys industry for high-resolution infrared and color cameras to enhance night vision vehicle driving," Military & Aerospace Electronics, July 20, 2019, www.militaryaerospace.com/sensors/article/14035150/night-vision-infrared-vehicles
Dave Hambling, "New Army Camera Promises Super-Wide Surveillance," Wired magazine, Aug 19, 2009. www.wired.com/2009/08/new-army-camera-promises-total-surveillance/

Laser Communications, Quantum Technologies

Area and Functions: Comm, C2

Description: Point-to-point communication link for air-ground. Camera/sensors for optical communication frequencies form the foundation to a quantum key distribution (QKD) system being tested at NASA Glenn Research Center for use on unmanned aircraft (UA). Test platform currently mounted on underbelly of a Twin Otter research aircraft. QKD uses specialized laser and photon detector technology to enable UAS to exchange encryption keys to communicate on extremely secure radio frequency channels. In addition, an optical channel provides a high data rate communication link for high bandwidth applications. The laser communication hardware attached to the aircraft has performed successfully in aircraft flight tests, and researchers hope to continue advancing state-of-the-art QKD technology focusing on simulated UA flight applications in a variety of environments. Laser communication to aircraft also used for secure communication in U.S. military.

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *A small-scale version with several miles of range is contained in a 10-inch scope less than 3-inch diameter.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Small-scale version weighs less than 5 lbs.*

4. Power

- *Small scale version runs on batteries.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Uses light frequency, not a part of radio frequency spectrum.*
- *Capable of 20 GBps, 20 Gigbits per second capacity.*
- *Range: Works earth to moon and back, more than enough range for UAM. Also used for Satcom.*
- *Line of sight unless a repeater/mirror is used.*

6. Cost

- *TBD, under development.*
- *Cost will rise with laser power. High power needed to burn through fog, clouds, rain, longer distances.*

7. Use Case Evaluation

- *Depends on frequency and power; unknown at this time due to systems being under development.*

8. Advantages relative to other technologies serving this function

- *Secure. High data rates. High bandwidth. Does not use existing congested frequencies.*

9. Disadvantages relative to other technologies serving this function

- *Still in early design phases. Most likely line of sight limited.*

10. Precision

- *TBD, under development.*

11. FAA Acceptance

- *None.*

12. Cybersecurity and Privacy

- *Secure link since it cannot be intercepted without being detected. Interception/eavesdropping would have to take place at the sender or the receiver.*
- *No privacy implications.*

13. Maturity in time: use at what UML levels?

- *UML 5 or 6. Not anticipated to be available by UML-4.*

14. Ground Architecture

- *At present, a single mobile laser transmitter is used to communicate with a single receiver, or one to one ground-to-air and air-to-ground. Future ground system would potentially be able to re-focus on any aircraft in range. For fast, high bandwidth, secure comms air-ground, would need a network of ground-based lasers with pointing motors or hydraulics. At present, ground based lasers appear to weigh less than 50 pounds and sit on a small tripod. To cover an urban environment, these may need to be spaced every three to five miles, depending on field of view, terrain, siting, and density of air traffic. Each would require networked ground communications and a power source.*

15. References

Stephen Carlson, "Marines conduct field test of laser-based communications system," Defense News, august 27, 2018, https://www.upi.com/Defense-News/2018/08/27/Marines-conduct-field-test-of-laser-based-communications-system/3511535389333/?st_rec=9251536091266. Accessed 04082020.

Stew Magnuson, "Game-Changing Laser Communications Ready For Fielding, Vendors Say," National Defense, January 1, 2013. https://www.nationaldefensemagazine.org/articles/2012/12/31/2013january-gamechanging-laser-communications-ready-for-fielding-vendors-say. Accessed 04082020

"Quantum Technologies are Changing the Face of Unmanned Aircraft Communications," NASA.gov, https://www.nasa.gov/glenn/feature/2020/quantum-technologies-are-changing-the-face-of-ua-communications

Lasergate Corridor Monitoring

Area and Functions: Surv, Ground

Description: A simple laser trip light system serves as a perimeter detection system where traffic is sparse, such as in early UMLs. The trip light system requires a returning reflective surface in order to detect an aircraft going by. The alternative, shining a laser into free-space and counting on it to return a signal when tripped by an aircraft could be tried but subject to much higher error rate. This technology assessment performed on the laser light being used to monitor a flight corridor, between two buildings. The transmitter and receivers are separate units and placed on separate buildings: for example, an air traffic tower and a parking garage.

1. Air or Ground Based? on vehicle?

- *Ground. Mounted on buildings to detect aircraft going by, breaking the beam.*

2. Size

- *Small cylinder less than 10-inch long and less than 3-inch diameter; larger for longer range.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Less than 5 lbs; larger for longer range.*

4. Power

- *120V-240V.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Eye safe light spectrum; not part of RF spectrum.*
- *Not licensed.*
- *Range: 100 feet up to several miles.*

6. Cost

- *Between $50 and $500.*

7. Use Case Evaluation

- *Works in high and low traffic, but provides no vehicle identifcation, only counts vehicles going by.*
- *Works in darkeness and wind; interrupted by flying debris and birds.*
- *City emergency and vehicle emergency have no effect on the technology.*

8. Advantages relative to other technologies serving this function

- *Known technology.*

9. Disadvantages relative to other technologies serving this function

- *Useless at detecting anything not flying right through the beam, so useful only as a perimeter monitor.*
- *If knocked out of alignment, requires maintenance.*
- *May become visible when refracted off fog, mist, rain.*
- *May be blinded by direct sunlight (causes false negatives continuously). Since sun angles change year round and diurnally, few angles are safe from sun interference.*
- *Probably more expensive to acquire and maintain than RF sensors.*

10. Precision

- *May have greater size estimating cpaabilities if a fan-splay of beams is fielded, but that would be a future technology.*

11. FAA Acceptance

- *None.*

12. Cybersecurity and Privacy

- *Could be hacked via the physical reporting line.*
- *No privacy implications.*

13. Maturity in time: use at what UML levels?

- *UML 1-2.*
- *COTS now.*

14. Ground Architecture

- *An emitter is affixed to one structure and aligned with a receiver on another structure, so that the space that requires monitoring is in the line of sight between the receiver and emitter. Emitter requires power, and ground communication method to the monitoring authority. One emitter and receiver required for each space to be monitored.*

15. References

https://veterangaragedoor.com/faq/the-light-on-one-of-the-safety-eye-sensors-on-my-garage-door-opener-is-not-solid-what-should-i-do/

LEO (Commercial IRIDIUM)

Area and Functions: Comm, C2, Nav, EnRt

Description: The Iridium satellite network consists of a fully meshed network of 66 low-earth orbiting (LEO) cross-linked satellites, and 9 in-orbit spares. The Iridium satellite constellation provides L-band voice and data information coverage to satellite phones, pagers, and integrated transceivers over the entire globe in a constellation of six polar planes. Each plane has 11 mission satellites performing as nodes in the telephony network. This constellation ensures that every region on the globe is covered by at least one satellite at all times. The satellites are in a near-polar orbit at an altitude of 485 miles (780 km). They circle the earth once every 100 minutes travelling at a rate of 16,832 miles per hour. Each satellite is cross-linked to four other satellites via K-band; two satellites in the same orbital plane and two in an adjacent plane. These links create a dynamic network in space - calls are routed among Iridium satellites without touching the ground, creating a highly secure and reliable connection. Cross-links make the Iridium network particularly impervious to natural disasters - such as hurricanes, tsunamis, and earthquakes - that can damage ground-based wireless towers. The Iridium ground network is comprised of the System Control Segment and gateways to the terrestrial networks. The System Control Segment is what commands and controls the satellites for the Iridium system. It provides global operational support and control services for the satellite constellation. It also delivers satellite tracking data to the gateways. It consists of three main components: four Telemetry Tracking and Control sites, the Operational Support Network, and the Satellite Network Operation Center. The primary linkage between the System Control Segment, the satellites, and the gateways is through a satellite-to-satellite communications system feeder links and cross-links (via K-band) throughout the satellite constellation.

Note that the second-generation Iridium satellites (Iridium NEXT) was first deployed in 2017 and service became commercially available in early 2019 [1]. The NEXT satellites incorporate a secondary payload for Aireon, a space-qualified ADS-B data receiver for use by air traffic control and, through FlightAware, by airlines.

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *Assume a new configuration of the "IRIDIUM Pilot" product (<2 sq. ft.).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Est. <10 lbs., including the processing system.*

4. Power

- *Unknown. ROM Est. 7W peak?*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *L-band (~1620 MHz).*
- *Obstructed by buildings, concrete, bridges.*
- *Used as commercial locating service (paid service GPS service) OR as a communications bounce-point from vehicle to UOC; that is, the communication is transmitted from the aircraft through the satellite to a ground operator.*

6. Cost

- *Devices are relatively cheap ($1500). Subscription is likely.*

7. Use Case Evaluation

- *Fine for all weather use.*
- *Deep building penetration/pass-thru.*
- *Examine possibility of multipath interference in deep urban canyons.*

8. Advantages relative to other technologies serving this function

- *Commercially available, being pushed in mobility market.*
- *Easily configured for priority FFS.*
- *Data rates from 22kbps to 700kbps based on need and subscription.*
- *High power L-band.*
- *IRIDIUM is teamed with many product vendors.*

9. Disadvantages relative to other technologies serving this function

- *Subscription cost for this high-reliability service is likely quite high.*
- *Several pay-per-minute, pay-per-bit models exist.*
- *Needs thought and ConOps developed for Certus use in UAM C3 (e.g., text message based?).*
- *Satellite signals are obscured when tall buildings block the line of sight to the satellite. The higher the frequency used (upper MHz to GHz), the worse the problem is.*
- *Approximate latency of 30 milliseconds.*

10. Precision

- *For STL: <1uS, 20m.*

11. FAA Acceptance

- *Aireon ADS-B is certified.*
- *Certus and STL should be easy to certify.*

12. Cybersecurity and Privacy

- *Encrypt as needed: Balance need with bandwidth utilization and cost.*
- *Possibly more cyber-secure than GNSS.*

13. **Maturity in time: use** at what UML levels?
    - *UML-1-6.*
    - *TRL 9 – already deployed and working.*
14. **Ground Architecture**
    - *The typical satellite communication system comprises of a ground segment, space segment, and control segment. The Iridium LEO satellite constellation particularly has an extensive, interconnected ground network that provides multiple layers of redundancy and back-up systems for all critical functions to ensure network reliability. The Iridium ground infrastructure provides terrestrial connections for satellite voice and data calls, as well as network command, control, monitoring, and technical support, including Satellite Network Operating Center (SNOC), Gateway, Ground Stations, Telemetry, Tracking and Control (TTAC) Stations, and Technical Support Center.*
    - *The SNOC is the nerve center of the Iridium space segment and ground network infrastructure. This nerve center is connected via a dedicated terrestrial fiber-optic system, comprised of a Mulit-Protocol Label Switching (MPLS) cloud and out-of-band satellite links, which directs and carries data to remote antennas and all other ground sites. The Gateway is the landing point for commercial voice and data traffic through the satellites, providing connections into the Public Switched Telephone Network (PSTN) and Internet cloud. The Iridium Network Ground Infrastructure (ground stations) serves as the primary landing points for Iridium OpenPort communications and as a backup landing point for commercial traffic, which is back-hauled via dedicated fiber-optic links to the primary gateway for processing. These ground stations can also serve as Tracking, Telemetry, and Control (TTAC) sites. The TTAC sites route the Iridium satellite health and safety information to the SNOC, provide upload command from SNOC to satellites, and serve as a delivery mechanism for satellite telemetry of key space network data.*
    - *Note that second generation of Iridium satellites (Iridium-NEXT), first deployed in January 2017, retains the same system architecture as the first generation of 66 satellites deployed from 1997 through 2002.*
15. **References**

[1] "Iridium NEXT Engineering Statement," Appendix 1, the Federal Communications Commission (FCC) Form 312, Main Form and Schedule S respond to the requirements specified in Sections 25.114, 25.143 and other FCC rules.
http://licensing.fcc.gov/myibfs/download.do?attachment_key=1031348
Edward Powers, "Implementing Galileo/GNSS to GPS Time Offset: Moving Further Towards Interoperability Through 'Time'," GPS.GOV, 2013,
https://www.gps.gov/governance/advisory/meetings/2013-05/powers.pdf

16. **Other Notes**
    - *LEO satellites were considered as an alternative to GNSS for Navigation. While LEO satellites face some build outs in order to be alternatives to pure GNSS, a GNSS+LEO fusion alternative has distinct and compelling advantages that should be separately considered. In particular, if LEO satellites are used to communication links, the timing of the comm signal can be harvested for GNSS corrections and more precise navigation.*
    - *The rest of the notes here concern use of LEO as a replacement for GNSS as primary navigation.*

- *LEO satellites would require several additions in order to be used in place of GPS satellites for positioning. While these additions are not impossible, they are also not costless and so would need to have a use case that makes the effort worthwhile. First, the LEO satellites would need to be programmed or outfitted to keep very accurate time. Iridium's clock, for example, is only accurate to 100 ns., or about 30 meters. (Ref: Divis, 2016; https://insidegnss.com/iridium-based-system-proposed-gps-backup-incorporates-crypto-protections/). Second, the LEO satellites would have to transmit a GPS-like message of position and time. Third, a method would need to be created for updating LEO satellite position on a frequent basis. LEO satellite orbits decay at an unpredictable rate, because they encounter drag from the earth's atmosphere, so keeping the LEO satellites' position known and accurate is a non-trivial task (more on this in the following paragraph). Fourth, the satellite's PRN number is the tracking signal by which a satellite is acquired by a receiver, and the PRN is subject to error caused by Doppler shift in the signal from satellite movement, confusing the receiver's readings of 0s and 1s. Because the LEOs travel much faster than GPS satellites (because they are very low and have to travel fast to stay in orbit), the Doppler shift in the frequency would be worse and an alternative coding scheme may be needed to tackle acquisition of the satellite frequency.*
- *Predicting own-position is not as easy for LEOs as it is for the GEOs. Decay of the LEO satellite orbit depends on the mass-to-cross-sectional area of the satellite in the direction of travel (which is not known until after launch) and the density of the upper atmosphere through which it travels. Atmospheric density depends on time, season, latitude, altitude, the incidence of solar x-ray flux hitting the atmosphere, and geomagnetism. Solar x-ray flux is a random event generated by the solar wind. "Even when most of the quantities are known there appears to be an irreducible level below which it is not possible to predict. This level appears to be around 10%." (Ref: Dr. Rakesh Panwar, "Satellite Orbital Decay Calculations," Australian Space Weather Agency.)*
- *The argument has been made that the LEOs are closer to earth and would therefore output a stronger signal than the GPS constellation satellites, which would make all this investment worthwhile. The next generation of GPS satellites (GPS III) will have a 1.5 dBm stronger signal strength in order to remain above the noise floor (Ref: GAO report 18-74), and some reports (Wikipedia) suggest that the existing satellite signal strength could be boosted (+20dB) by the U.S. with a software shift, if desired.*
- *Dual frequency (L1 and L2) receivers are available for civilian reception of GPS. Receiving GPS messages on two frequencies allows for ionospheric corrections that upgrade the raw GPS signal to the accuracy of a WAAS-enhanced GPS signal. Importantly, receiving both L1 and L2 provides increased immunity to spoofing. With WAAS available, the dual frequency receivers have been perceived as unnecessarily expensive and are not popular in civilian use.*

LEO (Commercial OneWeb Satellite Ku- and Ka-Band System)

Area and Functions: Comm, C2, Nav, EnRt

Description: The OneWeb system consists of a constellation of 720 small Low Earth Orbit ("LEO") satellites initially, with plans to eventually expand up to 900 satellites, in near-polar circular orbits of altitude 1,200 km, as well as associated ground control facilities, gateway earth stations, and end-user earth stations ("user terminals"). The OneWeb system provides high-quality, broadband Internet access to small low-cost user terminals located anywhere on the Earth. According to OneWeb filing with the U.S. FCC, the service provided by OneWeb will be comparable to the broadband terrestrial services available in densely populated areas of developed countries today.

As of March 28, 2020, OneWeb has filed for Chapter 11 relief in the U.S. Bankruptcy Court for the Southern District of New York and hoped to sell its business.

1. Air or Ground Based? on vehicle?

- *Air-based, satellite system in Low Earth Orbit (LEO).*

2. Size

- *30.0 cm x 75.0 cm (typical OneWeb Ku-band user terminal's antenna).*
- *Satellite unit: 1.0 m x 1.0 m x 1.3 m (OneWeb satellite's stowed dimensions). Specific information about Rockwell Collins' ESA antenna, refer to the Notes at the end.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *2 kg (estimated weight of typical small OneWeb Ku-band user terminal's antennas).*
- *Satellite unit: 145 kg.*

4. Power

- *200 W (on-orbit average power supply by two external solar panels).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Capacity: 1.56 Tbps. This is an estimated maximum system throughputs of 720 satellites and 71 ground stations operating in 18 polar planes (or 40 satellites/plane) at 1,200 km and 86.4o.*
- *Ku-band (User links: 10.70 – 12.70 GHz downlink and 12.75 – 14.50 GHz uplink).*
- *Ka-band (Gateway links: 17.8 – 20.2 GHz downlink and 27.5 – 30.0 GHz uplink).*
- *Licensed by the U.S. FCC for OneWeb to operate in these frequencies. [1]*
- *Obstructed by buildings, concrete, bridges.*
- *Used as commercial locating service (paid service GPS service) OR as a communications bounce-point from vehicle to UOC; that is, the communication is transmitted from the aircraft through the satellite to a ground operator.[1]*

6. Cost

- *$1 million per satellite (estimated cost to build OneWeb satellite is $1 million).[2]*
- *$200 - $300 per terminal user. [2]*

7. Use Case Evaluation

- *Rockwell Collins has teamed up with OneWeb to design and develop Ku-band Satcom terminals, which utilize electronically scanned array (ESA) technology (using rapid beam movement and reconfigurable antenna patterns). The goal is to provide secure cockpit and cabin inflight connectivity, which has potential UAM communication application. For more information about the Rockwell Collins' ESA antenna, see the data sheet at the end of this technology assessment (16. Other Notes).*
- *Ku-band and Ka-band signals affected by atmosphere situations like rain, snow and clouds. [3]*
- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: No impact is expected; however, study should be conducted for UAM aircraft operating in the urban environments.*
- *VMC and IMC at high local traffic levels such as a large sporting event: No impact is expected.*
- *Night operations at low and high traffic levels: No impact is expected.*

- *VMC and IMC with high winds, low and high traffic levels: UAM vehicles should not fly in the condition of high wind; however, OneWeb satellite signals are not affected by high wind in the urban environments, except high wind that brings in dust, rain, or snow.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: No impact is expected.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: No impact.*
- *Operator with ill intent: Not applicable. Security and safety may be the issue here?*
- *Bird events: Not applicable.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. Not applicable.*

8. **Advantages** relative to other technologies serving this function
   - *High system throughput (1.56 Tbps) and low latency (less than 50 ms).*
   - *High data rate.*
   - *A large constellation of LEO satellites to provide for global coverage.*
   - *Dual use.*
9. **Disadvantages** relative to other technologies serving this function
   - *Like other LEO systems, OneWeb cannot be used for sustained communications without an extensively large network of satellites.*
   - *Orbital decay (estimated seven years) is faster than those satellites operating GEO due to atmospheric gases' drag.*
   - *Other space environmental issues in Low Earth Orbit such as debris and other space objects.*
   - *Latency may prohibit use as UAM C2 link. Approximate latency of 30 milliseconds.*
   - *Satellite signals are obscured when tall buildings block the line of sight to the satellite. The higher the frequency used (upper MHz to GHz), the worse the problem is.*
10. **Precision**
    - *Not applicable.*
11. **FAA Acceptance**
    - *None.*
12. **Cybersecurity and Privacy**
    - *A large constellation consisting of hundreds or even thousands of satellites providing direct Internet connectivity may pose significantly higher exposures to cyber-disruptions inherent to all modes of digital networking. And OneWeb and other large LEO satellite systems are vulnerable to cyber attacks [4].*
13. **Maturity in time: use** at what UML levels?
    - *OneWeb began service in 2019. Network service available at UML 1 and 2, definitely at UML 4 and beyond.*
14. **Ground Architecture**
    - *The OneWeb Ground Segment architecture consists of the Satellite Operations Center (SOC), OneWeb Internal Interfaces and External Interfaces. The Satellite Operations Center is designed for Mission Management, including elements such as Earth Station Control, Mission Planning, SOC Infrastructure, Command and Control, Flight Dynamics, and Engineering. Linkage between the SOC and satellites via TT&C Earth Station Ka-band 3.4 antennas. The OneWeb Internal Interfaces include the Global Network Operations Center, Spacecraft, and Ground Segment factories. This internal interface comminicates with satellites through a network of ground Ka-*

band antennas. The external interfaces include but are not limited to the Joint Space Operations Center (JspOC), Launch Base, National Oceanic and Atmospheric Administration (NOAA), and International Earth Rotation and Reference Systems Service (IERS).

- *Note that OneWeb User Terminal (UT) consists of an electronically steerable satellite antenna, a receiver, and a customer network exchange (CNX) unit. The CNX connects the UT to the customer's network which in turn connects to end-user devices including laptops, smartphones, sensors, and more.*

15. References

[1] "OneWeb Non-Gestationary Satellite System (LEO)," Attachment A, FCC Technical Information to Supplement Schedule S, 23 January 2018. https://licensing.fcc.gov/myibfs/download.do?attachment_key=1357110; and https://licensing.fcc.gov/myibfs/download.do?attachment_key=1134939.

[2] Estimated cost per OneWeb satellite. https://spacenews.com/wyler-claims-breakthrough-in-low-cost-antenna-for-oneweb-other-satellite-systems/.

[3] Jalal J. Hamad Ameen, "Rain Effect on Ku-Band Satellite System," Electrical and Elecronics Engineering, International Journal, Vol 4, No 2, May 2015. https://wireilla.com/engg/eeeij/papers/4215elelij02.pdf.

[4] Larry F. Martinez, "Cyber-conflict with Regard to Large Satellite Constellations: Need for Cyberspace Rules of the the Road," Pacific Telecommunications Conference (PTC), Honolulu, January 2017. https://online.ptc.org/assets/uploads/papers/ptc17/PTC17_Tue_RTS_Security_Paper_Martinez.pdf.

16. Other Notes

- *Rockwell Collins' Electronically Scanned Array Antenna Data Sheet*
- *Performance:*
  - *Targeted reduction in system size and weight.*
  - *Integrated radome reduces drag and fuel costs.*
  - *Electronic beam steering.*
  - *Designed for global coverage and low latency.*
  - *Multi-beam capability.*
  - *2 GHz of Ku bandwidth.*
- *Specifications:*
  - *Power: 450 W.*
  - *Weight: 75 lbs.*
  - *Drag: 10 lbs.*
  - *H x L x W: 2-in x 60-in x 27-in.*
- *LEO satellites were considered as an alternative to GNSS for Navigation. While LEO satellites face some build outs in order to be alternatives to pure GNSS, a GNSS+LEO fusion alternative has distinct and compelling advantages that should be separately considered. In particular, if LEO satellites are used as communication links, the timing of the comm signal can be harvested for GNSS corrections and more precise navigation.*
- *The rest of the notes here concern use of LEO as a replacement for GNSS as primary navigation. First, the LEO satellites would need to be programmed or outfitted to keep very accurate time.*

Second, the LEO satellites would have to transmit a GPS-like message of position and time. Third, a method would need to be created for updating LEO satellite position on a frequent basis. Fourth, the satellite's PRN number is the tracking signal by which a satellite is acquired by a receiver, and the PRN is subject to error caused by Doppler shift in the signal from satellite movement, confusing the receiver's readings of 0s and 1s. Because the LEOs travel much faster than GPS satellites (because they are very low and have to travel fast to stay in orbit), the Doppler shift in the frequency would be worse and an alternative coding scheme may be needed to tackle acquisition of the satellite frequency.

LEO (Commercial STARLINK)

Area and Functions: Comm, C2, Nav, EnRt

Description: The Starlink LEO broadband system is anticipated to provide sufficient bandwidth to support most UAM datalink needs. The estimated bandwidth requirement for UAS C2 is 60-100 Kbps [1]. Potential disadvantages include communications latency (approximately 30 milliseconds for LEO) and urban canyon signal multipath. To date, Starlink does not offer commercial services but secure broadband Internet connectivity via IP-based services will be available as early as 2021. 600 Mbps data transfer to a flying aircraft has already been demonstrated. What remains to be developed is the commercial "terminal," though this can be expected to require a small antenna and fairly standard electronics package. (See link.)

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *Unknown. Typical VSAT antenna (~18in.), modem, etc. (similar to a DirectTV system).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Unknown. Est. <20lbs.*

4. Power

- *Unknown. Est. ~6W (based on DirectTV equipment, e.g., directv.com/cms3/about/sustainability/PDF/energy_star_products_page.pdf).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *> 600 Mbps.*
- *Uses several K-band sub-bands of Licensed Spectrum from 10 GHz to 30 GHz.*
- *- See FCC order DA-19-342A1.*
- *Obstructed by buildings, concrete, bridges.*
- *Used as commercial locating service (paid service GPS service) OR as a communications bounce-point from vehicle to UOC; that is, the communication is transmitted from the aircraft through the satellite to a ground operator.*

6. Cost

- *Equipment estimate: < $500.*
- *Subscription estimate: < $150 per month.*
- *Expected to be commercially competitive with GEO offerings (DirecTV) as well as compete favorably with terrestrial offerings (Comcast, Verizon).*

7. Use Case Evaluation

- *Summary: K-band RF has potential signal strength degradation due to rain fade.*
- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: No impact. System scales with each satellite launch and approximately 30,000 are projected.*
- *VMC and IMC at high local traffic levels such as a large sporting event: No impact. This is not used by "individuals." Anticipated UAM flock size is not likely to stress the system.*
- *Night operations at low and high traffic levels: No impact.*
- *VMC and IMC with high winds, low and high traffic levels: Wind can carry dust which degrades signal strength.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: No impact.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: No impact.*
- *Operator with ill intent: Denial is extraordinarily expensive. State-funded operator required.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. Not applicable. Wind can carry dust which degrades signal strength.*

8. Advantages relative to other technologies serving this function

- *UAM vehicle is a "thing" on the Internet-of-Things.*
- *Ubiquitous, higher bandwidth.*
- *Simple ConOps, easy implementation, universal support of new services.*
- *Vendor will make pricing "deals" for fleet use.*
- *Vendor partners will likely lead in implementation of "CNS-as-a-service."*
- *Dual use.*

9. Disadvantages relative to other technologies serving this function

- *Some see subscription-based as disadvantage (fleet terms are negotiated).*
- *Some see K-band as a disadvantage (mitigations available).*
- *Satellite signals are obscured when tall buildings block the line of sight to the satellite. The higher the frequency used (upper MHz to GHz), the worse the problem is.*
- *Approximate latency of 30 milliseconds.*

10. Precision

- *Given UAM vehicle is a connected IP address sending and receiving situational awareness information, the precision is as good as the data it sends/receives, so this is driven by connected sensor packages.*

11. FAA Acceptance

- *None at this time.*

12. Cybersecurity and Privacy

- *A large constellation consisting of hundreds or even thousands of satellites providing direct Internet connectivity may pose significantly higher exposures to cyber disruptions inherent to all modes of digital networking; and OneWeb and other large LEO satellite systems are vulnerable to cyber attacks [4].*

13. Maturity in time: use at what UML levels?

- *UML-2 -6.*
- *According to Space News (October 22, 2019), SpaceX plans to start offering Starlink broadband services in 2020 [2].*

14. Ground Architecture

- *As of March 18, 2020, SpaceX has launched 362 Starlink satellites of nearly 12,000 satellites that have been planned to be deployed in three orbital shells: first placing approximately 1,600 in a 550-kilometer-altitude (340 mi) shell, then approximately 2,800 Ku-and Ka-band spectrum satellites at 1,150 km (710 mi), and approximately 7,500 V-band satellites at 340 km (210 mi). With that many satellites operating at different Low Earth Orbits, SpaceX Starlink constellation will require a very large ground segment with hundreds of ground stations and as many as 3,500 Gateway antennas to operate at maximum throughput. In order to provide high-speed Internet to anywhere in the world, SpaceX has filed with the U.S. Federal Communications Commission (FCC) and has been authorized to begin rolling out as many as one million ground antennas that the company will need to connect users to its Starlink Internet network. Regardless of the number of satellites, ground stations, and antennas, the Starlink Ground Network architecure generally includes the Ground Segment and Control Segment. The Ground Segment consists of satellite interface station (Gateway), user station, and service station (Feeder station). The Control Segment includes TT&C station and Network Management Center.*

15. References

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[2] SpaceX Starlink Broadband Services to be available in 2020. https://spacenews.com/spacex-plans-to-start-offering-starlink-broadband-services-in-2020/

[3] "Request for Modification of the Authorization for the SpaceX NGSO Satellite System," FCC Order DA-19-342A1, Adopted: April 26, 2019. https://docs.fcc.gov/public/attachments/DA-19-342A1.pdf.

[4] Larry F. Martinez, "Cyber-conflict with Regard to Large Satellite Constellations: Need for Cyberspace Rules of the the Road," Pacific Telecommunications Conference (PTC), Honolulu, January 2017. https://online.ptc.org/assets/uploads/papers/ptc17/PTC17_Tue_RTS_Security_Paper_Martinez.pdf.

16. Other Notes

- *LEO satellites were considered as an alternative to GNSS for Navigation. While LEO satellites face some build outs in order to be alternatives to pure GNSS, a GNSS+LEO fusion alternative has distinct and compelling advantages that should be separately considered. In particular, if LEO satellites are used as communication links, the timing of the comm signal can be harvested for GNSS corrections and more precise navigation.*
- *The rest of the notes here concern use of LEO as a replacement for GNSS as primary navigation. First, the LEO satellites would need to be programmed or outfitted to keep very accurate time. Second, the LEO satellites would have to transmit a GPS-like message of position and time. Third, a method would need to be made for updating LEO satellite position on a frequent basis. Fourth, the satellite's PRN number is the tracking signal by which a satellite is acquired by a receiver, and the PRN is subject to error caused by Doppler shift in the signal from satellite movement, confusing the receiver's readings of 0s and 1s. Because the LEOs travel much faster than GPS satellites (because they are very low and have to travel fast to stay in orbit), the Doppler shift in*

the frequency would be worse and an alternative coding scheme may be needed to tackle acquisition of the satellite frequency.

LEO (Commercial Telesat LEO Satellite Ka-Band System)

Area and Functions: Comm, C2, Nav, EnRt

Description: Telesat LEO is the next generation of Low Earth Orbit satellite constellation being developed by the Canadian satellite communications company bearing its name. If all goes well as planned, Telesat LEO will begin service in 2023. According to a Telesat petition filing with the United States FCC for accessing the U.S. market, the proposed Telesat LEO system consists of a constellation of 117 satellites in 11 orbital planes, with 6 planes inclined 99.5 degrees in a circular orbit at 1000 km and 5 planes inclined 37.4 degrees in a circular orbit at 1248 km. These satellites are authorized to operate in Ka-band (for both user and gateway links).

1. Air or Ground Based? on vehicle?

- *Air-based, satellite system in Low Earth Orbit (LEO).*

2. Size

- *0.65 m x 0.65 m x 0.75 m (Telesat LEO satellite's stowed dimensions, based Telesat Phase 1 LEO satellite).*
- *45.7 cm H x 66.0 cm W Ka-band parabolic dish (ThinKom Model Ka2517).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *168 kg.*
- *About 2 kg.*

4. Power

- *Estimated > 200 W (Telesat LEO satellite).*
- *83 to 118 W (ThinKom Ka2517).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *2.66 Tbps. This is an estimated maximum system throughput of 117 satellites and 42 ground stations operating in six polar planes (12 satellites/plane) at 1,000 km and 99.5o and five planes (9 satellites/plane) at 1,200 km and 37.4o.*
- *Ka-band (Downlinks: 17.8 – 18.6 GHz, 18.8 – 19.3 GHz and 19.7 – 20.2 GHz; Uplinks: 27.5 – 29.1 GHz and 29.5 – 30.0 GHz).*
- *Licensed and authorized by the U.S. FCC for to operate in these frequencies[1].*
- *Obstructed by buildings, concrete, bridges.*
- *Used as commercial locating service (paid service GPS service) OR as a communications bounce-point from vehicle to UOC; that is, the communication is transmitted from the aircraft through the satellite to a ground operator.*

6. Cost

- *$1.5 million per satellite. This is a rough estimate based on 600 million Canadian dollars ($US 456.6) pledged by the Canadian government and Telesat for a total of 300 LEO satellites [2].*
- *ThinKom Ka2517 price is not available.*

7. Use Case Evaluation

- *Ka-band signals affected by atmosphere situations like rain[3], snow, and clouds.*

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: No impact is expected; however, study should be conducted for UAM aircraft.*
- *VMC and IMC at high local traffic levels such as a large sporting event: No impact is expected.*
- *Night operations at low and high traffic levels: No impact is expected.*
- *VMC and IMC with high winds, low and high traffic levels: UAM vehicles should not fly in the condition of high wind; however, OneWeb satellite signals are not affected by high wind in the urban enviroments, except high wind that brings in dust, rain, or snow.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: No impact is expected.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: No impact.*
- *Operator with ill intent: Difficult to spoof LEO signals.*
- *Bird event: Not applicable.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Not applicable.*

8. **Advantages** relative to other technologies serving this function
   - *High system throughput (2.66 Tbps) and low latency (30 to 50 ms).*
   - *High data rate.*
   - *A large constellation of LEO satellites to provide for global coverage.*
   - *Dual use.*
9. **Disadvantages** relative to other technologies serving this function
   - *Cannot be used for sustained communications without an extensively large network of satellites.*
   - *Orbital decay (estimated seven years) is faster than those satellites operating GEO due to atmospheric gases' drag.*
   - *Other space environmental issues in Low Earth Orbit such as debris and other space objects.*
   - *Latency may prohibit use as UAM C2 link. Approximate latency of 30 milliseconds.*
   - *Satellite signals are obscured when tall buildings block the line of sight to the satellite. The higher the frequency used (upper MHz to GHz), the worse the problem is.*
10. **Precision**
    - *Not applicable.*
11. **FAA Acceptance**
    - *Not applicable.*
12. **Cybersecurity and Privacy**
    - *A large constellation consisting of hundreds or even thousands of satellites providing direct Internet connectivity may pose significantly higher exposures to cyber disruptions inherent to all modes of digital networking; and OneWeb and other large LEO satellite systems are vulnerable to cyber attacks[4].*
13. **Maturity in time:** use at what UML levels?
    - *Telesat LEO satellite constellation is still under development and test.*
    - *Service is projected to be in 2023.*
14. **Ground Architecture**
    - *Telesat LEO is the next generation of Low Earth Orbit satellite constellation being developed by the Canadian satellite communications company bearing its name. As of February 27, 2020, the company updated the status of the LEO satellite network and anticipated that the Telesat LEO constellation to be partially operational and servicing "certain markets" by the end of 2022. With*

OneWeb filing for bankruptcy due to Covid-19 pandemic, the date of Telesat LEO full service may be pushed further into the future. According the company's claims, Telesat LEO constellation is a global network delivering fiber quality connectivity anywhere in the world. The ground network architecture includes 50 ground stations and Point of Presence (PoPs), and System Resource Manager (SRM). These ground stations, PoPs, and System Resource Manager (Satellite Operations Center) are connected seamlessly with the Internet and private networks.

15. References

[1] "FCC Grants Market Access for Telesat Canada NGSO Constellation," FCC-18-163A1, Adopted: November 15, 2018. https://www.fcc.gov/document/fcc-grants-market-access-telesat-canada-ngso-constellation.

[2] Breaktrhough in Low-cost Antenna, Space News, January 25, 2019. https://spacenews.com/wyler-claims-breakthrough-in-low-cost-antenna-for-oneweb-other-satellite-systems/.

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16. Other Notes

- *LEO satellites were considered as an alternative to GNSS for Navigation. While LEO satellites face some build outs in order to be alternatives to pure GNSS, a GNSS+LEO fusion alternative has distinct and compelling advantages that should be separately considered. In particular, if LEO satellites are used as communication links, the timing of the comm signal can be harvested for GNSS corrections and more precise navigation.*
- *The rest of the notes here concern use of LEO as a replacement for GNSS as primary navigation. First, the LEO satellites would need to be programmed or outfitted to keep very accurate time. Second, the LEO satellites would have to transmit a GPS-like message of position and time. Third, a method would need to be made for updating LEO satellite position on a frequent basis. Fourth, the satellite's PRN number is the tracking signal by which a satellite is acquired by a receiver, and the PRN is subject to error caused by Doppler shift in the signal from satellite movement, confusing the receiver's readings of 0s and 1s. Because the LEOs travel much faster than GPS satellites (because they are very low and have to travel fast to stay in orbit), the Doppler shift in the frequency would be worse and an alternative coding scheme may be needed to tackle acquisition of the satellite frequency.*

LIDAR, on Vehicle

Area and Functions: Nav, Alt, Land; Surv, U2X

Description: Altitudinal and lateral accuracy through light ranging. Used as a supplement to GNSS for near-precision approaches and precision landings. Light Detection and Ranging (LIDAR) is a sensor that generates pulsed laser light and measures timing of returned light to precisely measure the distance to the object being illuminated. Changes in the waveform return can be used to estimate slope or movement in the observed object. It can be used over very short ranges, such as under a foot; or with sufficient power and sighting precision, it can be used to measure the distance to objects on the moon from earth.

1. Air or Ground Based? on vehicle?

- *Air based.*

2. Size

- *Various sizes and power available, depending on range and power needed (en rt nav vs landing).*
- *Automotive Idris LIDAR "size of a soda can," down from size of a large coffee can (Velodyne, 2009).*
- *Topographic LIDAR the size of tissue box. [1]*
- *Garmin LIDAR-Lite 1.6" x 1.9" x 0.8."*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Ceilometer 31 kg/14 lbs (more power, more weight, more range).*
- *Car LIDAR, 2 lbs/1 kg (less power, less weight, less range).*
- *Garmin LIDAR-Lite, 22 grams.*

4. Power

- *Ceilometer: 310 W (920 W, 1/sec). [2]*
- *Automotive Idris LIDAR, 15 W.*
- *Garmin LIDAR-Lite, 1.3W.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Light: Visual line of sight only.*
- *Automobile LIDAR use either 905 nm (nanometer) or 1550 nm. 905 is more eyesafe when used for very small fractions of a second.*
- *Topographic LIDAR uses 1064 nm. Smaller wavelengths have greater precision.*
- *Spectrum is not licensed nor reserved.*

  Note: synthetic aperture LIDAR is an alternative but is too susceptible to platform vibration to be useful on air vehicle.

6. Cost

- *Velodyne LIDAR $75,000K.*
- *Projection for Luminar's Idris is $50 [2]; may have limited range or limited scan.*
- *Garmin/Adafruit offer a UAS single point (not scan) LIDAR for $129, 3 cm x 3 cm, 1.3 watt of power, weighs 22 grams, 40 meter range, precision 1 cm at 905 nm.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: LIDAR not effective in obscuring fog.*
- *VMC and IMC at high local traffic levels such as a large sporting event: LIDAR not effective in obscuring fog but poses no danger in high numbers.*
- *Night operations at low and high traffic levels: LIDAR works at night and poses no danger in high numbers due to diversity of angles of lasers.*
- *VMC and IMC with high winds, low and high traffic levels: Not effective in fog. Works in heavy rain.*

- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: LIDAR will function as long as power is applied. Works in high wind, high traffic levels, rain, snow. Does not work in fog. May have reduced function in blizzard conditions.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: LIDAR will function as long as power is applied. Works in high wind, high traffic levels, rain, snow. Does not work in fog. May have reduced function in blizzard conditions.*
- *Operator with ill intent: LIDAR operation not affected.*
- *Bird events: LIDAR dangerous to birds, may stun or blind them.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. LIDAR operation not affected.*

8. **Advantages** relative to other technologies serving this function
    - *The chief advantage of LIDAR is the scanning technology; it covers a 55-degree azimuthal and 180 degree horizontal field of view in a single scan, multiple times per second. [3]*
    - *Can scale to required heights for UAM approach, keeping in mind that longer range means larger units.*
    - *Can use crowd-sourced and UAS-gathered data for semi-precision approach paths.*
    - *With operator investment at landing site, could be used for landing precision as well as approach*
9. **Disadvantages** relative to other technologies serving this function
    - *Does not work in fog.*
    - *Fine scale (high nm wavelengths) lidar obscured by rain.*
    - *The limit of use in fog and rain is probably why radar and not LIDAR is used in GPWS. However, LIDAR would allow comprehensive scanning (forward and down), which the radar does not.*
    - *Longer-range units use a lot of power and require cooling, which is additional weight and power.*
10. **Precision**
    - *Older versions of automotive LIDAR at 905 nm were accurate to 5m. Accuracy has improved. Topographic (1064 nm wavelength) accuracy to 2 cm possible.*
    - *Garmin LIDAR-Lite advertises 1 cm precision over 40 m. [4]*
    - *The International Earth Rotation and Reference Systems Services (IERS) use laser ranging and achieve greater than 1 cm accuracy when measuring the distance to geodetic satellites in orbit around the earth over 3500 miles away. Although airborne LiDAR systems may not be this accurate, as it turns out the error contribution from the laser ranging is by far one of the least significant sources of overall error. Other sources of error like those introduced by the GNSS or inertial systems are far more important and are often the largest contributors to vertical error. [5].*
11. **FAA Acceptance**
    - *Ceilometers are accepted and tested for static use at airports. FAA acceptance of onboard LIDAR requires periodic testing.*
    - *No known FAA acceptance of onboard LIDAR.*
12. **Cybersecurity and Privacy**
    - *This is a sensor that does not exchange information. Privacy concerns not applicable.*
    - *Vulnerability to hacking or false signals would come from the software attached to the sensor, for example if sensing distances became an IoT application.*

13. Maturity in time: use at what UML levels?

- *UML-2 -6*
- *Use at UML levels limited only by certification time cycle, which is at zero time for this technology.*

14. Ground Architecture

- *LIDAR mounted on aircraft for use for collision avoidance requires no cooperative ground architecture.*
- *LIDAR mounted on aircraft for use in precision landing presumes the use of vertiport landing standards and procedures.*
- *LIDAR mounted on aircraft for use in ground mapping for approach requires mapping of the approach path, creation of a reference database of approach paths, and procedural definition of LIDAR-enhanced approach.*

15. References

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[4] Garmin Lite Lidar for UAS https://buy.garmin.com/en-US/US/p/557294

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"Analysis of Airborne Synthetic Aperture Ladar Imaging with Platform Vibration," Liang Guoa, Hongfei Yina, Xiaodong Zenga, Mengdao Xingb, Yu Tangba, National Lab of Radar,Signal Processing)

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LPDME - Low Power DME

Area and Functions: Nav, EnRt

Description: Low Power Distance Measuring Equipment (LPDME) is a component of instrument landing capability for precision and non-precision approaches that measures the distance from the aircraft to the runway. It generally has a range of 40 miles from the airport and aids the approach and allowing pilots to remain position oriented around the airport. This orientation is valuable in high terrain locations and helps airplanes to avoid obstacles or restricted areas. LPDME equipment in aircraft send a pulse signal to the ground-based LPDME, which responds with an answer pulse signal. The ground-based LPDME is a transponder in that it answers a querying pulse. The receiver in the aircraft measures the time delay between the sent and received pulses and calculates the slant range distance. There is no azimuth information, only distance. LPDME and DME (high power) differ only in the amplification of the signal from the ground-based unit. DME is used often with VOR for en-route navigation, which has a range of approximately 200 miles. The distance information from a VORTAC or TACAN unit is DME.

1. Air or Ground Based? on vehicle?

- *Ground.*

2. Size

- *Ht 1730 mm, width 580 mm, depth 635 mm. [1]*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Approximately 200/230 kg. [1]*

4. Power

- *Single or dual, 100 or 1000 W.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *DME: Operating frequency range of a DME according to ICAO Annex 10 is from 960 MHz to 1215 MHz. Aircraft equipped with TACAN equipment will receive distance information from a VORTAC automatically, while aircraft equipped with VOR must have a separate DME airborne unit.*
- *LPDME: 960 MHz to 1215 MHz. Generally has a range of 40 miles from the airport, capacity of up to 200 aircraft.*

6. Cost

- *LPDME: Under $50,000. [2]*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Normal function.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Signal unlikely to degrade in big numbers but does not provide information about collision avoidance.*
- *Night operations at low and high traffic levels: Signal interference from other sources at night.*
- *VMC and IMC with high winds, low and high traffic levels: LPDME used to augment position in low visibility. However, interference between DME band and GNSS L5 is known problem.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: LPDME used to augment position in low visibility. However, interference between DME band and GNSS L5 is known problem [3].*
- *Operator with ill intent: Not affected.*
- *Bird events: Not affected.*

- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Not affected.*

8. **Advantages** relative to other technologies serving this function
    - *Already FAA approved and interoperable with standards VOR/DME avionics.*
    - *Harmonized specifications with ICAO, EUROCAE.*
    - *Supports all weather operations.*
    - *Known/demonstrated reliability/availability of greater than 99.95 percent.*
    - *Mature supply chain.*
9. **Disadvantages** relative to other technologies serving this function
    - *Cost of equipment to equip vertiport landing site.*
    - *There is no azimuth information, only distance.*
    - *Interference between DME band and GNSS L5 is known problem. [3]*
10. **Precision**
    - *185 m. [4]*
    - *LPDME: Appears to be evidence to support that multiple LPDMEs can support low RNP navigation values. [https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8012000].*
11. **FAA Acceptance**
    - *FAA approved. Currently in use. LPDME specs are FAA, ICAO, and EUROCAE compliant.*
12. **Cybersecurity and Privacy**
    - *Currently no publically available information as to how difficult it would be to spoof LPDME signal as received by standard avionics.*
13. **Maturity in time: use** at what UML levels?
    - *UML-1-6.*
    - *LPDME: Currently in use. Has been in use for over 10 years.*
14. **Ground Architecture**
    - *LPDME would be used to support CAT I landings. Low power prevents addition of noise to the signal background for an extended range. An electrical cabinet and signal antennas greater than 6 ft in height would be located at the vertiport.*
15. **References**

[1] THALES DME 415/435 RPM, [https://fccid.io/BOJ435/User-Manual/USERS-MANUAL-2-857503]

[2] GovTribe, "Construction and Installation of a Thales 415SE Distance Measuring Equipment (DME) system to serve Runway 28 at Greater Rochester International Airport, Rochester, NY," Dec 30 2014. https://govtribe.com/opportunity/federal-contract-opportunity/construction-and-installation-of-a-thales-415se-distance-measuring-equipment-dme-system-to-serve-runway-28-at-greater-rochester-international-airport-rochester-ny-dot-dtfaen15r20011]

[3] Grace Xingxin Gao • Liang Heng • Achim Hornbostel • Holmer Denks • Michael Meurer • Todd Walter • Per Enge, "DME/TACAN interference mitigation for GNSS: algorithms and flight test results" GPS Solutions, February 6, 2012, DOI 10.1007/s10291-012-0301-9.

Max DeAngelis, R. Fantacci, S. Menci, C. Rinaldi, "Analysis of air traffic control systems interference impact on Galileo aeronautics receivers," 2005 IEEE International Radar Conference, June 2005. DOI: 10.1109/RADAR.2005.1435897.

[4] (DOT/DoD report,"2001 Federal Radionavigation Sources," 2001)

LPDME: Low Power (~100 W) Terminal DMEs, support "distance to end of runway" determinations. Replace need for Outer Markers.-Innovative Use: Multiple DMEs with "good" geometry support area navigation (RNAV) FAA PBN Strategy will maintain and expand DME coverage as APNT capability [https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8012000]

16. Other Notes

- *THALES 415 DME: The FAA is procuring LPDME from Thales, ATM, on a requirements contract signed in 2002. It is a COTS (Commercial Off the-Shelf) unit called the 415 SE. The FAA primarily uses LPDME for ILS in lieu of marker beacons. Besides the advantage of helping pilots remain position oriented during the entire approach, LPDME is often cheaper than using marker beacons because of the real estate requirements. Marker beacons must be at a set distance and be located along the line of the ILS approach. https://www.thalesgroup.com/en/worldwide/aerospace/dme-415435-rpm.*
- *The LPDMEs will replace older marker beacons at existing ILS locations and be implemented at new ILS locations. The availability of the new LPDME is greater than 99.95 percent, mean time to repair is less than one-half hour, mean time between failures is 14,231 hours, and mean time between outages is 15,193 hours. [https://www.transportation.gov/sites/dot.dev/files/docs/faa_fy_2009_budget_estimate.pdf] page 146.*
- *Service Volumes are depicted here: [https://www.faa.gov/air_traffic/publications/atpubs/aim_html/chap1_section_1.html]*
- *More information about the FAA's Navigation Programs and Sustainment Strategy: https://www.aopa.org/-/media/Files/AOPA/Home/Advocacy/Advocacy/Advocacy-Briefs/Navigation_Programs_Strategy_2018_Final.pdf.*
- *https://www.gps.gov/cgsic/meetings/2019/lawrence.pdf.*
- *Related: Distance Measuring Equipment Accuracy Performance Today and for Future Alternative Position Navigation and Timing (APNT) https://web.stanford.edu/group/scpnt/gpslab/pubs/papers/Lo_IONGNSS_2013.pdf.*

Machine Vision (Optical), Ground

Area and Functions: Surv, Ground

Description: Digital imagery is captured by digital video camera. Digital images are change referenced and run through a processor to distinguish moving objects. At current levels of technology, it is difficult to use both high definition video and high update rates. Processing capabilities for large pictures at high hz is still catching up to what video can produce. Present technology either limits or reduces the picture definition – generally through one of many reduction algorithms – or reduces the sampling rate, or does not perform in real time. If tracking of airborne objects is desired, one camera per object must be provided. Alternatively, a moving target indicator may simply sound an alarm on vehicle detection. It is not known that tracking will be required for UAM surveillance. A machine vision camera and software would need to transmit pictures, images, or results over a wired connection to the surveillance authority or aircraft owners.

1. Air or Ground Based? on vehicle?

- *Primarily ground, but some researchers use machine vision in sensor fusion for air-based detect and avoid (see second entry on machine vision).*

2. Size

- *Camera can be the size of cell phone camera, 0.5” x 0.5” x0.5. Connect to a processor and a database. Multiple cameras and laser findings will increase size by a multiplier.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *1-3 lbs (laptop size) for one.*

4. Power

- *From 0.33W to 75 W continuous while in operation, depending on size of database.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Bandwidth visible light, 400 to 700 nanometers.*
- *Line of sight only.*
- *Range: Range of a digital camera, unlimited. In dense urban environment, line of sight may only be a few blocks.*

6. Cost

- *Cost – a GoPro is a suitable camera, $400-$500. Laptop processor running imagery, $1000. Software in Python toolsets. All COTS materials, less than $2500. Database would require a mapping service to process and ready the database, would be an additional cost.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Would work in normal conditions; would be obscured by heavy fog. Would be useless in heavy rain, sleet, heavy snow. May be impaired by bright days with variable clouds that cast heavy shadows. May be confused by shadows of airlines if they pass overhead.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Limited use in heavy traffic due to one camera per vehicle for tracking.*
- *Night operations at low and high traffic levels: Not very effective at night.*
- *VMC and IMC with high winds, low and high traffic levels: Would work in high wind.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Works in high traffic levels; works without operator input (emergencies), works in high winds. Won’t work in all weather conditions.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Works in high traffic levels; works without operator input (emergencies), works in high winds. Won’t work in all weather conditions.*
- *Operator with ill intent: Can be easily blinded by bright lights. Would detect UAS.*
- *Bird events: Can be programmed to detect and ignore birds.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. Would detect non-cooperative traffic.*

8. Advantages relative to other technologies serving this function

- *COTS equipment is relatively cheap. Technology is mature.*
- *Machine vision produces less interference for others than radar.*

9. Disadvantages relative to other technologies serving this function

- *Nighttime, foul weather, and dusk non-operation is a concern.*

10. Precision

- *Used for detection not ranging. Location finding would only work for limited fields of view.*

11. FAA Acceptance

- *None.*

12. Cybersecurity and Privacy

- *Preservation of database quality is paramount. Would likely need a service or an organizational agreement to maintain currency of database. Bad or corrupt database would make tool useless to all users.*
- *Privacy a concern for taking aerial images. Mapping database images must not contain any personally identifiable information, such as faces, phone numbers, or license plates (federal law). Any PII in images gathered during navigation use must be purged – can do this by purging all images within a short period, like after flight, or only storing the identifying markers (e.g., for black box).*

13. Maturity in time: use at what UML levels?

- *UML-2 -6.*
- *This COTS-based item is not known as product offering; it would have to be assembled and brought to market, which could take two years, plus any certification time. At approximately TRL 8. Could potentially be ready for market beyond 2025.*

14. Ground Architecture

- *A relatively small, inexpensive (less than $100) camera can be mounted on the sides of buildings, on light poles; even on a station-keeping aerial vehicle to survey moving objects, using software to distinguish aircraft-sized moving objects. At UML 4, a mosaicked network measuring moving objects (number, speed) may have already been developed for traffic and would be re-usable for airspace density. If a station-keeping aerial platform under the clouds could be deployed, a small number of cameras could cover an urban environment, limited only by line of sight. If deployed on ground, obstructions would require a higher number of cameras per area. Cameras would need to communicate results to processor or processors; processor would need to communicate to the user of the surveillance. Both cameras and processors require power to operate.*

15. References

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Mohammad Mahdi Azari, Hazem Sallouha, Alessandro Chiumento, Sreeraj Rajendran, Evgenii Vinogradov, and Sofie Pollin, "Key Technologies and System Trade-Offs for Detection and Localization of Amateur Drones," Proceedings of the IEEE, arXiv:1710.08478v1 [cs.NI] 14 Oct 2017.

Machine Vision (Optical), Vehicle

Area and Functions: Nav, Land

Description: Digital imagery is captured by a camera (or cameras) on the air vehicle. For navigation, the images are geotagged for location and run through FPGA or ASICs processors in realtime to reduce the images to key points for identification. Starting with a known location (e.g., a GPS reference at point of departure), navigation can be maintained on the basis of map-matching to key points for lateral positioning. Vertical positioning may be less precise due to need to resolve angles of view in processing. As with machine vision for surveillance, processing capability at the present time has not caught up to imagery production in resolution and speed. At the present time, real time image processing must reduce the rate of images and/or limit or reduce the pixels per image considered. All the processing and computation is done on the processor on the air vehicle; latency in air networks would prohibit real-time use of complex images.

1. Air or Ground Based? on vehicle?
- *Air (see other technology assessment for ground-based surveillance).*

2. Size
- *Camera can be the size of cell phone camera, 0.5" x 0.5" x0.5." Connect to a processor chip and a database.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)
- *0.1 to 3 lbs (cell phone to laptop size).*

4. Power
- *From 0.33W to 75 W continuous while in operation, depending on size of database.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS
- *Bandwidth: visible light, 400 to 700 nanometers.*
- *Line of sight only.*
- *Range: Range of a digital camera, unlimited.*

6. Cost
- *A GoPro is a suitable camera, $400-$500. Laptop processor running imagery, $1000. Software in Python toolsets. All COTS materials, less than $2500. Database would require a mapping service to process and ready the database, would be an additional cost.*

7. Use Case Evaluation
- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Would work in normal conditions; would be obscured by heavy fog, heavy uncleared snowfall.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Would work at high traffic levels.*
- *Night operations at low and high traffic levels: Might not work at night.*
- *VMC and IMC with high winds, low and high traffic levels: Would work in high wind.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Works in high traffic levels; works without operator input (emergencies), works in high winds. Won't work in all weather conditions.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Works in high traffic levels; works without operator input (emergencies), works in high winds. Won't work in all weather conditions.*

- *Operator with ill intent: Database integrity needs to be maintained. Onboard camera can't be spoofed. Would be difficult to change the landscape enough so that mapping does not work.*
- *Bird events: Works around birds.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. Non-cooperative traffic not a factor.*

8. Advantages relative to other technologies serving this function

- *COTS equipment is relatively cheap. Technology is mature.*
- *Does not require allocation from RF spectrum.*

9. Disadvantages relative to other technologies serving this function

- *Nighttime and dusk non-operation is a concern.*

10. Precision

- *Sufficient precision in x-y plane for approach path, as this technology is used in DoD approaches.*

11. FAA Acceptance

- *None.*

12. Cybersecurity and Privacy

- *Preservation of database quality is paramount. Would likely need a service or an organizational agreement to maintain currency of database. Bad or corrupt database would make tool useless to all users.*

13. Maturity in time: use at what UML levels?

- *UML-2-6.*
- *This COTS-based item exists, partly, only in drone survey applications; it would have to be assembled and brought to market, which could take two years, plus any certification time. At approximately TRL 8. Could potentially be ready for market beyond 2025.*

14. Ground Architecture

- *Similar to synthetic aperture radar, this technology could be more easily turned into a non-precision approach system for lateral navigation using key visual indicators in place of radio beacons. Visual indicators could be multipurpose items such as the markers on power lines near airports, or QR type coded blocks. Use of markers would diminsh the image fidelity and processing required.*
- *Alternatively, non-precision approaches could be prepared without any ground-based markers, using processing of flight imagery for a navigation database.*

15. References

Lina Tang, Guofan Shao, "Drone remote sensing for forestry research and practices," Journal of Forestry Research, June 2015, 26(4):791-797.DOI: 10.1007/s11676-015-0088-https://www.researchgate.net/publication/283655699_Drone_remote_sensing_for_forestry_research_and_practices

Virginia Stouffer, "Signal Processing Architecture Using SAR for Aircraft Landing Guidance," GSPx and International Signal Processing Conference, April 2003.

16. Other Notes

- *Potential for combination inertial navigation + RF beacon location + machine (road/visual) mapping.*

Mode C/UAT Multilateration
Area and Functions: Surv, Ground; U2U

Description: Multilateration uses ground stations numbering from two to many. The ground stations are placed around an airport/terminal area to cover the surrounding airspace. These stations listen for aircraft transmissions, typically to responses to interrogation signals transmitted from a local SSR or from a multilateration station. Since individual aircraft will be at different distances from each of the ground stations, their replies will be received by each station at fractionally different times. These time differences allow an aircraft's position to be precisely calculated. Multilateration requires no additional avionics equipment, as it uses replies from Mode A, C, and S transponders, as well as military IFF and ADS-B transponders. Mulitlateration is the chief technology used by Aerobahn to track aircraft on the airport surface. If doing a broad area, best to put ground stations at, or near, perimeter.

1. Air or Ground Based? on vehicle?

- *Ground-based surveillance, using an aircraft's required Mode C, Mode S, or UAT signal.*
- *Air based detect and avoid.*

2. Size

- *Airside: 6" D x 3"H x5"W box; antenna 2" x 3" x1."*
- *Groundside: MIT-LL using a 4'x4' metal plates with eight dipole antennas sticking out 3" from plate, on a tower, plus a refrigerator-sized power rectifier and processor box. Getting 30 ft accuracy using just two stations.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Airside: Box, 1.3 lb., plus cables, plus antenna (0.5 lb). [Sandia STX 165]*
- *Groundside: Antenna weight depend on height, probably 100 lbs without tower. Power and processing box: 300 lbs.*

4. Power

- *Airside: 200 to 900 Watts.*
- *Groundside: 2kW at 28V.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Range/BVLOS/obstructions – Detroit airport uses multilateration at a distance of 20 miles. The frequency is line of sight for up to 100 nm. But the signals can bounce off walls and windows and travel around obstructions.*
- *Mode C, Mode S, and UAT frequencies are Aero-reserved.*

6. Cost

- *Cost of ground equipment estimated between $1 and $10 million.*
- *Airside: GA quality Mode C is $1000-$2000. Commercial air Mode C start at $20K and up.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Works at low traffic levels regardless of weather. May find urban canyons with severe multilateration problems where signal would be unrecognizable to receiver.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Mode C does not appear to have the same saturation problems as Mode S codes. Mode C would work in high density, regardless of weather. UAT also does not appear to have a code overload problem.*

- *Night operations at low and high traffic levels: Night has no impact on operation. May find urban canyons with severe multilateration problems where signal would be unrecognizable to receiver.*
- *VMC and IMC with high winds, low and high traffic levels: Wind has no impact on operation. May find urban canyons with severe multilateration problems where signal would be unrecognizable to receiver.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Mode C and Mode S transponder codes indicate emergency statuses and would be a plus.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: On-board transponder's primary function is to help vehicles avoid collisions, so having transponders on board would assist in reducing safety if external navigation sources are disrupted.*
- *Operator with ill intent: An operator could squawk the same code, or falsely squawk an emergency, but it's difficult to see how this technology would be used for ill.*
- *Bird events: No effect on operation.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. This technology would not help with non-cooperative traffic.*

8. **Advantages** relative to other technologies serving this function
   - *UAT is dual function use and could be designed to have situational awareness broadcast capabilities.*
   - *A minimal complement of ground stations can cover an urban area because the stations have sufficient range.*
9. **Disadvantages** relative to other technologies serving this function
   - *With two receivers, have difficulty resolving altitude (can only resolve distance.) The MIT unit may fix this.*
   - *Have had problems with window surfaces at particular airports where the multilateration gets too complex to be reliable. There are lots of flat window surfaces in urban environment.*
10. **Precision**
    - *Aerobahn achieves 30 ft precision now.*
    - *MIT is working on a "cheap airport radar" that achieves 30 ft precision and uses the angle of the beam to calculate altitude.*
11. **FAA Acceptance**
    - *TSO C74b, TSO-C74c.*
12. **Cybersecurity and Privacy**
    - *Mode C is private since frequency is assigned at flight.*
    - *Mode S is a permanent code and presents some privacy concerns, which the FAA is working to mitigate.*
    - *Mode S is spoofable.*
13. **Maturity in time: use** at what UML levels?
    - *UML-1-6.*
    - *Currently on market.*
14. **Ground Architecture**
    - *For air vehicle to air vehicle detect and avoid, cooperative vehicles can see each other or rely on ground rebroadcast of traffic information picture. Note that many GA operators comply with*

ADS-B Out on 1090 and receive a traffic information picture on a handheld traffic information broadcast over UAT, requiring correct setting of ADS-B Out pins to provide correct number of aircraft targets to ATC. ADS-B Out via UAT can be transmitted on an intermittent basis for air-to-air cooperative tracking. The FAA does not publish information on the location of ground antennas for UAT, but they may be co-located with Seconday Surveillance Radars (SSRs) that receive 1090 MHz transmissions. ADS-B information from both 1090 and UAT frequencies is relayed via ground networks to UAT rebroadcast transmitters, which broadcast traffic information to aircraft within range.

15. References

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Navigation, Aeronautical, and Terrain Databases

Area and Functions: Nav

Description: Air navigation relies on non-corrupt, updateable and up-to-date databases delineating approaches, land features, geophysical characteristics, frequencies, and memorandums guiding use. The important of these databases cannot be overstated, and so this section is reserved to note databases or notable data dependencies that emerging technology may require in order to support aviation use.

1. Air or Ground Based? on vehicle?

- *Air, database software would be loaded into the navigation/terrain avionics equipment in the UAM avionics bay.*

2. Size

- *Not applicable.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Not applicable.*

4. Power

- *Not applicable.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Not applicable.*

6. Cost

- *Estimate $50 - $100/month? Probably would be a 14/28-day update subscription by the equipment manufacturer. Typical standardized database formats used in the industry include:*
    - *ARINC 424, 816*
    - *DAFIF*
    - *ESRI*

7. Use Case Evaluation

- *LOA process would provide software database integrity, and would contribute to the system safety assessment finding and certification.*

8. Advantages relative to other technologies serving this function

- *Type 2 LOAs for databases are currently available from equipment manufacturers for use on numerous types of civil navigation and terrain avoidance avionics.*

9. Disadvantages relative to other technologies serving this function

- *Cost of an avionics manufacturers database subscription.*
- *An urban office will likely need to be established to work/coordinate with the database providers to ensure that routine infrastructure changes (e.g., new buildings raised) or temporary obstacles (e.g., cranes) are accounted for, in a timely manner to meet update cycles.*

10. Precision

- *Based on the Data Quality Requirements (DQR) for the selected navigation or terrain database.*

11. FAA Acceptance

- *FAA Letter of Acceptance (LOA) - A database LOA is a formal letter issued by an FAA aircraft certification office (ACO) documenting a data supplier has met the requirements of AC 20-153B. This is accomplished through an ACO audit in accordance with FAA Order 8110.55B, "How to Evaluate and Accept Processes for Aeronautical Database Suppliers." For those applications requiring database integrity (e.g., Area Navigation (RNAV), Required Navigation Performance (RNP), Synthetic Vision System (SVS), terminal procedures, airport moving map displays, Terrain Awareness and Warning System (TAWS), etc.), the LOA may be used as evidence of compliance with RTCA/DO-200B. With the database LOA, the FAA has evaluated the data quality requirements and data processes used, rather than treating a database as a part approval. The benefit to the LOA holder is that it provides evidence that robust data processes are in place, thus allowing updates to the data on aircraft without having to go through a case-by-case change approval process. AC 20-153B defines two types of LOAs:*
    - *Type 1 LOA (Data Service Provider) - Recognizes data supplier's compliance with RTCA/DO-200B with no compatibility with an aircraft system identified (e.g., Jeppesen).*
    - *Type 2 LOA (Application Integrator) - Recognizes data supplier's compliance with RTCA/DO-200B to process either Type 1 or source data to ensure compatibility with target hardware to support intended function (e.g., Garmin, Honeywell, etc.).*

12. Cybersecurity and Privacy

- *Addressed by RTCA/DO-200B and AC 20-153B.*

13. Maturity in time: use at what UML levels?

- *Database integrity standards currently exist to enable an OEM to apply and receive a Level 1 or 2 LOA for their database, Trusted Digital Repository (TDR) level 9.*

14. Ground Architecture

- *Database integrity is considered part of the ground architecture.*

15. References

https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-153B.pdf
https://www.faa.gov/documentLibrary/media/Order/FAA_Order_8110.55B.pdf
The complete RTCA DO-200B document may be purchased from RTCA, Inc. 1150 18th Street NW, Suite 910, Washington, DC 20036, www.rtca.org, Point of contact, Brad Miller, FAA AIR-6B2, 202-267-8533, Brad.Miller@faa.gov
Prior to issuance of Advisory Circular (AC) 20-153, "Acceptance of Aeronautical Data Processes and Associated Databases" in 2005, the FAA had no means to provide consistent and efficient oversight of these databases or verify their compatibility with the equipment. Before this guidance, data suppliers had no means to obtain FAA acceptance of their delivered data with formal verification and recognition of their processes.

16. Other Notes

- *Aeronautical data is data used for aeronautical applications such as navigation, flight planning, flight simulators, terrain awareness, and other purposes (e.g., navigation data, terrain and obstacle data, and airport mapping data). Since the 1970s, installed systems relied on navigation databases to support their intended function. Bottom Line – It is expected that navigation and terrain databases used on UAM vehicles will have to meet the RTCA/DO-200B data quality management system requirements, or its equivalent, as deemed appropriate by the FAA Administrator.*
  Note: An example of an emerging, industry lead UAS aeronautical database, intended to support remote ID and UTM function, is the InterUSS network platform. [https://github.com/interuss/dss] This is a database that, for participating UTM providers, allows situational awareness for the operators to see the drones around them, and allows the required identification data to be provided to law enforcement and other agencies. "This repository contains a simple, open, and scalable API used for separate UAS Service Suppliers (USS) to communicate during UAS operations as a Discovery and Synchronization Service (DSS) in accordance with ASTM WK65041. This flexible and distributed system is used to connect multiple USSs operating in the same general area to share safety information."

RADAR FMCW in GHz, mmWave Phased Array for Vehicle

Area and Functions: Surv, U2X, Nav, Land

Description: Frequency modulated continuous wave millimeter-wave radar is being tested in a number of laboratories in search of a low cost, high resolution, small footprint radar. Many of the technologies available are prototypes for market and thus information is often proprietary. This small planar array radar would be used for detection and tracking (surveillance) of non-cooperative aircraft, flying objects and obstacles, using multiple-element antennas located on the outside of an air vehicle, and connected to dedicated firmware processors.

1. Air or Ground Based? on vehicle?

- *Air.*

2. Size

- *Six- cm side to side physical antenna footprint on skin of vehicle.*
- *Antenna are restricted in focal view so multiple antennas are needed on skin. At present TRL, each focal view limited to between 15 degrees, so 12 needed for front 180 degrees; similar for back 180 degrees; and potentially more sensors for underside and topside, as needed for detection (numbering perhaps 6-12 topside, 6-12 underneath for landing).*
- *Processor – minimal size; several small circuit cards, using ASICs or FPGA firmware.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Estimated 20 lb antenna.*

4. Power

- *15 W each antenna: Low-power, light weight processors needed on each antenna.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *28 GHz beam-formed Phased Arrays, unlicensed band.*
- *Each beam has 5-degree effective beamwidth.*
- *Range: Reliable at 2 km range; up to 7 km azimuth plane and 55o elevation plane.*
- *Obstructed by obstacles but decluttering accomplished using Doppler measurements with CW waveform; would work in urban canyons.*

6. Cost

- *Each element of the array is currently in the thousands of dollars range in cost but at high demand rates could be brought down to hundreds per element. Add in software, processors, mounting, cabling and install could result in parts cost of $40K for one three-element unit, without considering certification costs.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Works but attenuated by rain; heavy rain would be a problem.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Works but attenuated by rain; heavy rain would be a problem.*
- *Night operations at low and high traffic levels: No problem resolving multiple targets at high traffic levels due to beamforming.*
- *VMC and IMC with high winds, low and high traffic levels: No problem resolving multiple targets at high traffic levels due to beamforming.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Could be used to help safely steer/land vehicles in distress.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Good failsafe to loss of other (cooperative) signals.*
- *Operator with ill intent: Detects all non-cooperative traffic at a range effective for avoidance, unless object is traveling much faster than 100 mph.*
- *Bird events: Will resolve birds and small UAS.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Detects all non-cooperative traffic at a range effective for avoidance, unless object is traveling much faster than 100 mph. Will resolve birds and small UAS.*

8. Advantages relative to other technologies serving this function

- *Technology looks very promising at prototyping level; effective for detecting and resolving multiple targets, small targets, in high clutter environments. Multiple elements creates redundancy.*

9. Disadvantages relative to other technologies serving this function

- *This is a sensitive technology so dramatically improved units are unlikely to be approved for commercial sale, even with export restrictions. Export restrictions limit market size and thus reduce probability of being brought to market.*

10. Precision

- *Small beamwidth can resolve objects with cross section of less than one meter.*

11. FAA Acceptance

- *Not started.*

12. Cybersecurity and Privacy

- *Anonymous. Does not look through buildings. Does not resolve personal identities. No privacy concerns.*
- *Operation of unit would have to be inside the aircraft (without remote control) to remain cyber secure.*

13. Maturity in time: use at what UML levels?

- *UML-3-6.*
- *TRL level 6 or 7 at present; technology works but is restricted.*
- *In 10-15 years could reduce number of required antennas by one-fourth for same field of view.*

14. Ground Architecture

No ground architecture needed.

16. References

Based on in-person conversations with NASA researchers Jim Downey, 30 October 2019.

RADAR Holographic, Ground

Area and Functions: Surv, Ground

Description: Holographic pictures are created by recording the phase position of coherent light (usually the source is a laser). This light is divided into a reference wave and an illumination wave through a semitransparent mirror and projected/recorded onto a surface (film). If this film is then illuminated with the same reference source, then the light rays are diffracted differently, which creates the illusion of a three-dimensional image through a window. For a radar, a stable coherent oscillator is used instead of the coherent laser light; the mirror becomes a splitter. A reference wave and an illumination wave are created. The illumination wave is sent to a surveilled object and the echo is compared with the echo of the reference wave. This highlights any moving objects and makes clutter invisible. This moving object tracker can be created from any base pulse or CW radar; only the mirrors and processors need to be added. For ground surveillance of aircraft, a beam-formed phased array is used. UWB is recommended: used with multiple frequency gates, multiple ranges are possible.

1. Air or Ground Based? on vehicle?

- *Ground based, to surveil aircraft.*

2. Size

- *Antenna: About 10 ft high, 10 ft wide, 10 ft long. (Aveillant Ltd Holographic radar phased array with 100 elements).*
- *Processing: Probably a rack or two of processors, currently contained in a cargo container (TEU). Likely smaller computer components with progression of Moore's law.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *At least 2000 lbs, possibly 5000 lbs at present technology.*

4. Power

- *Antenna and processors require heavy power, up to 2KW, estimated.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Recommended for GHz bandwidths, unlicensed.*
- *Line of sight range only, less than 5 miles.*
- *Not Aero-reserved.*
- *No BVLOS.*

6. Cost

- *This is a relatively new technology with few users, so likely to be up to $10 million per unit for the first units.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Excellent.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Excellent.*
- *Night operations at low and high traffic levels: Excellent.*
- *VMC and IMC with high winds, low and high traffic levels: May be impaired by blowing objects such as snow. Likely to get returns off close-in snow. May see snow when surveilling in snowfall.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Will be impaired by airborne non-aircraft objects; will detect plastic bags, large leaves, snow. Will detect moving aircraft.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Will be impaired by airborne non-aircraft objects; will detect plastic bags, large leaves, snow. Will detect moving aircraft.*
- *Operator with ill intent: Will detect and track all moving objects, even very small ones, so this will be effective at detecting moving operators.*
- *Bird events: Detects birds only at close range, inside of 50 meters.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Will detect and track all moving objects, even very small ones, so this will be effective at detecting moving operators.*

8. Advantages relative to other technologies serving this function

- *Of all the surveillance radars in the urban environment, this one shows great (perhaps greatest) promise for eliminating urban clutter and detecting and tracking all aircraft, drones, and uncooperative airborne objects.*

9. Disadvantages relative to other technologies serving this function

- *Size is large and weight is heavy: These will have to be reduced to allow easier siting of ground equipment.*

- *Cost is high and there are few users to drive the cost down before UML.*
- *These calculations require computing power in the range of up to 50 teraflops.*
- *Radar with more than three elements currently can't be exported. This has 100 elements.*

10. Precision

- *Scanning four times per second.*
- *Resolution depends on wavelengths used, but will resolve an aircraft.*

11. FAA Acceptance

- *None.*

12. Cybersecurity and Privacy

- *No PII surveilled or collected.*
- *No inputs required, limiting hacking vulnerabilities.*

13. Maturity in time: use at what UML levels?

- *UML-4 -6.*
- *Currently being prototyped for sale. Would be mature for UML-4 if there is a user buying units in the meantime, such as maritime defense.*

14. Ground Architecture

The holographic radar requires a large ground station and a large amount of power. If sited on a point of elevation overlooking the urban environment, the holographic radar could provide surveillance over a distance approaching five miles. Without such point of overlook, the radar would be limited to unobstructed line of sight, and many would be needed to surveill a large urban metropolitan area.

15. References

"Radar Basics - Holographic Radar Imaging," https://www.radartutorial.eu/10.processing/sp52.en.html., Accessed 2/9/20.
Rahman, S., Robertson, D.A. "Radar micro-Doppler signatures of drones and birds at K-band and W-band." Sci Rep 8, 17396 (2018). https://doi.org/10.1038/s41598-018-35880-9.
https://www.nature.com/articles/s41598-018-35880-9

RADAR Ka-Band 5G FMCW, 28-65 GHz, Phased Array for Ground

Area and Functions: Surv, Ground

Description: High resolution and medium-distance (100-250 m) frequency modulated continuous wave (FMCW) radar system based on 5G 28 to 64 GHz phased arrays. The system achieves more than 110 m detection range for a small UAV with SNR > 15 dB. Proposed systems show that 5G base stations can provide more function than communications, and can be used for UAM vehicle tracking and range finding.

1. Air or Ground Based? on vehicle?

- *Ground based.*

2. Size

- *Shared use of future ground 5G infrastructure. Concept suggests time-sharing between 5G communications functions and UAV/UAM tracking functions at close range (100-200m).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Processor unit 4"x19"x24" (server size) plus channel unit, similar size, plus conical antenna (see Ref).*

4. Power

- *Standard groundside power, 120 VAC for one unit.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Ka-band and higher (28 and 65 GHz).*
- *Range: Less than a mile.*
- *Aero-reserved: No.*
- *BVLOS: No.*

6. Cost

- *Estimated $125K base station.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Good for short-range detection only. Will not work in heavy rain.*
- *VMC and IMC at high local traffic levels such as a large sporting event: TRL level is such that resolving multiple targets will require research. Will not work in heavy rain.*
- *Night operations at low and high traffic levels: TRL level is such that resolving multiple targets will require research. Will not work in heavy rain.*
- *VMC and IMC with high winds, low and high traffic levels: TRL level is such that resolving multiple targets will require research. Will not work in heavy rain.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Good for short-range detection only. Will not work in heavy rain.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Good for short-range detection only. Will not work in heavy rain.*
- *Operator with ill intent: Good for short-range detection only. Will not work in heavy rain.*
- *Bird events: Likely occluded by large flocks of starlings.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Good for short-range detection only. Will not work in heavy rain.*

8. Advantages relative to other technologies serving this function

- *Would be combined with 5G telco infrastructure.*

9. Disadvantages relative to other technologies serving this function

- *Weather impacts.*
- *Short range (100-250m).*
- *ConOps uncertain. Limited utility with stationary, short range detection.*

10. Precision

- *<1m RCS.*

11. FAA Acceptance

- *None.*

12. Cybersecurity and Privacy

- *Undefined at this immature stage.*

13. Maturity in time: use at what UML levels?

- *UML 4-6.*
- *TRL 6+ - concept prototypes demonstrated; would require 15 years maturation.*

14. Ground Architecture

- *This short-range radar is not fully developed and so ground architecture needs estimated here may be inaccurate for a mature product. Each radar would require power and ground communication lines to return its findings to the user. The short range radar would need to be located approximately every three miles in order to cover the area of interest.*

15. References

John T Clark, Andre K Witcher, and Eric D Adler, "Ka Band Channelized Receiver," U.S. Army Research Laboratory, ARL-TR-7446 Adelphi, MD. Sept 2015, https://www.arl.army.mil/arlreports/2015/ARL-TR-7446.pdf

"RF Design Considerations for Ka and Ku Band Systems," Blog by Bliley Technologies on Jun 15, 2016. https://blog.bliley.com/rf-design-considerations-for-ka-ku-band-systems.

RADAR K-Band (18-26 Ghz), on Vehicle

Area and Functions: Surv, U2X

Description: A phased-array radar system with electronically steered beams detects weather, aircraft, ground vehicles, buildings, and people. Electronically steered beams reduce size, weight, power consumption, and complexity compared to mechanically-steered antennas. Software controls operation and performance parameters, including the radar's range and resolution of certain types of objects.

1. Air or Ground Based? on vehicle?

- *Principally air, for on-vehicle precision navigation functions. May potentially be deployed for vertiport functions as well.*

2. Size

- *Antenna is roughly 1 sq. ft. plate that attaches to vehicle in several locations. Networked units work together to provide a 360-degree view.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Estimated <15 lbs., including the processing system.*

4. Power

- *Unknown. ROM Est. 100W peak, (likely depends on configuration and range).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *K-band (18-26 GHz).*

6. Cost

- *Unknown. Phased array elements currently pricing in the thousands of dollars.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Works.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Works but attenuated by rain; heavy rain would be a problem.*
- *Night operations at low and high traffic levels: No problem resolving multiple targets at high traffic levels due to beamforming.*
- *VMC and IMC with high winds, low and high traffic levels: No problem resolving multiple targets at high traffic levels due to beamforming.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Could be used to help safely steer/land vehicles in distress.*

- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Good failsafe to loss of other (cooperative) signals.*
- *Operator with ill intent: Detects all non-cooperative traffic at a range effective for avoidance, unless object is traveling much faster than 100 mph.*
- *Bird events: Will resolve birds and small UAS.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Detects all non-cooperative traffic at a range effective for avoidance, unless object is traveling much faster than 100 mph. Will resolve birds and small UAS.*

8. Advantages relative to other technologies serving this function

- *Commercially available, being marketed for UAM/UAS market.*
- *May be integrated in multi-sensor fusion package.*

9. Disadvantages relative to other technologies serving this function

- *Possible weather impacts (need more information and possibly research).*
- *Software licensing questions.*

10. Precision

- *Resolves a radar cross section of less than one meter.*

11. FAA Acceptance

- *None.*

12. Cybersecurity and Privacy

- *Developmental systems at this time are proprietary and protected, so cybersecurity of the units is largely unknown. No comm exchange is expected, so cybersecurity would be in the programming and maintenance.*

13. Maturity in time: use at what UML levels?

- *UML-3-6.*
- *TRL 8+ - not yet (publicly) deployed, but being marketed.*

14. Ground Architecture

- *No ground architecture needed for on-vehicle detect and avoid.*

15. References

Honeywell's IntuVue RDR-84K Radar.

RADAR Phased Array, Ku in GHz, Ground

Area and Functions: Surv, Ground

Description: Phased array provides improvements in radar functionality and performance, including beam agility, effective radar resource management, and graceful degradation with module failures. Two types of phased array radar antenna technology are known as passive phased array (or passive electronically scanned array) and active phased array (or active electronically scanned array), the later has a separate transmitter and receiver (T/R) for each antenna element, and more resistant to jamming. Most phased array radars in the world are PESA; however, the current trend is towards active arrays with distributed T/R modules due to high levels of subarray integration at significantly low unit cost.

All surface and airborne phased array radars are almost exclusively in C-, S-, L- and X-band. With the exception of the Raytheon's KuRFS (Ku-band) Advanced Electronically Scanned Array (AESA) radar developed for the U.S. Army, which cost the U.S. Army $191 million for the development and delivery of

40 of these KuRFS radar systems, the majority of the ground surveillance Ku-band phased array radars are low cost and reduced SWaP. We will use one of these lightweight and small size ground surveillance radars from Blighter Surveillance Systems (www.blighter.com) for the ground surveillance Ku-band phased array technology assessment. See "References."

1. Air or Ground Based? on vehicle?

- *Ground-based, Ku-band phased array radar.*

2. Size

- *W x H x D: 66.6 cm x 50.3 cm x 12.8 cm.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *56 kg.*

4. Power

- *105 W.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Ku-band (15.7 – 17.2 GHz).*
- *Range: Detects a moving vehicle at 16 km and a person walking at 7 km. Capable of detecting a large moving object up to 32 km if the radar cross section (RCS) is 1000 m2.*
- *Azimuth scan angle: 90º horizontal e-scan (PESA); 360º via integrated positioner and 20º in the elevation plane.*
- *Obstructions and BVLOS: Will be obstructed by buildings in the city; however, may not be a problem for surveillance on the ground of the vertiport.*

6. Cost

- *Unknown. Phased array elements currently pricing in the thousands of dollars.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Blighter Orbiter radar is IP66 rating (dust tight and protected against powerful water jets), however, Ku-band over 10 GHz, the effect of heavy rain (rain fade) on the signals is a noticeable degradation.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Rain and snow may be a problem.*
- *Night operations at low and high traffic levels: Support continuous scanning day and night.*
- *VMC and IMC with high winds, low and high traffic levels: No impact.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: No impact.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: PESA radar may have a problem due to jamming, which may be a factor in an emergency/threat situation. But for ground surveillance, this may not be a problem.*
- *Operator with ill intent: Detects moving non-cooperative traffic (person or vehicle).*
- *Bird events: No effect on signals due to birds.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: No impact.*

8. Advantages relative to other technologies serving this function

- *Ku-band antenna is small.*
- *Provides wide beam coverage, as compared to other bands.*
- *Higher throughput.*

- *High beam agility.*
- *Effective radar resource management, and graceful degradation with module failures (failure of some components does not result in a complete system failure).*
- *Low cost for ground radars compared to large high powered units.*

9. Disadvantages relative to other technologies serving this function

- *Ku-band suffers from rain fading due to absorption of electromagnetic radiation waves by water droplets.*

10. Precision

- *Ku-band phased array radar uses passive electronically scanned array, which uses many small antennas, rather than a single powerful antenna, to allow for better control of the beam. It operates in the Ku-band of the electromagnetic spectrum, which allows for higher-resolution imaging – an important part of tracking small objects with radar cross section (RCS) about 0.1 square meters.*

11. FAA Acceptance

- *None.*

12. Cybersecurity and Privacy

- *Commercialized API packages developed for a variety of operating systems. Not encrypted out of the box.*

13. Maturity in time: use at what UML levels?

- *In the market for many years and deployed in many countries around the world.*

14. Ground Architecture

- *Representative radar has 1 s scan across 90 degrees electronically and 360 degrees with integrated positioner; spec sheets indicates 70 targets. Range from 1 to 20 miles. Ground-based radar angled upward would have good range where not blocked by obstacles; a network would be needed to cover a city or urban metropolis, with power, ground comm, and central processing facility.*

16. References

- *Blighter Orbiter Ku-Band E-Scan Frequency Modulated Continuous Wave (FMCW) Doppler Ground Surveillance Radar Tech Sheet.*

RF Beacon/ RF Guidance System, Landing Site Augmentation (Precision Landing System)

Area and Functions: Surv, Ground

Description: One example of an RF Beacon system would be a combined RF ranging signal with ILS-like beacons for glideslope, both at lower power. No such system has been designed or marketed yet, but with digital frequency manipulation, would be possible in an entirely new market like UAM. Another example, already available in the market, is GE's Precision Landing Guidance System. The GE Precision Landing Guidance System uses an eye-safe laser (IR) to establish an x,y coordinate grid, and then determines the aircraft's position (azimuth, elevation, and distance) relative to the grid. This positioning information is then transmitted to the aircraft's EO detectors via a modulated laser signal where an onboard processor calculates steering signals to the landing platform similar to an ILS. The system is comprised of the following three components:

1. Electro Optical (EO) Grid Transmitter – Eye-safe IR laser transmitter mounted at fixed landing sites. Provides a relative x,y navigation reference grid for landing aircraft, then determines the aircraft's 3-D position relative to the grid.

2. Data link – Between the ground transmitter and landing aircraft's receiver via modulated laser signal. The signal contains the aircraft's current position information (relative to the grid) to the aircraft detectors.

3. EO Grid Detectors – Sensors mounted on landing aircraft receive the ground systems information and processes this position information into error signals for display to the pilot (like an ILS) or for autopilot steering.

1. Air or Ground Based? on vehicle?

- *Both air and ground. Has a ground-based EO transmitter that sends to detectors on the vehicle to provide constant 3-D positioning (either to a pilot display or for autopilot steering).*

2. Size

- *On ground landing platform – 4" x 4" x 5" EO Grid transmitter.*
- *Vehicle has small EO Grid detector/sensor 1.5" x .875 x .875 and navigation processor 4" x 2.5" x 1."*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Installed on ground – 5 lbs.*
- *Airborne equipment (detectors and processor) – 1 lb (next generation equipment).*

4. Power

- *On ground - < 100 watts (connected to ground AC power with backup power).*
- *Airborne - < 4 watts (off aircraft bus).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Low bandwidth data encoding on the laser signal - update rate unknown but estimated greater than 10 Hz.*

6. Cost

- *Not known.*

7. Use Case Evaluation

- *VMC at low traffic levels, and IMC at low traffic levels: Designed for maritime operation (oil rig) in poor to fair weather.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Sensors are all optical so won't be overwhelmed by high traffic counts; however, likely only one aircraft can use one ground installation at a time.*
- *Night operations at low and high traffic levels: Night operations supported.*
- *VMC and IMC with high winds, low and high traffic levels: Wind will make landing more difficult; may or may not make keeping optical comm link difficult.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Not applicable.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: Ground emergency only impacts this capability if ground outage affects the three pieces that make this technology function.*
- *Operator with ill intent: Not useful to unequipped aircraft.*
- *Bird events: No effect on signals due to birds.*

- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. No impact.*

8. Advantages relative to other technologies serving this function

- *GPS independent.*
- *Operates in degraded visual environments.*
- *Accurate to less than 1 inch.*

9. Disadvantages relative to other technologies serving this function

- *Possible weather impacts (need more information to make this judgment).*

10. Precision

- *Proposed accuracy of < 1" (3-D at 100 feet).*

11. FAA Acceptance

- *Need to demonstrate Part 23/27.1301 for intended function, and 23/27.1309 for safety assurance if 14 CFR part 135 operation.*

12. Cybersecurity and Privacy

- *TBD, but function (modulated laser signal) would be difficult to spoof.*

13. Maturity in time: use at what UML levels?

- *UML-2-6.*
- *TRL 6+, not yet (publicly) deployed, but has been tested.*

14. Ground Architecture

- *Vertiport-based lasers and light sensors needed for each landing/touchdown zone. Aircraft must be equipped to receive signals and use them appropriately.*

15. References

GE Precision Landing Systems
Optical Airbus Autonomous Landing System Development

RF Detection, Airside, and Groundside

Area and Functions: Surv, Ground, U2X

Description: Using passive RF emanations as a detection mechanism, listening for C2 frequency in order to detect UAS. All UAS have a distinctive 30, 60, and 90 Hz control modulation for command and control [1], even if operating in autonomous mode. This is distinct from W-Fi signals at 10Hz, and works passively.

1. Air or Ground Based? on vehicle?

- *Air or ground-based surveillance. Can be used airborne to detect other vehicles or on ground to surveill UAS and UAM.*

2. Size

- *Airside would probably be the size of an aeronautical radio, plus antennas, if developed for this application. Pprototype equipment was a single board computer, the Ettus B200, 2" x3" x0.75." Large antennas needed for range above 15 meters.*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *20-30 lbs for multiple antennas, processor, radio interface unit, cabling.*

4. Power

- *Low power; 6V at 4A.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *The frequency mentioned in research is unlicensed and open.*
- *Range is very short due to interference and noise; range 5 to 15 meters; whether or not the waves are BVLOS (they are) at this range is largely irrelevant*
- *High gain needed antenna to capture at range more than 50 m.*

6. Cost

- *Prototype equipment assembled at cost of less than $2K; hardening for certification would be similar to the cost of an aeronautic radio.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels:*
  - *Ground based – this would only work as a ground surveillance technology if you wanted to surveill a limited region of airspace, such as the air corridor above a street.*
  - *Air based – applied on a UAM for detecting drones and electrically powered motors would detect over a very short range, but is subject to noise and interference in the same band in an urban environment. At current level of development, it is not proven enough to stake your life on it.*
- *VMC and IMC at high local traffic levels such as a large sporting event:*
  - *Ground based – at high levels of traffic this would required multiple units, presently one detector per aircraft, with increase in power, expense, complexity.*
  - *Air based – applied to short range aircraft/drone detection the range limits detection to aircraft nearby and thus number of aircraft unlikely to be high enough to saturate the system.*
- *Night operations at low and high traffic levels: Might work better at night but otherwise unaffected.*
- *VMC and IMC with high winds, low and high traffic levels: See earlier comments about density requiring multiple ground systems; otherwise unaffected by winds.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels:*
  - *Ground-based – hot electronics and electromagnetic (EM) problems on board an aircraft would look "hot" to a ground detector.*
  - *Air-based – if there are uncontained EMIs on board the aircraft, this system may be unusable as an external aircraft detector; detection would be drowned out by the signal noise generated by own-aircraft.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels:*
  - *Ground based – grounding all traffic for a city emergency would make this system very effective at detecting noncompliance. High levels of traffic would confuse a ground-based system.*
  - *Air based – works at detecting external collision threats in all named condition, but only when the target is already very close.*
- *Operator with ill intent: Ground based and air based; this system would be difficult to jam except with an electromagnetic pulse (EMP) or nuclear weapon.*
- *Bird events: Does not detect birds.*

- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Detects any non-cooperative traffic using electricity and emitting EMFs.*

8. **Advantages** relative to other technologies serving this function
   - *This is a largely passive system to detect UAS and UAM that is effective against non-cooperative traffic and is not confused by birds.*
   - *Ground-based system is cheap. Without certification, these receivers could be miniaturized and mounted on multiple signposts, buildings, etc., to provide traffic monitoring of numbers of UAS and UAM (dynamic density). Per-unit cost could be $100 or less, allowing for blanketing an urban environment.*
   - *Paired with a laser tracking system, multiple ground units could provide a distributed radar for urban environments that would report all low altitude (under 15 meters) aircraft. Highly effective under 15 meters.*
9. **Disadvantages** relative to other technologies serving this function
   - *Short range of this system is its biggest disadvantage.*
   - *Also does not perform well in clutter at amplified ranges.*
   - *Ground-based system is relatively immature and at present level of maturity would not be a first choice for positive ground surveillance due to the range limitations. Would work fine if density is all that's desired.*
   - *Air-based – At present level of maturity, would not be a first choice for air surveillance, due to unproven technology and high potential Type I errors.*
   - *Large effort is involved in analyzing, detecting, and locating transmissions or anomalies in the sensed RF spectrum.*
10. **Precision**
    - *Could be paired with a laser targeting system for positive tracking and precision would be at least as good as 5 meters.*
11. **FAA Acceptance**
    - *Not accepted; not considered.*
12. **Cybersecurity and Privacy**
    - *Could be used to snoop on electronics and listen to cell phone conversations if misused.*
13. **Maturity in time: use** at what UML levels?
    - *UML-4-6.*
    - *Might be ready at UML-4. More likely for UML-6.*
14. **Ground Architecture**
    - *Ground hardware is cheap and widely available: Radio receiver of correct size (for frequency) and horn antenna, pointing mechanism and pivoting/turning stand, possibly with elevation. Requires software to distinguish signals from noise. An automatic sensing configuration would likely have multiple horns instead of turning and processor routine on a small processor interpreting each signal. Would require communications link and power, regular maintenance to keep birds out of the unit.*
15. **References**

[1] Phuc Nguyen, Mahesh Ravindranathan, Anh Nguyen, Richard Han and Tam Vu, "Investigating Cost-effective RF-based Detection of Drones," DroNet'16, June 26 2016, Singapore.

[2] Mohammad Mahdi Azari, Hazem Sallouha, Alessandro Chiumento, Sreeraj Rajendran, Evgenii Vinogradov, and Sofie Pollin, "Key Technologies and System Trade-Offs for Detection and Localization of Amateur Drones " IEEE Proceedings, arXiv:1710.08478v1 14 Oct. 2017.

Ultra Wide Band (UWB) MIMO

Area and Functions: Comm, ATC; C2; Ground

Description: Ultra-wide-band (UWB) technology combined with multiple transmit and receive antennas (MIMO) is a viable way to achieve data rates of more than 1 Gb/s for wireless communications. UWB is typically applied to short range and therefore mainly indoor communications in environments characterized usually by dense multipath propagation. For this type of environment, MIMO systems allow for a substantial increase of spectral efficiency by exploiting the inherent array gain and spatial multiplexing gain of the systems.

1. Air or Ground Based? on vehicle?

- *Air-to-ground communication, such as AOC, video, etc.*
- *Ground-based cooperative surveillance.*

2. Size

- *Comm air and ground units: within 2" x 2" x 0.5" Very small. Radio fits within a cellphone.*
- *Ground sensing unit: within 5" x 5" x 2" plus mounting apparatus (ef. Kinexon).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *Less than 0.55 lb.*

4. Power

- *Small. Under 5000mA-Hr for all day operation.*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *7-9GHz.*
- *Lower GHz and short distances, can see through the wall transmitting. Longest distance tends to be 200 meters on clear line of sight. Ideal range is 30 ft.*
- *Dual use licensed frequencies. Not Aero-reserved, unless a special Aero Band is authorized by FCC and NTIA.*

6. Cost

- *Airside: $250-$20 (uncertified cost).*
- *Probably similar for ground unit.*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Generally good below about 3 GHz in all weather. Higher F2 frequencies are affected by weather.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Supports scaling to high numbers of communicants easily.*
- *Night operations at low and high traffic levels: No problems with night comm.*
- *VMC and IMC with high winds, low and high traffic levels: No problems with winds. More obscuration in signal path decreases signal range so may have limited range in rain, particularly heavy rain.*

- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Permits precise geolocation of troubled craft.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: The comm frequencies won't saturate due to the OFDM and long bandwidth. However, this solution will require a network to operate and if the network goes down, the comms go down, which would be an emergency.*
- *Operator with ill intent: If network is taken down, everyone will need to land.*
- *Bird events: Not affected.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events: Surveillance via UWB comms only works on cooperative traffic; does not surveill non-cooperative.*

8. Advantages relative to other technologies serving this function

- *10 MHz bandwidth with data rates of 1 GBPS in 4G. Probably safe to say 100 kbps to 100 MBPS usable in all cases.*
- *MIMO processing depends on the RANK of the channel. This is the MINIMUM of the number of antennas at the TX and RX, and number of usable reflections. Often the more reflections the better within limits of number of antennas. Hence it works great in urban high reflection environments.*
- *SU-MIMO (Single User) is most commonly used today in 4G. 5G has MU-MIMO built in (Multi-User). It can support a combination of users some using SISO (Single Input Single Output) lower date rate and some using MU-MIMO at higher data rates.*
- *The MU-MIMO processing does not permit cellular signals to be eavesdropped upon. So one cannot listen to the signal to hack it.*
- *In general, MIMO uses antenna arrays. The higher frequencies allow 4x4 or even 16x16 arrays within a small size. A subset of the elements is often used in digital beamforming to support a number of scanning beams to support several users spatially.*

9. Disadvantages relative to other technologies serving this function

- *Range of 200m max in clear air is biggest disadvantage: Would require a network for comm to function.*
- *Requires a network infrastructure, such as cellular or commercial provider.*

10. Precision

- *Centimeter precision. Positioning is inimical to the comm function.*

11. FAA Acceptance

- *Not at present. This is an unusual waveform for the FAA which would take far longer than CSMA or TDMA for adoption.*

12. Cybersecurity and Privacy

- *Regarded as highly secure due to RTK; the device knows the location of the receiver to the centimeter, so "man in the middle" attacks not possible. Low signal strength fades into background, so does not appear when a hacker is scanning for frequencies.*
- *Uses standard encoding.*
- *While a small local area may be jammed, have not seen an entire cellular network being jammed. The bigger threat is in the terrestrial IP domain, where hackers can attack a network with denial of service techniques (this will be a common problem in future FAA communications also, if it depends on today's IP). The MU-MIMO processing does not permit cellular signals to be*

eavesdropped upon. So one cannot listen to the signal to hack it. If one were to try to jam a single cell sector using a narrowband jammer to concentrate the power, the OFDM format of 4G and the non-orthogonal frequency subcarrier signal of 5G will allow the affected subcarriers to be marked off as unusable and the remaining can be used to provide the service to the same customers. There may have to be a slight rate reduction; but it is not anticipated that UAM will be dropped, due to the embedding of the control channels within the subcarriers.

- *GPS could be a single point of failure for cellular coms since towers use GPS for Timing. But to jam all GNSS is almost impossible.*

13. **Maturity in time: use** at what UML levels?
    - *UML 1-6. Available now in 2020.*
14. **Ground Architecture**
    - *Due to its short range (200 m) and limited applications that are only suitable for indoor, peer-to-peer, and "see-through-the-wall" precision radar-imaging, UWB multiple-antenna systems (such as MIMO) have been used to increase system throughput and reception reliability. Coupling MIMO spatial multiplexing with UWB's high throughput gives the possibility of short-range networks with high data rates (1 Gbps) for emerging wireless local-area networks (WLAN) and home audio/visual network applications. This short-range and high data rate communications may not be suitable for UAM C2.*
15. **References**

[1] Kinexon, "Industrial IoT Real-Time Locating Service," https://kinexon.com/technology/real-time-locating-system-rtls?gclid=Cj0KCQiA7aPyBRChARIsAJfWCgIvY05GmhF2WBBu-hSHPuoEF5elpUke-RpkXjRj_A6bVxx8NHgqHPgaAvFvEALw_wcB
[2] Lucas Mearian, "Ultra Wideband (UWB) explained (and why it's in the iPhone 11)," ComputerWorld, Dec. 31, 2019. https://www.computerworld.com/article/3490037/ultra-wideband-explained-and-why-its-in-the-iphone-11.html
[3] Flexible FCC regulations for UWB transmissions make the use of UWB radars a viable alternative for detecting/tracking drones.
[4] Guvenc, Ozdemir, Yapici, Mehpouyan and Matolak, "Dectection, Localization and Tracking of Unauthorized UAS and Jammers," ICNS 2017.

VDL Mode 2

Area and Functions: Comm, C2, AOC

Description: The VHF Digital Link Mode 2 (VDL Mode 2) is a radio link used for communication between aircraft and ground stations at a higher rate and more reliable than ACARS. VDL Mode 2 operates in the VHF spectrum from 118-137 MHz or 19 MHz frequency band, which is divided up into 760 communication channels (of 25 kHz) in the NAS. More specifically, it is used as the primary physical channel for VHF ground/air subsystem that is used for the Aeronautical Telecommunication Network (ATN). VDL Mode 2 has already been implemented in many aircraft to transport ACARS messages simplifying the addition of Controller Pilot Data Link Communications (CPDLC). Networks of ground stations providing VDL Mode 2 service have been deployed by ARINC and SITA with varying levels of coverage. The ICAO standard for the VDL Mode 2 specifies three layers: the Subnetwork, Link, and Physical Layer. The Subnetwork Layer complies with the requirements of the ICAO ATN standard which specifies an end-to-end data protocol to be used over multiple air-ground and ground subnetworks including VDL. The VDL Mode 2 Link Layer is made up of two sublayers: a Data Link service and a media access control (MAC) sublayer. The Data Link protocol is based on the ISO standards used for dial-up HDLC access to X.25 networks. It provides aircraft with a positive link establishment to a ground station, and defines an addressing scheme for ground stations. The MAC protocol is a version of Carrier Sense Multiple Access (CSMA). The VDL Mode 2 Physical Layer specifies the use in a 25 kHz wide VHF channel of a modulation scheme called Differential 8-Phase-shift keying with a symbol rate of 10,500 symbols per second. The raw (uncoded) physical layer bit rate is thus 31.5 kilobit/second.

1. Air or Ground Based? on vehicle?

- *Both air and ground. The primary purpose of VDL Mode 2 (VDL2) is to exchange data between aircraft and ground stations at a higher data rate and more reliably than ACARS.*

2. Size

- *L x W x H: 14.98" x 3.74"x 7.87" (Example: Rockwell Collind VHF-2100 or later Model VHF-2200 transceiver).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *4.8 kg (10.6 lbs) – based on the Rockwell Collins VHF-2100/2200 transceiver.*

4. Power

- *25 watts minimum into 50 ohm resistive load (Mode A/ACARS).*
- *15 watts minimum into 50 Ohm resistive load (VDL Mode 2).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Range: A critical feature of the VDL2 signal propagation is the line-of-sight (LOS). The VHF radio signal travels with the LOS to the horizon of the Earth. However, the maximum propagation distance generally turns out to be greater, due to the refraction of the radio signal. The signal is bent depending on the properties of the atmosphere. A typical way to take the refraction into account is to scale the radius of the earth by 4/3, which is called the k factor. This k factor does change with weather, and different locations exhibit different refractive properties, hence the maximum distance is variable.*
- *Physical characteristics: Aeronautical VHF band between 118 to 137 MHx with 25 kHz channel spacing; Data only; Signal to Noise requirement: 26 to 27 dB; Guard channel requirement 2.*
- *Data communications characteristics: Data rate - 31.5 kbps (10 times faster than ACARS); Modulation scheme: D8PSK; Air-to-Ground subnetwork; Ground controlled and no timing required.*
- *Range: The range of a VHF signal from a station at sea level and an aircraft at 37,000 feet is approximately 200 NM.*
- *Aero-reserved.*
- *Robust to BVLOS due to bounce and distance.*

6. Cost

- *Estimated ground-based station costs for digital radio transceiver and antenna is $30,000, including $4000 yearly site lease, and $500 - $5000 yearly maintenance.*
- *According to Outright Avionics (www.outrightavionics.com), estimated equipment cost per aircraft is between $100,000 and $300,000 depending on the equipment previously available on*

the aircraft and the complexity of the existing avionics configuration. For example, equipment cost for a new aircraft is $80,000, $300,000 for an existing aircraft with analog avionics, and $100,000 for an existing aircraft with digital avionics (For example, ACARS).

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Currently served by a ground network that favors higher altitudes for service. New ground receivers would be needed to serve low altitudes. Network timing is unreliable.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Network timing is unreliable. Low altitude network would need to be established.*
- *Night operations at low and high traffic levels: No effect on service.*
- *VMC and IMC with high winds, low and high traffic levels: No problems with winds. No effect.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: Current network latencies are unpredictable. An acknowledgement protocol for emergency use would be needed.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: This solution will require a ground network to operate. Ground systems may be vulnerable.*
- *Operator with ill intent: Ground systems may be vulnerable.*
- *Bird events: No effect on service.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. No effect.*

8. Advantages relative to other technologies serving this function

- *The main benefit of VDL Mode 2 is that it is capable of providing faster data rate than ACARS (31.5 kbps vs 2.4 kbps).*
- *According to the the FAA NextGen Data Communications (DataComm) program, VDL2 (for CPDLC) provides a much needed digital link between ground automation and flight deck avionics for safety-of-flight air traffic control clearance, instructions, traffic flow management, flight crew request and reports.*
- *VDL2 system is bit-oriented versus the character-oriented ACARS.*
- *Using CSMA medium acces control protocol allows statistically equal access to the channel by all users.*
- *VDL2 system is currently available and installed in every aircraft capable of long flights. In Europe, an aircraft flying above 28,500 feet is mandated by the European Commision to be equiped with VDL Mode 2 CPDLC.*

9. Disadvantages relative to other technologies serving this function

- *High cost.*
- *VDL Mode 2 over a single frequency has already reached its capacity limits. According to the recent study ("VDL Mode 2 Capacity and Performance Analysis") released by the Single European Sky ATM Research Joint Undertaking (SESAR JU), VDL Mode 2 data link technology has reached its operational limit and the next generation datalink technology must be developed to meet the projected air traffic growth in Europe.*
- *High delay. One of the major causes of high delay times is the result of a phenomenon called "Hidden Node Problem" in the networking literature, and another cause of delay is co-channel interference.*

10. Precision

- *Not applicable.*

11. FAA Acceptance

- *Yes. FAA NexGen Data Comm Program includes VDL Mode 2.*

12. Cybersecurity and Privacy

- *Eurocontrol VHF Security Study Final Report identified a number of threats that can compromise VHF voice communications (25/8.33 kHz DSB-AM) and VDL Mode 2 data communications. These threats include jamming, system network attack, masquerade, replay/spoofing, data modification, and interception.*

13. Maturity in time: use at what UML levels?

- *UML-1-4.*
- *VDL Mode 2 equipment has been in the market for many years, and it may have reached its capacity limit.*

14. Ground Architecture

- *VDL Mode 2 is a digital radio link used for communication between aircraft and ground stations. VDL Mode 2 specifies Open System Interconnection (OSI) Layer 1 through 2 and partly Layer 3 (subnet, link and physical) for air/ground communication. Data flow in VDL Mode 2 typically consists of messages to pilots from ATS/AOC or from pilots to ATS/AOC. VDL Mode 2 is a data link only. VDL Mode 2 supports connectivity to the ATN, the Internet of civil aviation authorities. The ATN provides an architecture which basically sees a VDL Mode 2 ground station as just another node in the ATN network.*

15. References

[1] "Data Link Communications Compliance Guide," Data Link Authorization A056, FAA Flight Technologies and Procedures Division, Version 04.20. https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/afx/afs/afs400/afs410/datacomm/media/a056_compliance_guide.pdf.

VDL Mode 3

Area and Functions: Comm, C2

Description: VDL Mode 3 provides both Aeronautical Telecommunication Network (ATN) data and digital voice services. VDL Mode 3 operates in the same VHF spectrum as VDL Mode 2 from 118-137 MHz or 19 MHz frequency band, which is divided up into 760 communication channels (of 25 kHz) in the NAS. It was proposed to the International Civil Aviation Organization in 1994 by the United States Federal Aviation Administration as an alternative to using 8.33 KHz channel spacing to relieve VHF congestion. VDL Mode 3 works by providing four logical independent channels in a 25 kHz frequency assignment. Each channel can be used for voice or data transfer. The appealing capability of VDL Mode 3 is that it uses a frequency channel that can carry one analog voice transmission and turns it into three or four simultaneous transmissions using Time-Division Multiple Access (TDMA). There are seven configurations defined for VDL Mode 3 in the ICAO VDL Mode 3 Standards and Recommended Practices (SARPs). The standard range or 4-slot configurations include 4V (four voice), 3V1D (three voice and one data), 2V2D (two voice and two data) and 3T (three trunked).

Note that VDL Mode 3 uses the same modulation scheme as VDL Mode 2, which is Differential 8 Phase Shift Keying (D8PSK) at a data rate of 31.5 kbps. VDL Mode 3 has the same subnetwork architecture for

ATN communications as other VDL Modes, although in Mode 3 a different form of link layer protocol is employed, known as Acknowledged Connectionless Data Link (A-CLDL). VDL Mode 3 includes a Digital Communications Equipment (DCE) in the aircraft side of the subnetwork, which is not present in other modes.

1. Air or Ground Based? on vehicle?

- *Both air and ground. VDL Mode 3 (VDL3) provides both Aeronautical Telecommunication Network (ATN) data and digital voice services. It was proposed by the FAA as an alternative to using 8.33 kHz channel spacing to relieve VHF congestion. VDL3 works by providing four logical independent channels in a 25 kHz frequency assignment. Each channel can be used for voice or data transfer.*

2. Size

- *According to an article in Aviation Today, "Are We Nearer to NEXCOM?" (December 1, 2003), Rockwell Collins was the only avionics supplier to successfully demonstrate CPDLC through the NEXCOM VDL Mode 3 ground network. Simultaneous digital voice and data, along with enhanced voice features of Mode 3, were demonstrated during the tests, which used Rockwell Collins VHF-920A data radio and CMU-900 communications management unit, along with a Gables Engineering G7424-302 radio tuning panel.*
- *L x W x H: 12.76" x 3.74"x 7.87" (Based on only known Rockwell Collins VHF-920A transceiver).*

3. Weight (weight of the unit, specify whether processors or sensor are included/extra)

- *4.76 kg (10.50 lbs) – based on the Rockwell Collins VHF-920A transceiver.*

4. Power

- *15 watts (this is transmit power, which is about 42 dBm).*

5. Frequency band and/or Frequencies, Range, Aero-reserved? Licensed? Handling of obstructions and BVLOS

- *Physical characteristics: Aeronautical VHF band between 118 to 137 MHz with 25 kHz channel spacing; Digital Voice and Data simultaneously; Required Signal-to-Noise Ratio: 26 dB to 27 dB; Guard channel requirement: 2.*
- *Range: VDL Mode 3 uses the same aeronautical VHF band as VDL Mode 2 (118 MHz – 137 MHz).*
- *VDL3 signal propagation is line-of-sight (LOS). The VHF radio signal travels with the LOS to the horizon of the Earth. However, the maximum propagation distance generally turns out to be greater, due to the refraction of the radio signal. The signal is bent depending on the properties of the atmosphere. A typical way to take the refraction into account is to scale the radius of the Earth by 4/3, which is called the k factor. This k factor does change with weather, and different locations exhibit different refractive properties, hence the maximum distance is variable.*
- *Data communications characteristics: Data rate - 31.5 kbps (Simplex Burst Rate is 16.5 kbps per 25 kHz channel, and Voice Rate is 19.2 kbps per 25 kHz channel); Modulation scheme: D8PSK (same as VDL Mode 2); Air-to-Ground subnetwork; Ground controlled and Ground Timing required. Note that VDL3 has different configurations, for instance, 3 Voice and 1 Data (3V1D) or 2 Voice and 2 Data (2V2D), that allow data and voice to be transmitted simultaneously by using Time Division Multiple Access (TDMA) frame structure per a single 25 kHz channel.*
- *Range: The range of a VHF signal from a station at sea level and an aircraft at 37,000 feet is approximately 200 NM.*

- *License: Aero-reserved.*

6. Cost

- *Estimated ground-based station costs for digital radio transceiver and antenna is not available.*
- *Based on the MITRE Technical Report, "Air Transport Cost Estimation Related to Future Communicaiton Transitions: Coordination Draft." (April 2000), estimated VDL Mode 3 equipment cost per aircraft (in 2000) is $64,500 for a new aircraft, $256,300 for an existing aircraft with analog avionics, and $116,000 for an existing aircraft with digital avionics. (Note that with inflation, $1 in 2000 is about $1.49 in 2019.)*

7. Use Case Evaluation

- *VMC at low traffic levels (Nominal), and IMC at low traffic levels: Ground network needed.*
- *VMC and IMC at high local traffic levels such as a large sporting event: Low altitude network would need to be established.*
- *Night operations at low and high traffic levels: No effect on service.*
- *VMC and IMC with high winds, low and high traffic levels: No problems with winds. No effect.*
- *On-board emergency in VMC, IMC, high winds, and/or high traffic levels: No effect.*
- *City emergency in VMC, IMC, high wind, and/or high traffic levels: This solution will require a ground network to operate. Ground systems may be vulnerable.*
- *Operator with ill intent: Ground systems may be vulnerable.*
- *Bird events: No effect on service.*
- *Non-cooperative traffic in VMC, IMC, high traffic, high winds, and emergency events. No effect.*

8. Advantages relative to other technologies serving this function

- *The main benefit of VDL Mode 3 is that it is capable of providing faster data rate than ACARS (31.5 kbps vs 2.4 kbps).*
- *Capacity of TDMA is four times larger than VDL Mode 2, due to its ability to transmit both digital voice and data simultaneously in the same frame. VDL Mode 3 supports both digital voice and data simultaneously by using 4 TDMA slot configuration: 4V, 3V1D, 2V2D, 1V3D, 3T (1 Voice and 2 Data or 3 Data).*
- *VDL3 key features for voice include:*
  - *Anti blocking: Resolution for stepped-on transmission.*
  - *Controller override: Controller can preempt ongoing pilot transmission.*
  - *Next channel uplink: Uplink of the next frequency.*
  - *Urgent downlink request: Pilot can notify controller of his urgent donwlink voice request.*
- *VDL3 key features for data include:*
  - *Priority control for data transmission: Supports up to four types of priority.*
  - *Slot allocation based on reservation request: Avoids simultaneous data transmission.*
  - *Secures received data by Forward Error Correction (FEC): Reed Solomon (72,62) code, and correction of up 5 bytes error in received data.*

9. Disadvantages relative to other technologies serving this function

- *High cost. See estimated cost provided earlier.*
- *VDL Mode 3 has never been implemented. FAA abandoned implemention of VDL Mode 3 in 2004 because airlines could not be convinced to install VDL Mode 3 avionics.*

10. Precision

- *Not applicable.*

11. FAA Acceptance

- *FAA proposed VDL Mode 3 system but it was not accepted by airlines.*

12. Cybersecurity and Privacy

- *Although it has never been tested or implemented, one of the features of VDL Mode 3 is improvement in security, due its ATN subnetwork.*

13. Maturity in time: use at what UML levels?

- *UML-1-6.*
- *VDL Mode 3 prototype system was developed and tested jointly by FAA and Rockwell Collins.*

14. Ground Architecture

- *In November 2004, Rockwell Collins successfully completed the demonstration of VDL Mode 3, the first time a commercial passenger aircraft was able to use the FAA NEXCOM VDL Mode 3 for voice and data communications between air traffic controllers and pilots. Other than this successful demonstration of VDL Mode 3, there has never been an actual VDL Mode 3 ground network proposed and implemented. However, acccording to the ICAO Standards and Recommended Practices (SARPs), the following options may be used to develop a ground network architecture, should VDL Mode 3 be used for air/ground communications:*
  1) *VDL Mode 3 and ATN network operated by the Civil Aviation Administration (CAA) — only CAA-operated VDL Mode 3 ground stations, connected to CAA router(s), providing at least ATS communications (ATSC);*
  2) *VDL Mode 3 and ATN network operated by a commercial services provider — only ground stations operated by a commercial services provider, supporting aeronautical operational communication (AOC) and, if so required by the local CAA, ATSC, and connected to the service provider router, which may be located in a different State (country);*
  3) *VDL Mode 3 network and ATN network operated by both a commercial services provider and the CAA — ground stations providing both AOC and ATSC, simultaneously connected to an AOC router (which may be outside the State) and to a CAA router (within the State); and,*
  4) *VDL Mode 3 and ATN network operated by both a commercial services provider and the CAA — CAA ground stations (for ATSC) and commercial service provider ground stations (for AOC), operating within the same designated operational coverage.*

15. References

[1] T.C. Nguyen, S. Bretmersky, R. Murawski, "Impact of CPDLC Traffic Loads on VHF Digital Link Mode 3," the IEEE 23rd Digital Avionics Systems (DASC) Conference, October 2004.
[2] A.M. Shamma,T.C. Nguyen, R.D. Apaza, "Frequency Reuse, Cell Separation, and Capacity Analyis of VHF Digital Link Mode 3 TDMA," NASA Glenn Research Center, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20030112522.pdf.

Aeronautical Data Integrity

Area and Functions: Navigation, Terrain Databases

Description: Aeronautical data is data used for aeronautical applications such as navigation, flight planning, flight simulators, terrain awareness, and other purposes (e.g., navigation data, terrain and obstacle data, and airport mapping data). Since the 1970s, installed systems relied on navigation databases to support their intended function. Bottom Line – It is expected that navigation and terrain databases used on UAM vehicles will have to meet the RTCA/DO-200B data quality management system requirements, or its equivalent, as deemed appropriate by the FAA Administrator.

1. Air or Ground Based?
    - *Air, database software would be loaded into the navigation/terrain avionics equipment in the UAM avionics bay.*
2. Size
    - *Not applicable, database software for installation on avionics equipment.*
3. Weight
    - *Not applicable, database software for installation on avionics equipment.*
4. Power
    - *Not applicable, database software for installation on avionics equipment.*
5. Bandwidth/Operational band
    - *Not applicable, database software for installation on avionics equipment.*
6. Cost
    - *Estimated $50 - $100/month, probably would be a 14/28-day update subscription by the equipment manufacturer. Typical standardized database formats used in the industry include:*
    - *ARINC 424, 816*[1]
    - *DAFIF*[2]
    - *ESRI*[3]
7. Use Case Evaluations
    - *LOA process would provide software database integrity, and would contribute to the system safety assessment finding and certification.*
8. Advantages
    - *Type 2 LOAs for databases are currently available from equipment manufacturers for use on numerous types of civil navigation and terrain avoidance avionics.*
9. Disadvantages
    - *Cost of an avionics manufacturers database subscription.*
    - *An urban office will likely need to be established to work/coordinate with the database providers to ensure that routine infrastructure changes (e.g., new buildings raised) or temporary obstacles (e.g., cranes) are accounted for, in a timely manner to meet update cycles.*
10. Precision
    - *Based on the Data Quality Requirements (DQRs) for the selected navigation or terrain database.*

---

[1] The **Aeronautical Radio Inc. (ARINC) data format** is compatible with most avionics manufacturer's flight management systems. To make DAFIF® useful for the majority of aircraft flight management systems (FMS), it must be converted to the international ARINC 424 format.

[2] Digital Aeronautical Flight Information File (DAFIF®) which is a proprietary tab-delimited format of data developed by the National Geospatial-Intelligence Agency (NGA). DAFIF® is a unique format that is suitable for mission planning but has limited FMS applications

[3] Environmental Systems Research Institute (ESRI) is an international supplier of geographic information system (GIS) software, web GIS and geodatabase management applications. The company is headquartered in Redlands, California.

11. **FAA Acceptance**
    - *RTCA/DO-200B, "Standards for Processing Aeronautical Data" is the standard used to develop, assess change, and support implementation of a data quality management system. Implementing a process as described by RTCA/DO-200B provides a level of assurance for maintaining data quality throughout all phases of the data handling process. Several characteristics define data quality including accuracy, resolution, assurance level, timeliness, completeness, traceability and format. The scope of this standard includes the interface to a data supplier, receipt of the data, processing of the data, database distribution, and the interface to a customer (user). It is not the intent of RTCA/DO-200B to ensure the quality of Contracting State-originated data addressed through other means such as ICAO standards.*
    - *FAA Letter of Acceptance (LOA) - A database LOA is a formal letter issued by an FAA aircraft certification office (ACO) documenting a data supplier has met the requirements of AC 20-153B. This is accomplished through an ACO audit in accordance with FAA Order 8110.55B, "How to Evaluate and Accept Processes for Aeronautical Database Suppliers." For those applications requiring database integrity (e.g., Area Navigation (RNAV), Required Navigation Performance (RNP), Synthetic Vision System (SVS), terminal procedures, airport moving map displays, Terrain Awareness and Warning System (TAWS), etc.), the LOA may be used as evidence of compliance with RTCA/DO-200B. With the database LOA, the FAA has evaluated the data quality requirements and data processes used, rather than treating a database as a part of the approval. The benefit to the LOA holder is that it provides evidence that robust data processes are in place, thus allowing updates to the data on aircraft without having to go through a case-by-case change approval process. AC 20-153B defines two types of LOAs:*
        - Type 1 LOA (Data Service Provider) - Recognizes data supplier's compliance with RTCA/DO-200B with no compatibility with an aircraft system identified (e.g., Jeppesen).
        - Type 2 LOA (Application Integrator) - Recognizes data supplier's compliance with RTCA/DO-200B to process either Type 1 or source data to ensure compatibility with target hardware to support intended function (e.g., Garmin, Honeywell, etc.).
12. **Cybersecurity and Privacy**
    - *Addressed by RTCA/DO-200B and AC 20-153B.*
13. **Maturity in time**
    - *Database integrity standards currently exist to enable an OEM to apply and receive a Level 1 or 2 LOA for their database, TDR level 9.*
14. **Ground Architecture**
    - *Referential maps and standards are considered part of the ground architecture. Their construction, validity, and use requires consistent and ongoing use and verification.*
15. **References**

    https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-153B.pdf
    https://www.faa.gov/documentLibrary/media/Order/FAA_Order_8110.55B.pdf
16. **Notes**
    - *The complete RTCA DO-200B document may be purchased from RTCA, Inc. 1150 18th Street NW, Suite 910, Washington, DC 20036, www.rtca.org. Point of contact, Brad Miller, FAA AIR-6B2, 202-267-8533, Brad.Miller@faa.gov*

- *Prior to issuance of Advisory Circular (AC) 20-153, "Acceptance of Aeronautical Data Processes and Associated Databases" in 2005, the FAA had no means to provide consistent and efficient oversight of these databases or verify their compatibility with the equipment. Before this guidance, data suppliers had no means to obtain FAA acceptance of their delivered data with formal verification and recognition of their processes.*

Contract Number: GS00Q14OADU130 Delivery Order: 80GRC019D0017, Deliverable 5

Reliable, Secure, and Scalable Communications, Navigation, and Surveillance (CNS) Options for Urban Air Mobility (UAM)

Appendix C: Acronym List

12 August 2020

Prepared for:
NASA Glenn Research Center

Prepared by:
SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

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The material is based upon work supported by the National Aeronautics and Space Administration under Contract Number GS00Q14OADU130.

TABLE OF CONTENTS

APPENDIX C: ACRONYM LIST

2V2D	Two Voice and Two Data
3GPP	3rd Generation Partnership Project
3T	Three Trunked
3V1D	Three Voice and One Data
4V	Four Voice
5G	5th Generation cellular
14 CFR	Title 14 of The Code of Federal Regulations

A

A-1	Airframe Issue Paper
AAIP	Approved Aircraft Inspection Program
AASP	Air Authority Service Provider
AC	Advisory Circular
ACAS-X	Airborne Collision Avoidance System
ACARS	Aircraft Communications Addressing and Reporting System
ACO	Aircraft Certification Office
AD	Airworthiness Directive
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
ADS-R	Automatic Dependent Surveillance – Rebroadcast
AED	Aircraft Evaluation Division (FAA)
AFR	Autonomous Flight Rules
AFS	Flight Standards Office (FAA)
AGL	Above Ground Level
AI	Artificial Intelligence
AM	Amplitude Modulation
AN/TPQ	Army/Navy nomenclature Transportable Special Radar System
ANSP	Air Navigation Service Provider
AOC	Airline Operations Center
APALS	Autonomous Precision-Approach and Landing System
ARINC	Aeronautical Radio, Inc.
ARL	Army Research Laboratory
ARS	Airborne Receiving System
ARSR	Air Route Surveillance Radar
ARTS	Automated Radar Terminal System
ASDE	Airport Surface Detection Equipment
ASIC	Application Specific Integrated Circuits
ASR	Airport Surveillance Radar
ASTI	Alaskan Satellite Telecommunications Infrastructure
ASTM	Industry standards organization formerly known as American Society for Testing and Materials
ATC	Air Traffic Control
ATCBI	Air Traffic Control Beacon Indicator
ATCRBS	Air Traffic Control Radar Beacon System
ATCT	Air Traffic Control Tower
ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management

ATN	Aeronautical Telecommunications Network
A/W	Airworthiness
B	
bps	bits per second
BLE	Bluetooth Low Energy
BR/EDR	Bluetooth Basic Rate/Enhanced Data Rate
BVLOS	Beyond Visual Line Of Sight
C	
C-V2V	Cellular Vehicle-to-Vehicle
C-V2X	Cellular Vehicle-to-Everything
C2	Command and Control
CAA	Civil Aviation Administration
CAASD	Center for Advanced Aviation System Development
CFIT	Controlled Flight Into Terrain
CFR	Code of Federal Regulations
CNPC	Control and Non-Payload Communications
CNS	Communications, Navigation, and Surveillance
CNX	Customer Network Exchange
COA	Certificates of Waiver or Authorization (FAA)
ConOps	Concept of Operations
COTS	Commercial-Off-The-Shelf
CPA	Closest Point of Approach
CPDLC	Controller Pilot Data Link Communication
CSMA	Carrier-Sense Multiple Access
CTIA	Cellular Telecommunications and Internet Association
CVR	Cockpit Voice Recorder
D	
DA	Decision Altitude
DAA	Detect-And-Avoid
DAFIF	Digital Aeronautical Flight Information File
DAL	Design Assurance Level
DARPA	Defense Advanced Research Projects Agency
DC	District of Columbia
DCE	Digital Communications Equipment
DCL	Departure Clearance
DER	Designated Engineering Representatives
DGPS	Differential GPS
DH	Decision Height
DME	Distance Measuring Equipment
DMIR	Designated Manufacturing Inspection Representative
DO	Document
DoD	Department of Defense
DOT	Department of Transportation
DQR	Data Quality Requirements
DSRC	Dedicated Short-Range Communications
E	
EASA	European Aviation Safety Agency
ED	EUROCAE Document

EFVS	Enhanced Flight Vision Systems
EGPWS	Enhanced Ground Proximity Warning System
EIRP	Equivalent Isotropic Radiated Power
eLoran	enhanced Long Range Navigation
ELT	Emergency Locator Transponder
EM	Electromagnetic
EMF	Electromagnetic Field
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EO	Electro Optical
ESA	Electronically Scanned Array
ETA	Estimated Time of Arrival
EUROCAE	European Organisation for Civil Aviation Equipment
eVTOL	Electrically-Powered Vertical Take Off and Landing
EWR	Newark Liberty International Airport

F

F&R	Function and Reliability
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FCC	Federal Communications Commission
FDMA	Frequency-Division Multiple Access
FDOA	Frequency Difference Of Arrival
FEC	Forward Error Correction
FHA	Functional Hazard Assessment
FIMS	Flight Information Management System
FIS-B	Flight Information System Broadcast
FLARM	Flight Alarm
FM	Frequency Modulation
FMCW	Frequency Modulated Continuous Wave
FMS	Flight Management System
FOG	Fiber Optic Gyro
FPGA	Field Programmable Gate Array
FSB	Flight Standards Board (FAA)
FSDO	Flight Standards District Office

G

G-1	General Issue Paper
GA	General Aviation
GAMA	General Aviation Manufacturers Association
GBAS	Ground Based Augmentation System
GBps	Gigabits per second
GBSAA	Ground-Based Sense and Avoid
GCAS	Ground Collision Avoidance System
GEO	Geosynchronous Equatorial Orbit
GHz	Gigahertz
GIS	Geographic Information System
GLONASS	GLObal NAvigation Satellite System (Russian)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPWS	Ground Proximity Warning Systems

GRC	Glenn Research Center
GSPx	Global Signal Processing Expo
H	
HAS	Houston Airport System
HF	High Frequency
HIRF	High Intensity Radiated Fields
HOU	William P. Hoppy Airport
HTAWS	Helicopter Terrain Awareness and Warning System
HUD	Head-Up Display
I	
IAH	George Bush Intercontinental Airport
ICAO	International Civil Aviation Organization
ICNS	Integrated Communications, Navigation and Surveillance Systems
IEEE	Institute of Electrical and Electronics Engineers
IERS	International Earth Rotation and Reference Systems Service
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMA	Integrated Modular Avionics
IMC	Instrument Meteorological Conditions
IMSAR	IMSAR, LLC
INR	Integrated Navigation Receiver
INS	Inertial Navigation System
IOSR	International Organization of Scientific Research
IOSR-JECE	IOSR Journal of Electronics and Communication Engineering
IP	Issue Papers
IPP	Integration Pilot Program
IR	Infrared
IRNSS	Indian Regional Navigation Satellite System
IRS	Inertial Reference System
ISAR	Inverse Synthetic Aperture Radar
ISI	Intersymbol Interference
ISM	Industrial, Scientific and Medical (reserved frequency band)
ITAR	International Traffic in Arms Regulations
J	
JHU-APL	Johns Hopkins University Applied Physics Laboratory
JspOC	Joint Space Operations Center
K	
Kbps	Kilobits per second
KEK	Key Encryption Key
KHz	Kilohertz
L	
LAANC	Low Altitude Authorization and Notification Capability
LAAS	Local Area Augmentation System
LAN	Local-Area Network
LAX	Los Angeles International Airport
LCD	Liquid-Crystal Display
LDRCL	Low Density Radio Communications Link
LEO	Low Earth Orbit

LIDAR	Light Detection and Ranging
LOA	Letter of Acceptance
Loran-C	Low Frequency 100 KHz Hyperbolic Radio Navigation System
LOS	Line Of Sight
LPDME	Low Power DME
LPV	Localizer Performance with Vertical Guidance
LRM	Line Replaceable Module
LRU	Line Replaceable Unit
LTE	Long-Term Evolution
M	
MASPS	Minimum Aviation System Performance Standards
MDW	Chicago Midway International Airport
MEL	Minimum Equipment List
MEMS	MicroElectroMechanical System
MFD	Multi-Function Display
MHz	Megahertz
MIDO	Manufacturing and Inspection District Office (FAA)
MIMO	Multiple-Input Multiple-Output
MIT	Massachusetts Institute of Technology
MIT-LL	Massachusetts Institute of Technology – Lincoln Laboratories
ML	Machine learning
MLS	Microwave Landing System
MMEL	Master Minimum Equipment List
MMR	Multi-Mode Receiver
MoC	Means of Compliance
MOPS	Minimum Operational Performance Standards
Mpls	Mulit-Protocol Label Switching
MPS	Minimum Performance Standard
MRB	Maintenance Review Board (FAA)
ms	millisecond
MSL	Mean Sea Level, also Mean Street Level
MSO	Message Start Opportunities
MU	Multi User
MW	Millimeter Wave
N	
N/A	Not Applicable
NACp	Navigation Accuracy Category for Position
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCC	Network Control Center
NEXRAD	Next Generation Weather Radar
NFV	Network Function Virtualization
NGA	National Geospatial-Intelligence Agency
NGSO	Non-Geostationary
NIC	Navigation Integrity Category
nm	Nautical Mile
NMC	Network Management Center
NOAA	National Oceanic and Atmospheric Administration
NPA	Non-Precision Approach

NPRM	Notice of Public Rule Making
NTIA	National Telecommunications and Information Administration
O	
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency-Division Multiplexing
OpSpec	Operation Specification
ORD	O'Hare International Airport
OSI	Open System Interconnection
OTA	Over-The-Air
OTW	Out The Window
P	
P-1	Propulsion Issue Paper
PAH	Preliminary Hazards Assessment (FAA)
PANYNJ	Port Authority of New York/New Jersey
Pax	passengers
PBCS	Performance Based Communication Systems
PBN	Performance Based Navigation
PBR	Passive Bistatic Radar
PESA	Passive Electronically Scanned Array
PI	Principal Investigator
PMA	Parts Manufacturer Approval
PNT	Position Navigation Timing
PSTN	Public Switched Telephone Network
PTC	Pacific Telecommunications Conference
PTT	Push To Talk
Q	
QKD	Quantum Key Distribution
R	
RAIM	Receiver Autonomous Integrity Monitoring
RCAG	Remote Communications for Air-Ground
RCL	Radio Communications Link
RCS	Radar Cross Section
RF	Radio Frequency
RID	Remote Identification, also Remote ID
RLG	Ring Laser Gyroscopes
RMM	Remote Maintenance Monitoring
RNAV	Area Navigation
RNP	Required Navigational Performance
RNP-AR	Required Navigation Performance - Authorization Required
RNSS	Radio Navigation Satellite Service
RPAS	Remotely Piloted Aircraft Systems
RPIC	Remote Pilot in Command
RTA	Run Time Assurance
RTCA	An organization now known as RTCA, formerly known as the Radio Technical Commission for Aeronautics
RTK	Real Time Kinematics
RX	(Radio) Receiver

S

S-1	Systems Issue Paper
SA	Situational Awareness
SAA	Sense and Avoid
SAE	Society of Automotive Engineering
SAR	Synthetic Aperture Radar
SARPs	Standards and Recommended Practices
Satcom	Satellite Comunication
SC	Special Conditions
SD	Situation Display
SDA	System Design Approval
SDN	Software Defined Networking
SDR	Software Defined Radio
SESAR JU	Single European Sky ATM Research Joint Undertaking
SIG	Special Interest Group
SISO	Single Input Single Output
SITA	Société Internationale de Télécommunications Aéronautiques
SNOC	Satellite Network Operating Center
SP	Service Provider
SRD	Short Range Device
SSR	Secondary Surveillance Radar
STARS	Standard Terminal Automation Replacement Systems
STC	Supplemental Type Certificate
STO	Standard Technical Order
SU	Single User
SV	State Vector
SVO	Simplified Vehicle Operations
SVS	Synthetic Vision System
SWaP	Size, Weight, and Power
sUAS	Small Unmanned Aircraft System

T

TA	Traffic Alert
TABS	Traffic Awareness Beacon System
TACAN	Tactical Air Navigation
TAWS	Terrain Avoidance and Warning System
TC	Type Certificate or Type Certification
TCAS	Traffic Collision Alerting System
TDMA	Time-Division Multiple Access
TDOA	Time Difference Of Arrival
TDR	Trusted Digital Repository
TEK	Traffic Encryption Key
TEU	Twenty-foot Equivalent Unit
TIA	Type Inspection Authorization
TIS-B	Traffic Information Service-Broadcast
TIR	Type Inspection Report
TSO	Technical Standards Order
TT&C	Telemetry, Tracking and Control
TTAC	Telemetry, Tracking and Control
TX	Transmitter

U	
UA	Unmanned Aircraft
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UAT	Universal Access Transceiver
UAT2	Second Universal Access Transceiver on 1104 MHz
UAV	Unmanned Aerial Vehicle
UCAT	UAM Coordination and Assessment Team
UHF	Ultra High Frequency
UML	UAM Maturity Level
UOC	UAM Operational Center
USB	Universal Serial Bus
USC	United States Code
USNO	United States Naval Observatory
USS	UAS Service Supplier
UT	User Terminal
UTM	UAS Traffic Management
UWB	Ultra Wide Band
V	
V-n	V denotes Velocity and n denotes load factor
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VDC	Volts Direct Current
VDL M2	VHF Data Link Mode 2
VDL M3	VHF Data Link Mode 3
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VOR	VHF Omnidirectional Ranging
VORTAC	Radio-based navigation aid includes VOR and TACAN
VTOL	Vertical Take Off and Landing
W	
W	Watt
WAAS	Wide Area Augmentation System
WAVE	Wireless Access in Vehicular Environments
WG	Working Group
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local-Area Network
WMS	Wide-area Master Station
WRS	Wide-area Reference Station
Wx	Weather

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
08/11/2020	Final Written Report	08/13/2019 - 08/12/2020

4. TITLE AND SUBTITLE	
Reliable, Secure, and Scalable Communications, Navigation, and Surveillance (CNS) Options for Urban Air Mobility (UAM)	**5a. CONTRACT NUMBER** 80GRC019D0017
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Stouffer, Virginia L., Cotton, William B., DeAngelis, Randall A., Devasirvatham, Daniel M., PhD., Irvine, Thomas B., Jennings, Richard E., Lehmer, Ronald D. PhD., Nguyen, Thanh C., Shaver, Michelle A.	**5d. PROJECT NUMBER** 4200706922
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Science Applications International Corp 12010 Sunset Hills Road Reston, VA 20190-5856	N/A
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) NASA Glenn Research Center 21000 Brookpark Road Cleveland, OH 44135	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.
The work was funded as a NASA award under contract.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Aeronautics Research Mission Directorate directed a study to identify, evaluate, and recommend viable communications, navigation and surveillance systems and technologies to enable safe, secure, and efficient Urban Air Mobility operations in US cities. The focus is on UML-4, when commercial air taxi operations take place in all weather, are widespread, and include autonomous systems. This report recommends technologies for independent navigation, collaborative communication, and surveillance, based on capacity, availability, precision, and update rate, size, weight, power, cost and other values. Recommendations for maturing and implementing the technologies are included.

15. SUBJECT TERMS

Urban Air Mobility, Advanced Air Mobility, Communications, Navigation, Surveillance, CNS, Requirements, Small Unmanned Aerial System, sUAS, UAM, AAM

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr Ronald Lehmer
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU		925-257-3438