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U.S. Department of Transportation

ELECTRONIC CONSPICUITY:

Exploring the Use of Advanced Radiofrequency Technologies to Enable Unmanned Aircraft Systems Integration

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Contents

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Problem Statement

The aviation sector has experienced a remarkable surge in the production of unmanned aircraft systems (UAS), with projections from the International Civil Aviation Organization (ICAO) forecasting worldwide growth from 2 million units in 2021 to an estimated 6.5 million units by 2030.[1] This increase highlights a significant shift in airspace composition as unmanned aircraft (UA) are set to vastly outnumber manned aircraft, which in the United States includes more than 45,000 daily flights receiving Federal Aviation Administration (FAA) Air Traffic Control (ATC) services along with many more manned flight operations conducted under visual flight rules (VFR).[2] Ineffectively addressed, these escalating numbers represent a threat to both aviation safety and security and pose increased hazards to persons and property on the surface.

Present-day airspace deconfliction methods, which were designed to detect larger aircraft with significant radar cross sections and pilots onboard, were not designed to manage this level and type of air traffic and are unsuited for this emerging environment. Since 2017, there have been 12 confirmed, or deemed highly probable, collisions between unmanned and manned aircraft.[3] While none of these collisions resulted in injuries, they caused minor to substantial damage to the manned aircraft, which in some cases required more than $100,000 in repairs. Currently, UAS operators in the United States do not have a viable method to command and control (C2) or deconflict UA in Beyond Visual Line of Sight (BVLOS) scenarios. Without deconfliction, it is not a matter of *if* a significant midair collision (MAC) between manned and unmanned aircraft will take place, but *when*. For the United States to maintain its position as the global leader in aviation safety, security, and technology, it must prepare for the exponential growth and variation in air traffic throughout the National Airspace System (NAS).

To address these concerns, this paper proposes several methods through which the application of advanced communication and electronic conspicuity technologies may not only support the safe integration of UAS into the NAS today but also create a safe and secure environment for future evolutions. The key topics discussed in this paper include an understanding of the aviation environment, an understanding of electronic conspicuity, a scalable solution for the BVLOS C2 of UAS, and a comparison with European Union (EU) aviation conspicuity efforts.

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[1] ICAO. 2021. *Increased use of unmanned aircraft systems (UAS).* Accessed 4/1/24: https://www.icao.int/annual-report-2021/Pages/emerging-and-cross-cutting-aviation-issues-increased-use-of-unmanned-aircraft-systems-uas.aspx.

[2] FAA. 2023. *Air Traffic By The Numbers*. Accessed 4/1/24: https://www.faa.gov/air_traffic/by_the_numbers.

[3] Aviation Safety Network. 2024. *Confirmed and suspected drone collisions with aircraft*. Accessed 8/26/24: https://asn.flightsafety.org/database/issue/drones.php.

Conspicuity and Detection

Before defining the problem set and solutions, it is important to understand how ATC systems currently address aircraft deconfliction. Conspicuity is defined as being discernable or conspicuous to others. In aviation, this is demonstrated by an aircraft being detectable by other aircraft and/or by ATC. To achieve this trait and ensure deconfliction, aircraft are designed or equipped with a variety of components or systems used to amplify the situational awareness of ground controllers and other aircraft/pilots in the NAS.

Conspicuity enhances detection. Detection systems, whether active or passive, are used to determine the presence of other aircraft through exteroceptive sensing and advanced radiofrequency transmissions. As described in Table 1, aircraft detection is achieved through either the reflection of electromagnetic waves, acoustic or visual detection, or the reception of telemetry data via a radio wave receiver. Such detection systems can be ground-, air-, or even space-based.

Table 1. Conspicuity and detection methods and limitations.

Conspicuity Method	Detection Method	Limitations
Visual (active) - Most manned aircraft use special lighting to make the aircraft more visible (e.g., aircraft lighting requirements under 14 CFR Part 91.209[4])	**Visual sensor (passive)** - Optical: the human eye - Electro-optical: camera-aided vision - Night vision: used to enhance optical - Infrared: wavelength-dependent detection - Thermal: heat detection	- Weather - Time of day, thermal crossover - Ground clutter
Sound emission (active, but unintentional) - Sound emissions are generated by an engine or rotary blade; frequency and amplitude are a result of the design of the aircraft (power, thrust, size, etc.)	**Acoustic sensor (passive)** - Subsonic: below human audible range - Audible: sound humans can detect - Ultrasonic: above human audible range	- Weather, especially wind - Aerostructure angle of incidence to airflow - Reverberation - Ground noise for low altitude
Design (passive) - Paint schemes and designs are used to either amplify the reflectivity, refract energy, or absorb energy (e.g., stealth technology)	**Radar (active)** - Active detection method by which an electromagnetic transmission is used to determine the range and direction of aircraft - Amplitude of the return signal is determined by the reflectivity of the detected object	- Weather, especially rain, can refract or absorb energy in certain bands - Air-based radars are primarily forward-looking
Cooperative electromagnetic interrogation (active) - A transmission is used to generate a response (interrogate) from the transceiver of another aircraft (e.g., **Traffic Alert and Collision Avoidance System [TCAS]** via 1030 and 1090 MHz)		- Requires cooperative aircraft - TCAS is weight-prohibitive to small UAS
Cooperative radio wave transceiver (active) - **Automatic Dependent Surveillance—Broadcast (ADS-B)** out and in via 1090 and 978 MHz - Aircraft transmits an omnidirectional telemetry signal to alert other aircraft of its position, velocity, and identification - Signal can be received directly or through ground relays and retransmitted		- Requires cooperative aircraft - Unencrypted - Saturation in dense airspace

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[4] 14 CFR Part 91.209, Aircraft lights. Accessed 10/16/24: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-C/section-91.209.

Electronic Conspicuity Today

TCAS: Traffic Alert and Collision Avoidance System

First used operationally in 1981, TCAS is an independent Airborne Collision Avoidance System (ACAS) designed for manned aircraft that serves as the last line of defense to prevent MACs. Unlike ADS-B, TCAS is an active interrogation system based on secondary surveillance radar (SSR) through which an aircraft sends out a transponder message that generates a response from the transponders of aircraft within proximity.[5] Unlike traditional radar, TCAS SSR requires that both aircraft have active transponders on 1090 and 1030 MHz. This technology evolved from the need for an electronic identify friend or foe (IFF) capability to respond to radio interrogations for the military during World War Ⅱ, which used transponders called "parrots." Today, the coded identification signals sent from interrogated TCAS-equipped aircraft are called "squawks." Though there are many codes an aircraft can transmit, Table 2 provides a simplified explanation of the three primary modes (coded signals) used in commercial aviation. Additionally, the responding four-digit squawk codes are used to inform ATC of the disposition of the aircraft (weather reconnaissance, military operations, emergency states, etc.).

Table 2. Primary transponder modes.

Mode	Message	Purpose
A	Four-digit identification code (squawk code) assigned by ATC	Assist ATC to differentiate aircraft on their radar screens, providing both range and direction from the radar site but not altitude
C	Squawk code plus altitude derived from a barometric altimeter	Allow ATC to add altitude for three-dimensional position awareness and deconfliction
S	Registration code (who) plus telemetry information (where)	Provides improved situational awareness for a pilot to avoid potential MACs

Since 1991, TCAS Ⅱ has been "mandated by the U.S. for commercial aircraft, including regional airline aircraft with more than 30 seats or a maximum takeoff weight greater than 33,000 lb (14,969 kg). Although not mandated for all general aviation (GA) use, many turbine-powered GA aircraft and some helicopters are also equipped with TCAS Ⅱ."[5] To assist with deconfliction, TCAS Ⅱ transponders send a constant Mode S (selective) signal called a "squitter." Once this signal is received by an aircraft within range, the new aircraft sends out a corresponding Mode S signal to interrogate the received signal. Once decoded, both aircraft enter a communication mode through which they are constantly transmitting their telemetry information to one another. The TCAS Ⅱ system uses this information to determine the potential for a collision between the two aircraft. As the distance between aircraft decreases, each give Traffic Advisory (TA) messages to the pilots to alert them to a potential collision. As depicted in Figure 1, if the closing distance continues to decrease, the pilot will be given a Resolution Advisory (RA) that denotes the actions required for avoiding conflict that both TCAS Ⅱ systems have cooperatively devised. Some resolutions only require pilots to maintain their course to avoid conflict, while others require corrective action to deconflict the flight paths (e.g., increase or decrease altitude). The algorithms used to determine when and how an aircraft should

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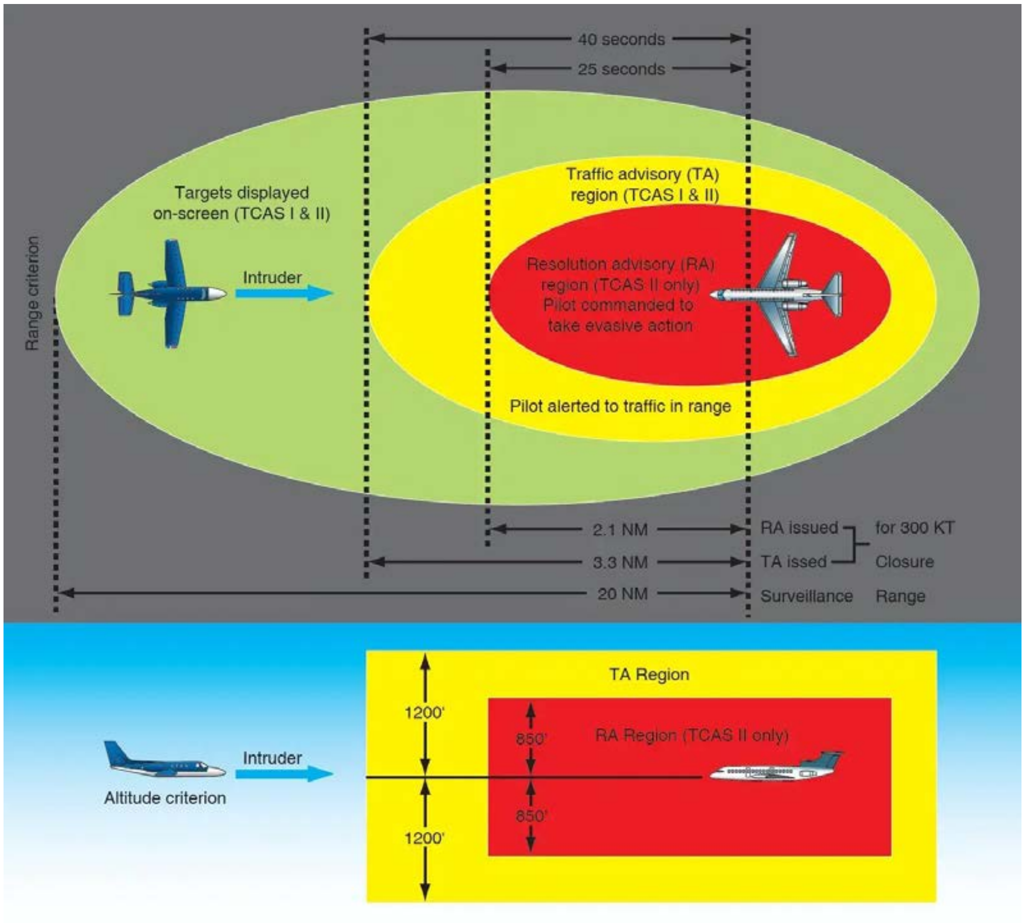
[5] FAA. 2011. *Introduction to TCAS Ⅱ Version 7.1*. Accessed 06/06/18: https://www.faa.gov/documentlibrary/media/advisory_circular/tcas%20ii%20v7.1%20intro%20booklet.pdf.

deconflict are what separates TCAS from traditional detection and avoidance methods that rely on the pilot to devise and act upon a collision avoidance strategy.

Figure 1. TCAS II detection and alert ranges and regions.



Source: Aircraft Systems Tech (2024).[6]

Though TCAS II is an essential part of the airborne collision avoidance strategy, it is far from perfect. In *Introduction to TCAS II Version 7.1*, FAA states:

> *It must be stressed however that TCAS II cannot resolve every near mid-air collision and may induce a near mid-air collision if certain combinations of events occur. Consequently, it is essential that ATC procedures are designed to ensure flight safety without any reliance upon the use of TCAS II and that both pilots and controllers are well versed in the operational capabilities and limitations of TCAS II.*[5]

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[6] Aircraft Systems Tech. n.d. “Aircraft Collision Avoidance Systems (TCAS)” [webpage]. Accessed 4/16/24: https://www.aircraftsystemstech.com/2017/05/collision-avoidance-systems.html.

One should view TCAS II as a critical automation method for deconfliction. However, to the extent these systems rely on human intervention and decision-making, they may not solely be relied upon to maintain safety of flight.

ADS-B: Automatic Dependent Surveillance–Broadcast

Similar to TCAS II, but without the need for aircraft–aircraft signal interrogation, ADS-B is the latest evolution of cooperative electronic conspicuity used across the world:

- **Automatic:** this assumes that no external stimulus is required (i.e., no interrogation).
- **Dependent:** the aircraft relies on a global navigation satellite system (GNSS) to determine its position.
- **Surveillance:** air traffic information is received by those within range of either an airborne transmitter or a ground relay station.
- **Broadcast:** this is an omnidirectional signal (ADS-B Out) that is always emitting while the system is on.

Though development started in the early 1990s, it was not until 2007 that FAA began installing ADS-B infrastructure across the Nation. Three years later, 14 CFR Part 91.225[7] was published, mandating the equipage of ADS-B Out capabilities by 2020 on all manned aircraft operating in airspace that also required a transponder. As illustrated in Figure 2, this includes airspaces A, B, and C as well as E at certain altitudes.

Figure 2. ADS-B airspace requirements.

Source: FAA (2024).[8]

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[7] 14 CFR Part 91.225, Automatic Dependent Surveillance-Broadcast (ADS-B) Out equipment and use. Accessed 10/16/24: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-C/section-91.225.

[8] FAA. 2024. ADS-B Airspace Requirements. Accessed 4/4/24: https://www.faa.gov/sites/faa.gov/files/air_traffic/technology/equipadsb/research/airspaceRequirements.jpg.

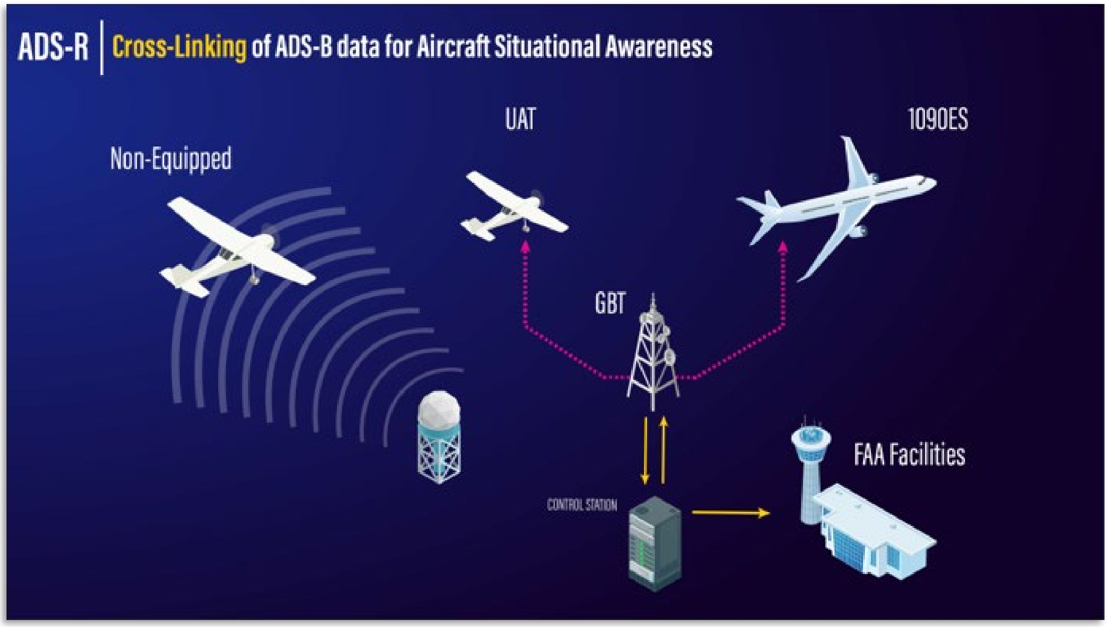
ADS-B is transmitted on two frequencies:

- **978 MHz:** The Universal Access Transceiver (UAT), available to aircraft in the United States below 18,000 ft (5,486 m).
- **1090 MHz:** The Mode S Extended Squinter transponder, which may be used at all altitudes but is required for certain operations in ATC-controlled airspace and for aircraft above 18,000 ft (5,486 m). (It is called an "extended" squitter because it relays much more data than the original Mode S TCAS signal).

ADS-B enables the following functions:

- It automatically detects the three-dimensional position of all similarly equipped (and transmitting) aircraft within range. The position is derived from the GNSS receiver and a barometric pressure altimeter.
- Reception of ADS-B telemetry from other equipped aircraft not in radio line of sight is made possible through an ADS Rebroadcast (ADS-R) network of ground-based relays, as illustrated in Figure 3.

Figure 3. ADS-R: cross-linking of ADS-B data for aircraft situational awareness.



Source: FAA (2023).[9]

- With more than 600 rebroadcast stations across the United States, Figure 4 illustrates a section of the coverage area in the southeast region of the United States (dark shaded areas) for ADS-R signals at 500 ft (152 m) above ground level (AGL).

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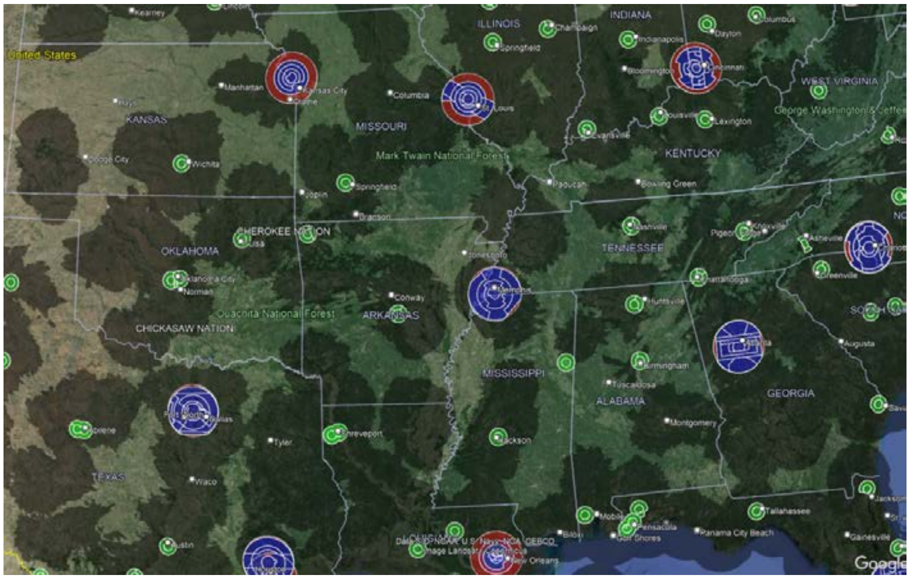
[9] FAA. 2023. "Ins and Outs" [webpage]. Accessed 3/19/24: https://www.faa.gov/air_traffic/technology/equipadsb/capabilities/ins_outs.

Figure 4. ADS-B coverage at 500 ft (152 m).



Source: Google Earth™, FAA.[10]

- As altitude increases, so does the radio line-of-sight coverage between the ADS-R transmitter and aircraft. Once above approximately 10,000 ft (3,048 m) AGL, there is complete coverage of the continental United States, as shown in Figure 5.

Figure 5. ADS-B coverage above approximately 10,000 ft (3,048 m).

Source: Google Earth™, FAA.[10]

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[10] Google Earth™ [map]. Accessed 10/17/24: https://earth.google.com/web/@0,-1.4135,0a,22251752.77375655d,35y,0h,0t,0r/data=CgRCAggB; FAA [data overlay]. US ADS-B Coverage. Accessed 10/17/24: https://www.faa.gov/sites/faa.gov/files/air_traffic/technology/equipadsb/research/2020ADS-BAirspaceMap.kmz.

- Traffic Information Services (TIS-B) provide surveillance data of non-ADS-B equipped aircraft operating in areas with ground radar coverage (commonly near B and C airspace). This information is broadcast in the same manner as the ADS-R but only includes aircraft with active transponders.
- Flight Information Services (FIS-B) provide meteorological and aeronautical environment data and are only available on 978 MHz UAT.

ACAS X: Airborne Collision Avoidance System

Just as TCAS evolved from a radar-based system to a collision avoidance system, ACAS is now evolving toward an air traffic management system designed to enhance detection algorithms for conflict resolution. ACAS X uses probabilistic modeling to provide more refined guidance to pilots than the limited "climb, descend, or maintain altitude" RAs available from TCAS II based on the relative location and trajectory of nearby aircraft. To accommodate the various changes in the airspace environment, ACAS is divided into several concepts:

- **ACAS Xa:** Base model for the next evolution of TCAS.
- **ACAS Xu:** System model for UA (in development).
- **ACAS sXu**: System model for small UA (in development).
- **ACAS Xr:** System model for rotorcraft, including advanced air mobility (in development).

ACAS X will improve the potential effectiveness of avoidance maneuvers for equipped manned aircraft; however, like ADS-B and TCAS, it does not address the need to detect small UAS (sUAS) or the ability of sUAS to detect unequipped manned aircraft. The ACAS Xu and ACAS sXu systems will be capable of ingesting sensor data from UAS; however, the fidelity of the information is dependent on the reliability and accuracy of the corresponding sensor (refer to the limitations in Table 1).

Limitations of Current Electronic Conspicuity Systems

The following are limitations of current electronic conspicuity systems:

- Electronic conspicuity systems require cooperative aircraft (i.e., both aircraft must be equipped and transmitting):
    - TCAS requires both aircraft to be equipped with active transponders. TCAS is also weight and cost prohibitive for sUAS (current systems add approximately 17 lb (8 kg) at a cost of $25,000–150,000).[11]
    - ADS-B In (which UAS are permitted to be equipped with) cannot detect aircraft that are not transmitting ADS-B Out.
    - Unless authorized by the FAA Administrator or operating under a flight plan and in two-way communication with ATC, UAS are not permitted to transmit ADS-B Out and are therefore nearly undetectable to manned aircraft or other UAS without advanced onboard sensors.

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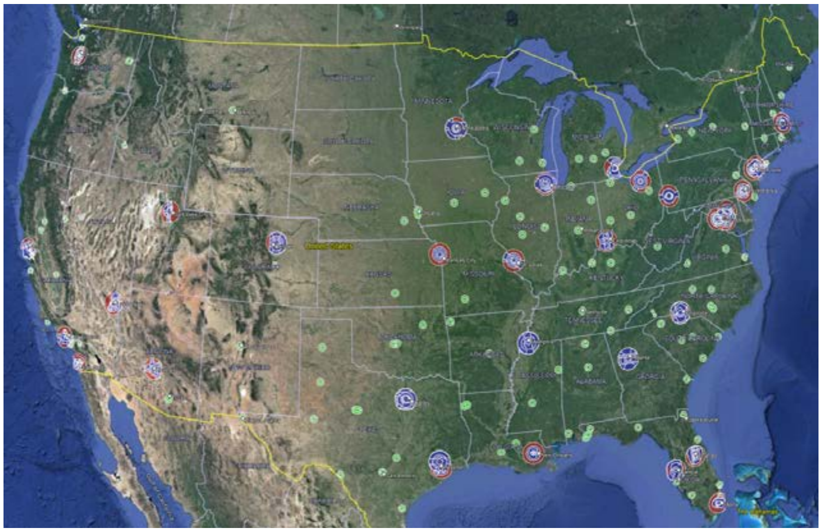
[11] L3Harris. 2024. "T^{3}CAS® | TCAS Traffic Collision Avoidance System | L3Harris" [webpage]. Accessed 10/18/24: https://www.l3harris.com/all-capabilities/t3cas-traffic-collision-avoidance-system.

- Electronic conspicuity is not required or available everywhere:
    - TCAS cannot consistently perform effectively below approximately 1,000 ft (305 m) AGL due to the ranges required for the resolution and traffic advisories.[12]
    - ADS-B is required when an aircraft with an electrical system is operating within one of the 37 Mode C veils (large circles in Figure 6), inside or within the lateral boundaries of the 122 Class C airspaces (small circles in Figure 6), or operating above 10,000 ft (3,048 m) mean sea level (MSL) and more than 2,500 ft (762 m) AGL. In any other airspace, with few exceptions, ADS-B is not required by airspace rule.

Figure 6. U.S. Class B and C airports.



Source: Google Earth™, FAA.[13]

- Radio line of sight is required for ground-based systems (e.g., air surveillance radar and ADS-R).
- ADS-B is unencrypted. Anyone can receive this signal, which presents a privacy concern for aircraft pilots.[14]

If universal equipage is all that is required to ensure detection, then why is it not mandated? To answer this, we must first address how noncooperative avoidance is accomplished today.

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[12] SKYbrary. 2024. "TCAS II RA at Very Low Altitudes | SKYbrary Aviation Safety" [webpage]. Accessed 10/18/24: https://skybrary.aero/articles/tcas-ii-ra-very-low-altitude.

[13] Google Earth™ [map]. Accessed 10/18/24: https://earth.google.com/web/@0,-1.4135,0a,22251752.77375655d,35y,0h,0t,0r/data=CgRCAggB; FAA [data overlay]. US ADS-B Coverage. Accessed 10/18/24: https://www.faa.gov/sites/faa.gov/files/air_traffic/technology/equipadsb/research/2020ADS-BAirspaceMap.kmz.

[14] Agbeyibor, R.C. 2014. *Secure ADS-B: Towards Airborne Communications Security in The Federal Aviation Administration's Next Generation Ai Transportation System*, Report No. AFIT-ENG-14-M-02. Accessed 4/18/24: https://apps.dtic.mil/sti/pdfs/ADA600893.pdf.

How Manned Aircraft Detect and Avoid UA

Generally, pilots are incapable of detecting UA during the day—and this is especially true for identifying sUAS that easily blend in with the background and have no lighting requirements during daylight hours. Currently, the only method of situational awareness available to a pilot is visual detection with their own eyes. During daylight hours, the GA community flying under VFR relies on unaided vision to detect other aircraft that are not electronically conspicuous. Though some may argue this method is sufficient in ATC-uncontrolled airspace, FAA Advisory Circular 90-48D advises the following:

> *Research has shown that the average person has a reaction time of 12.5 seconds. This means that a small or high-speed object could pose a serious threat if some other means of detection other than see and avoid were not utilized, as it would take too long to react to avoid a collision. This is particularly important with small Unmanned Aircraft Systems (sUAS).*[15]

In a head-on collision scenario between the most common GA aircraft and a UA, the pilot would have to visually detect the UA from at least 4,400 ft (1,341 m) away to avoid a collision and at least 4,900 ft (1,493 m) to avoid a near midair collision (NMAC). This assessment assumes the GA is flying at the average cruising speed of a Cessna 172 at 144 mph (i.e., 125 knots [kt]) and the UA is flying at the maximum Part 107 speed of 100 mph (i.e., 87 kt). Several studies have been conducted over recent years to determine how far away a pilot can detect a UA.[16,17] One study conducted at Embry-Riddle Aeronautical University determined there is a very low probability of the manned aircraft pilot ever detecting the UA, even in optimal conditions.[18] Figure 7 depicts the probability of detecting UA of various sizes, while at increasing airspeeds, in time to avoid a collision. As illustrated in the figure, at a 125 kt cruising speed, a manned aircraft has less than a 10 percent chance of detecting a large UA and a near zero chance of detecting a sUAS in time to avoid a collision.

Today, UAS are predominantly used for aerial photogrammetry, inspection, cargo delivery, and recreation, often below 1,000 ft (305 m) AGL—an altitude regularly traversed by helicopters, agriculture aircraft, and recreational fliers. Because UA may be operated within 400 ft (122 m) of a structure, there are cases where it may fly in Class E airspace above 1,000 ft (305 m) AGL (e.g., when used to inspect radio masts or tall buildings) without any additional approvals. Though 14 CFR Part 91.119,[19] which defines the minimum safe altitudes for aircraft, requires most manned aircraft to remain 500 ft (152 m) away from the surface, structures, vehicles, and people, there are several exceptions. Helicopters, powered parachutes, and weight-shift controlled aircraft, in addition to Part 101 aircraft, may operate closer than 500 ft (152 m). Additionally, in rural areas, GA pilots often perform agricultural spraying and follow waterways and linear infrastructure

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[15] FAA. 2016. Advisory Circular 90-48D, *Pilots' Role in Collision Avoidance*. Accessed 8/26/24: https://www.faa.gov/documentlibrary/media/advisory_circular/ac_90-48d_chg_1.pdf.

[16] Jacob, J., T. Mitchell, J. Loffi, M. Vance, R. Wallace. 2018. "Airborne visual detection of small unmanned aircraft systems with and without ADS-B," *2018 IEEE/ION Position, Location and Navigation Symposium (PLANS)*. Accessed 8/26/24: https://doi.org/10.1109/PLANS.2018.8373450.

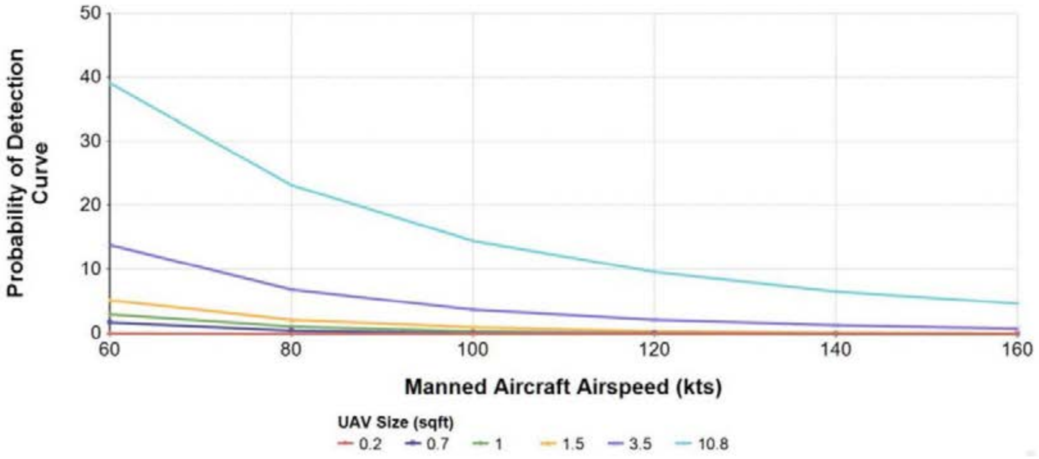
[17] Vance, S.M., R.J. Wallace, J.M. Loffi, J.D. Jacob, J.C. Dunlap, T.A. Mitchell. 2017. "Detecting and Assessing Collision Potential of Aircraft and Small Unmanned Aircraft Systems (sUAS) by Visual Observers," *International Journal of Aviation, Aeronautics, and Aerospace* 4(4). Accessed 8/27/24: https://doi.org/10.15394/ijaaa.2017.1188.

[18] Woo, G.S. 2017. *Visual Detection of Small Unmanned Aircraft: Modeling the Limits of Human Pilots*. Accessed 8/26/24: https://assureuas.com/wp-content/uploads/2022/03/ERAU-External-Research.pdf.

[19] 14 CFR Part 91.119, Minimum safe altitudes: General. Accessed 10/18/24: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-B/subject-group-ECFRe4c59b5f5506932/section-91.119.

like roads, pipelines, railroads, and powerlines at altitudes well below 500 ft (152 m) AGL, thus inviting an unpredictable collision threat.

Figure 7. Composite probability of detection graph.



Source: Woo (2017).[18]

Considering the very low probability of a manned aircraft seeing and avoiding a UA and the requirement for most UA to give way to manned aircraft, it is incumbent upon the UAS operator to determine and implement a method for both detecting and reliably avoiding all other aircraft. The issue remains, however, of how a UAS can detect and avoid an aircraft that does not want to be identified.

How UAS Detect and Avoid Other Aircraft

Though found in Class B, C, D, and E airspaces, UA primarily operate in Class G airspace below 400 ft (122 m) AGL. Under the current regulatory framework—particularly 14 CFR Parts 91.215,[20] 91.225,[7] and 107.37[21]—UAS are not only responsible for deconflicting from manned air traffic but are also generally prohibited from emitting ADS-B signals unless under a flight plan and in two-way communication with ATC, rendering them virtually invisible to other aircraft types, including other UA, balloons, and ultralights. This conspicuity limitation, compounded by the size, weight, power, and cost constraints of most UAS, limits the technological solutions for detection and avoidance.

Most UAS today fall under the sUAS category, which are defined as UA weighing under 55 lb (24 kg). sUAS are regulated by 14 CFR Part 107,[22] which includes operating rules and is supplemented by specific statutes

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[20] 14 CFR Part 91.215, ATC transponder and altitude reporting equipment and use. Accessed 10/18/24: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-C/section-91.215.

[21] 14 CFR Part 107.37, Operation near aircraft; right-of-way rules. Accessed 10/18/24: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107/subpart-B/section-107.37. CFR

[22] 14 CFR Part 107, Small Unmanned Aircraft Systems. Accessed 4/8/24: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107.

like 49 U.S. Code § 44809,[23] which defines hobbyist and recreational UAS, and § 44807,[24] which allow for deviations from nonwaiverable provisions of Part 107. UAS heavier than 55 lb (24 kg) are regulated by existing manned aviation rules, including but not limited to 14 CFR Parts 91[25] and 135.[26] The carrying capacity of UA, dictated by aerodynamic principles and their compact size, prohibits the use of larger physical sensor systems used for deconfliction on manned aircraft (e.g., traditional radar, TCAS). These limitations are often analyzed using a SWAP (size, weight, and power) calculation. As weight increases, due to the equipage of sensor systems, additional power is required to maintain lift. Additional power requires more batteries, increasing the weight even further. As the power draw increases, the overall endurance of the aircraft decreases, thus limiting the utility of the operation. While smaller onboard sensor systems are available, including phased array radars, acoustic sensors, and optical sensors, their high cost and weight affect the overall operational viability and endurance of the aircraft (refer to Table 1 for capabilities and limitations of sensors). The majority of sUAS, and many larger UAS, are electrically powered aircraft that rely on rechargeable batteries, further restricting flight durations due to the additional weight and energy storage limitations of currently common lithium-ion, lithium-polymer, and similar battery technologies.[27] Any additional weight incurred by a detection sensor would further reduce the endurance of the aircraft. Although ground-based sensors provide a viable detection capability, their effectiveness is limited to their line of sight and they are economically infeasible for smaller companies attempting beyond visual line-of-sight operations that require a system of over-the-horizon relay stations. Additionally, leveraging ground-based sensors necessitates a reliable C2 link for relaying avoidance commands to the aircraft.

In airspace where aircraft do not transmit a conspicuity signal, UAS operators must solely rely on either unaided human vision via the pilot and visual observers or onboard and/or ground sensors for detection and situational awareness. Due to multiple environmental and situational factors, these systems may not consistently provide the comprehensive coverage or the advanced notice needed to effectively avoid conflicts with manned aircraft or other inconspicuous UA. Due to these factors, ensuring the safe integration of UAS into the NAS has become a decade-long problem demanding innovative solutions to enhance detection and avoidance capabilities, advance automated decision-making, and evolve air traffic management systems.

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[23] 49 USC § 44809, Exception for limited recreational operations of unmanned aircraft. Accessed 10/18/24: https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title49-section44809&num=0&edition=prelim.

[24] 49 USC § 44807, Special authority for certain unmanned aircraft systems. Accessed 10/18/24: https://uscode.house.gov/view.xhtml?req=granuleid:USC-prelim-title49-section44807&num=0&edition=prelim.

[25] 14 CFR Part 91, General Operating and Flight Rules. Accessed 10/18/24: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91.

[26] 14 CFR Part 135, Operating Requirements. Accessed 10/18/24: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-135?toc=1.

[27] Townsend, A., I.N. Jiya, C. Martinson, D. Bessarabov, R. Gouws. 2020. “A comprehensive review of energy sources for unmanned aerial vehicles, their shortfalls and opportunities for improvements,” *Heliyon* 6(11). Accessed 4/30/24: https://doi.org/10.1016/j.heliyon.2020.e05285.

Status of UAS Integration in United States NAS

Among the many factors required for safe UAS operations BVLOS, there are three critical components:

1. An airworthy aircraft.
2. A reliable control link to send command instructions and receive telemetry data.
3. An effective method for detecting and avoiding other aircraft.

Currently, the majority of UA in the United States are controlled via unlicensed 47 CFR Part 15[28] frequencies. These frequencies have limited power outputs (1 or 4 watts EIRP [effective isotropic radiated power]) and were never intended for transmitting an omnidirectional signal over great distances with a high degree of reliability, thus impeding the potential for supporting safe BVLOS operations. Additionally, due to the proliferation of unlicensed frequencies like industrial, scientific, and medical (ISM) and Wi-Fi across the Nation, frequency saturation in suburban and rural areas is increasingly likely. It is also important to note that unlicensed frequencies are not afforded the same protections from interference as licensed frequencies and therefore present an increased risk to operators using them for radionavigation. The Federal Communications Commission (FCC) is working toward the licensing of a C-Band frequency for UAS operations in channels from 5030–5091 MHz; except for 5040–5060 MHz, which has been allocated for Non-Network Access (NNA), it is currently unknown how the entirety of the bandwidth will be channelized. We do know, however, that a portion of this band is intended for NNA and another for Network-Supported Services (NSS).[29] NNA will support point-to-point communications while NSS will enable networked solutions. Satellite communications are also available but are cost prohibitive for most operators and suffer from extended latency issues due to the extended range and atmospheric and exoatmospheric interference. Regardless of which frequencies are used for controlling UA, in the future, as the degrees of automation increase and approach what might be deemed “fully autonomous,” the control link may become irrelevant due to the aircraft’s ability to learn and dynamically respond to its environment.

The most critical need for UAS integration is the ability to detect and avoid all other aircraft while avoiding all collisions with the surface and structures. Presently, technologies exist that may enable universal aircraft deconfliction; however, these capabilities require additional research and development to assure reliability, especially in greater numbers and/or increased traffic density. Adopting these capabilities may require a modification to manned aviation rules to mandate equipage and usage on all aircraft. As previously stated, even transponders are not required in most of the U.S. airspace, which is in part likely due to recreational pilot concerns over costs, equipage, and potential government tracking. Some stakeholders have also voiced concerns that FAA or other authorities will use personally identifiable information (e.g., the data in a Mode S ADS-B transmission) to identify airspace or operator violations perpetrated by pilots. This concern has recently been addressed in the FAA Reauthorization Act under section 829:

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[28] 47 CFR Part 15, Radio Frequency Devices. Accessed 11/12/24: https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-15.

[29] FCC. 2024. *Spectrum Rules and Policies for the Operation of Unmanned Aircraft Systems* (FCC-24-91). Accessed 10/18/24: https://docs.fcc.gov/public/attachments/FCC-24-91A1.pdf.

> *The Administrator of the Federal Aviation Administration may not initiate an investigation (excluding a criminal investigation) of a person based exclusively on automatic dependent surveillance-broadcast data.*[30]

Since ADS-B transmits Mode S publicly, anyone with an ADS-B receiver can identify and track a transponding aircraft, thus eliminating operator privacy unless operators take additional steps to anonymize their operation via FAA's Privacy ICAO Address (PIA) program. Additionally, these data are often uploaded to the internet so that anyone can monitor active flight tracks across the world. While some may argue it is irresponsible not to track all aircraft in a post-9/11 environment, the operating regulation as outlined in 14 CFR Part 91.225[7] does not require ADS-B transmitting, with few exceptions, outside ATC-controlled airspace.

Proposed Methods to Enable UAS Integration

This section describes several electronic conspicuity methods to support and expedite the safe integration of UAS into the NAS.

Immediate Applications: ADS-B or ADS-B-Like Transmissions for All Manned Aircraft

Approach

The simplest immediate solution to UAS integration and deconfliction from manned aircraft is not to adopt a new technology but to further implement, and possibly modify, an existing one. As previously described, 14 CFR Part 91.225[7] specifies the ADS-B Out equipage requirements and use on aircraft operating in the NAS. If the policy were amended to require all manned aircraft to transmit real-time telemetry information, then UA would only need a radiofrequency (RF) receiver to ensure detection. Once equipped, it would only be a matter of applying operational performance parameters—such as those currently being developed under RTCA (previously known as the Radio Technical Commission for Aeronautics) DO-377B,[31] Minimum Aviation System Performance Standards (MASPS) for C2 Link Systems Supporting Operations of Uncrewed Aircraft Systems in U.S. Airspace—to prioritize deconfliction and maneuver UA well-clear of manned aircraft. Whether ADS-B or another method is used for transmitting conspicuity signals from a manned aircraft, policy adoption for universal equipage in dual-use airspace is critical for the safe operations of both manned and unmanned aircraft.

Technological Complications

The presumed technological issue with implementing this approach is the potential for RF saturation to occur in high traffic areas (e.g., 1090 MHz ADS-B use near busy airports). ADS-B currently transmits using pulse position modulation (PPM) at 1 Mbits/s, which means the entire message of 112 bits for the extended

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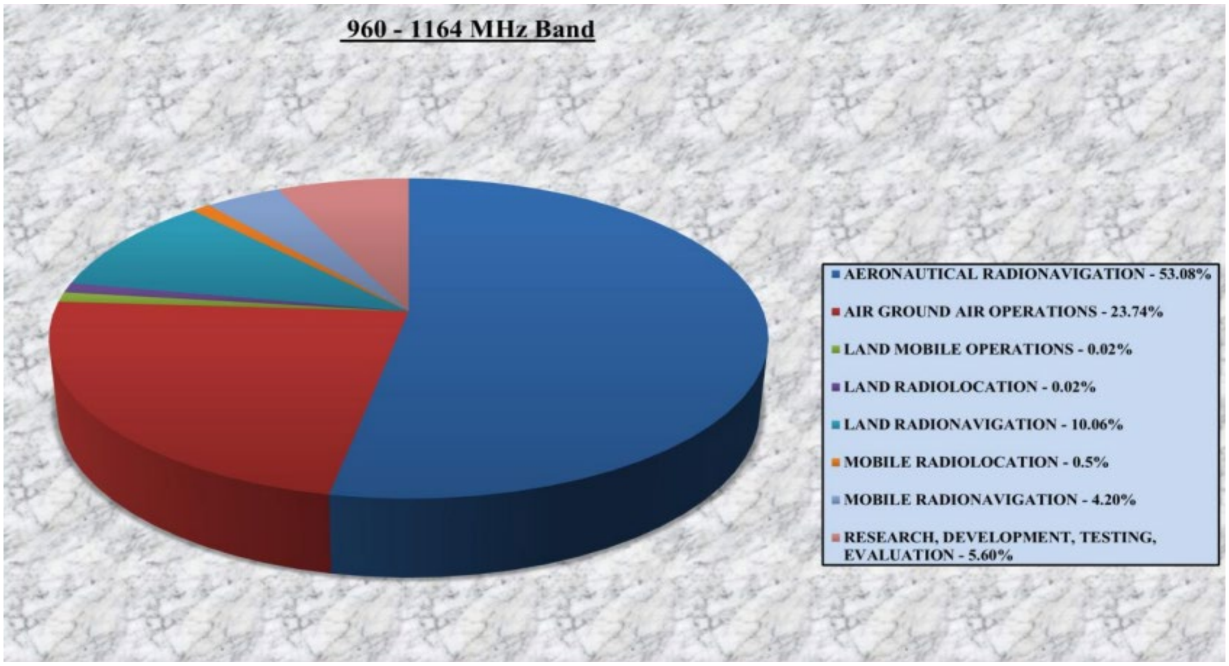
[30] Public Law No. 118-63: FAA Reauthorization Act of 2024. Accessed 10/21/24: https://www.congress.gov/bill/118th-congress/house-bill/3935/text.

[31] RTCA. 2023. Minimum Aviation System Performance Standards for C2 Link Systems Supporting Operations of Uncrewed Aircraft Systems in U.S. Airspace (DO-377B). Accessed 10/21/24: https://standards.globalspec.com/std/14655349/do-377b.

squitter is transmitted every second. With hundreds of aircraft in proximity broadcasting over the same frequency, there is the potential for saturation, especially when you consider the bandwidth for ADS-B is only 2MHz,[32] thus limiting spread spectrum capabilities that would otherwise enable more simultaneous users. Additionally, 1090 MHz is not only used for ADS-B airborne validation but also TCAS, military IFF, and ground system verification. There are also many other adjacent frequencies allocated within the aeronautical radionavigation band, as illustrated in Figure 8, implying potential cases where interference may further limit channel capacity.

Figure 8. Aeronautical radionavigation allocation.



Source: NTIA (2015).[32]

Alternatively, the 978 MHz UAT ADS-B signal is not assigned any other functions and therefore holds promise as a potential near-term solution for universal manned aircraft conspicuity, especially since it is already allocated specifically for GA operating below 10,000 ft (3,048 m) AGL. If saturation is found not to be an issue on UATs, ADS-B equipage for UA-to-UA deconfliction may also be possible. Alternatively, a third frequency used solely for deconfliction from UA could be implemented to not interfere with current bands. A similar approach is being examined by the European Union Aviation Safety Agency (EASA) and will be discussed later in this document.

Policy and Public Acceptance

Modifying regulations takes time and public acceptance. As previously mentioned, the 2024 FAA Reauthorization Act[30] addressed the GA community's concern over prosecutorial actions based on government-leveraged ADS-B data. However, there remain concerns over cost, equipage, federal mandates, and civilian tracking. Equipage for aircraft without a sufficient electrical system to support an active

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[32] NTIA. 2015. *960-1164 MHz*. Accessed 8/1/24: https://www.ntia.gov/files/ntia/publications/compendium/0960.00-1164.00_01MAY15.pdf.

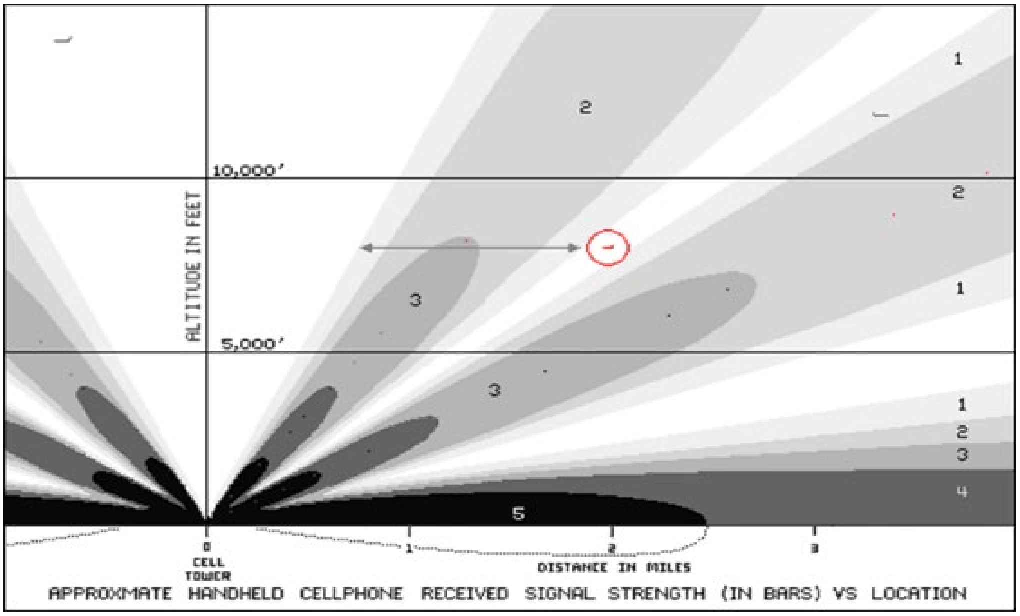
transceiver (e.g., gliders, paragliders, free balloons) will require alternate methods of compliance, which will be discussed in the next section. As for the cost to operators of aircraft with electrical systems, current estimated ADS-B Out equipage costs range from approximately $2,000–5,000 depending on equipage choices and installation. It is hard to put a cost on safety; however, for some, ADS-B Out has been cost prohibitive. For this reason and others, this white paper presents data that supports a cost-effective method that may ensure aviation safety for both manned and unmanned aircraft.

Near-Term Applications: Leveraging the Existing Terrestrial Cellular Network

Command and Control of UAS

Research and trials conducted by mobile network operators (MNOs) (also known as cell phone service providers), private enterprises, and educational institutions indicate that the United States' terrestrial cellular network infrastructure may be sufficient to support multiple aviation functions, including C2, electronic conspicuity, and even sensor downlinks in addition to terrestrial network traffic. Though cellular towers are designed to radiate energy toward the ground, Figure 9 illustrates how the sidelobe radiation patterns produced by the vertical collinear arrays of dipoles also propagate signals well beyond 5,000 ft (1,524) AGL and potentially beyond the threshold for ADS-B-required airspace at 10,000 ft (3,048 m) above mean sea level.

Figure 9. Approximate handheld cell phone received signal strength versus location.



Source: Fritzius (2016).[33]

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[33] Fritzius, R. 2016. *Airborne Cell Phone Performance*. Accessed 10/21/24: http://shadetreephysics.com/cell-air.htm.

To determine the suitability of the terrestrial network to adequately support various aviation functions, it is important to understand key network performance measurements and how they apply to UAS operations:

- **Reference signal received power (RSRP)** is a value that indicates the strength of the signal received at any given time and is measured in decibel milliwatts (dBm). To maintain a connection with a cellular modem, the RSRP should be at least −120 dBm or better. Once below this threshold, or “cell edge,” the aircraft will typically lose connection and enter an interrupted state. However, the lost-link state is not permanent; the aircraft transceiver will continue to search for a connection. If the signal is not re-established by the preprogrammed lost-link threshold, typically 20 seconds or less, the aircraft are typically designed to execute lost-link procedures and follow a mitigation plan (e.g., land immediately, hover in place, descend to a safe altitude). These contingencies must be programmed into the mission planner software prior to takeoff.
- **Reference signal received quality (RSRQ)** is a value that refers to the quality or fidelity of the signal received. Just as with RSRP, RSRQ is also measured in dBm but on a different scale. RSRQ is considered sufficient if above −20 dBm. Below this value, the signal is typically of such poor quality that the connection may be lost. As throughput—or the amount of data that are transmitted in a period—increases, the RSRQ value becomes more important. This value is critical when determining the quality of a sensor downlink, such as a full-motion 4K video or other high-throughput data. It is not, however, as critical for C2 or telemetry information that has a very low throughput. To put this into perspective, think of a sensor downlink comparably to streaming a 4K video on your phone where the quality can vary greatly and be far less than intended (e.g., trying to receive 4K but getting only 360p and/or intermittent dropouts due to connection limitations). Telemetry or C2 links might be seen as similar to a text message—while critically important to receive it promptly and accurately, the message itself is very small and easily transmitted over a network of compromised quality.
- **Latency** is the delay between signal transmission and signal reception. Cellular data are transmitted in data packets. The longer the delay between packet reception, the higher the latency value. Cellular networks are designed specifically to accommodate certain latency thresholds without dropping a connection. The network accomplishes this by storing received data until the time they can be sent to the intended recipient. A familiar example of delayed packets occurs when turning on your cell phone after landing at an airport—the stored text messages in the network are all received at once as soon as the cell phone is reconnected to the network. The latency is a critical value for UAS C2 functions and often has an inverse correlation to the RSRP value. More research is required to determine what latency values are required to maintain a stable system for aircraft at various altitudes. For reference, ideal RSRP and RSRQ values are presented in Table 3.

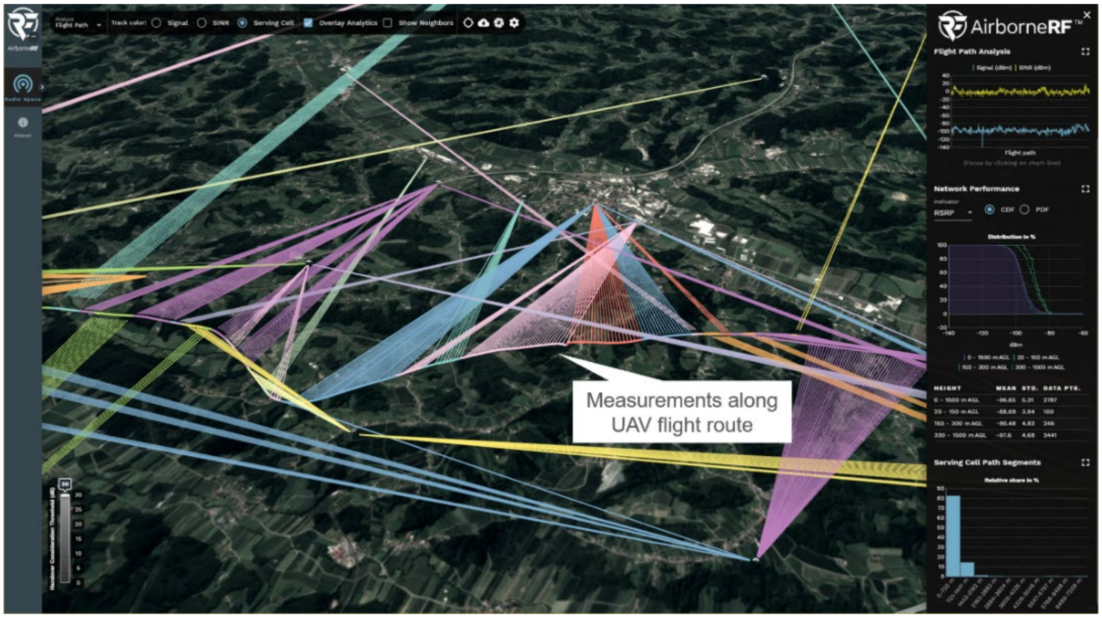
Table 3. RSRP and RSRQ value thresholds.

Scale	RSRP (dBm)	RSRQ (dBm)
Excellent	>−80	>−10
Good	−80 to −100	−11 to −14
Fair	−100 to −105	−15 to −20
Cell edge	<−120 = LOS	<−20

LOS = loss of signal.

At the 2019 Connected Skies Conference in Portland, OR, TEOCO Corp., a provider of services to network operators, presented testing data collected by their AirborneRF measurement tool that revealed more clearly the capabilities of a 4G terrestrial cellular network to support UAS C2 functions. These data were gathered from a fixed-wing aircraft flying along a designated flight path up to 4,921 ft (1,500 m). Figure 10 illustrates the handovers between tower emitters as the aircraft proceeded along its path. Of note, it was not always the tower in proximity to the aircraft that was designated as the primary transceiver. This phenomenon is due to the overlapping and variability of the sidelobe emissions for towers calibrated at various power levels and the angle of the aircraft antenna to that tower over the course of the flight.

Figure 10. AirborneRF data collection.



HEIGHT	MEAN	STD.	DATA PTS.
0 - 1500 m AGL	-96.65	5.31	2787
20 - 150 m AGL	-88.69	3.94	100
150 - 300 m AGL	-90.48	4.83	246
300 - 1500 m AGL	-97.6	4.68	2441

Source: AirborneRF (2019).[34]

In 2020, FAA signed a memorandum of agreement (MOA) with Skyward, a Verizon subsidiary, for the purpose of acquiring operational testing data of Verizon's network's capability to support C2 functions up to 400 ft (122 m) AGL in various environments across the United States. To ensure the collection of useful data, FAA developed key performance indicators, which were agreed upon by a consortium of MNOs, chipset manufactures, and other government agencies, including the FCC and the National Telecommunications and Information Administration (NTIA). These metrics, as well as the testing data, have been widely disseminated and can be found in the appendix. Table 4 illustrates the aggregate results acquired from these tests.

Table 4. Verizon test campaign metrics.

Metric	Description
When	November 2020–January 2022
Flights	414 flights over 332 hours
Frequencies	LTE bands 13, 4, and 2
Altitude	127–459 ft (39–140 m) AGL
RSRP Values	Average −70 to −80 dBm (Good to Excellent per Table 3)
RSRQ Values	Average −15 to −17 dBm (Fair to Good per Table 3)
Latency	Average 350 ms (range 48-670 ms)
Connectivity	99.008%

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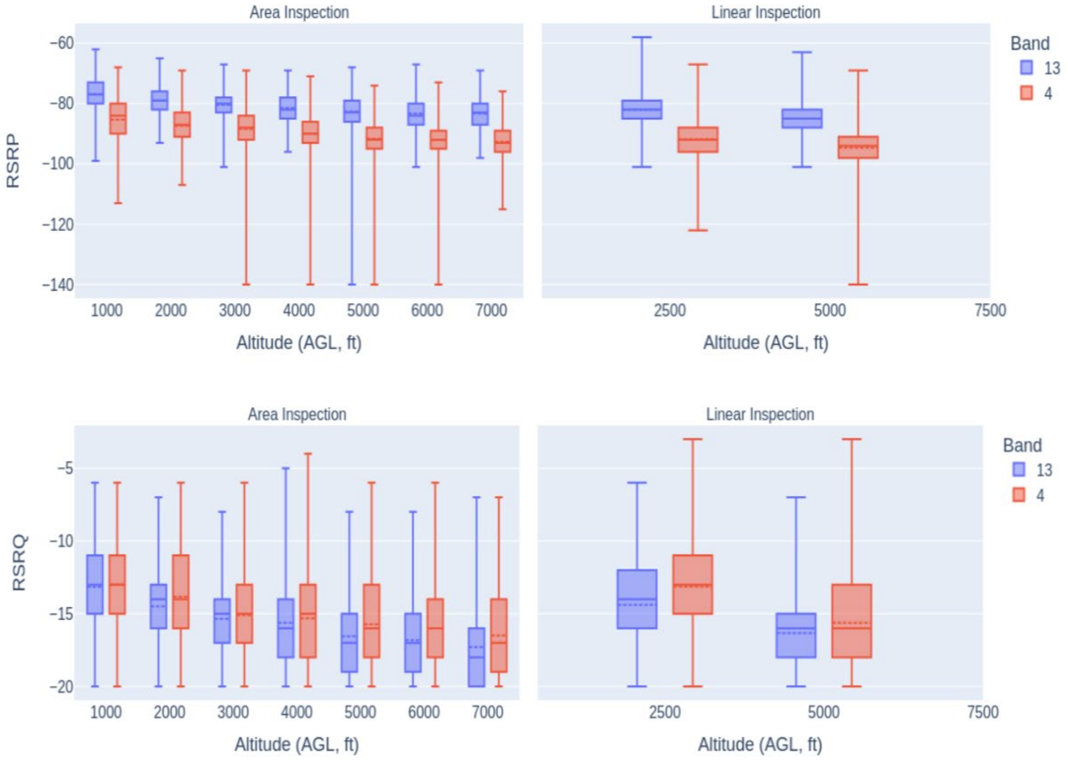
[34] AirborneRF. 2019. Cellular Data Collection. Available at https://airbornerf.com/.

In the final report, Skyward concluded that “Verizon’s existing network is sufficient to support the cellular command and control (C2) mission within the tested altitudes.”[35] The same opportunity was also offered to T-Mobile and AT&T, but to date, these MNOs have not accepted a cooperative testing agreement with FAA. As such, it is unknown how those networks perform at various altitudes.

In 2022, via broad area announcement, FAA funded the aviation company Appareo to conduct cellular testing up to 7,000 ft (2,134 m) AGL to determine the capability of the network to support sensor downlinks. This campaign was carried out in Grand Forks, ND, in cooperation with the Northern Plains UAS Test Site and with support from Verizon. The operation collected data using an ACU-200 aircraft communication unit with airborne LTE capabilities over the Verizon network. The unit was affixed to the wing and tail of two different fixed-wing manned aircraft and used to transmit 720p images at 30 frames per second. Figure 11 illustrates the aggregate RSRP and RSRQ values at various altitudes collected during the operation. The full report is publicly available and included in the appendix.

Figure 11. Appareo-recorded RSRP and RSRQ values at increasing altitudes.



Source: Appareo (2022).[36]

These data support assertions that the cellular network may not only likely support C2 capabilities up to 7, 000 ft (2,134 m) AGL but may also support higher throughput sensor systems. Like the AirborneRF data, there were occasions when the control signal was not relayed by the closest tower to the aircraft but one that was more than 20 mi (32 km) away. This is a critical finding that may alleviate concerns over localized network

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[35] Verizon. 2022. *Verizon/FAA Memorandum of Agreement Cellular Technologies to Support UAS Activities Report*. (Refer to appendix.)

[36] Appareo. 2022. *Pre-commercialization Effort for Real Time Transport Protocol UAS Video*. (Refer to appendix.)

saturation in areas of high traffic density as experienced during large-scale disasters. Additional testing is required to confirm these results under various network, operational, and environmental conditions and over other cellular bands and MNO networks.

Policy Barrier

Today, many large-scale UAS operators are leveraging the cellular network for their C2 functions. The FCC has an ongoing proceeding to consider the use of existing networks as platforms for UAS and that seeks comment on whether the Commission's rules are adequate to ensure co-existence of terrestrial mobile operations and UAS or whether changes to the rules are necessary. Refer to FCC 24-91 *Spectrum Rules & Policies for the Operation of Unmanned Aircraft Systems*[37] and RM-11798 *Wireless Telecommunications Bureau Seeks to Refresh the Record on Unmanned Aircraft Systems Use of the 5 GHz Band*,[38] which covers the 5030–5091 MHz band, for more information.

As UAS cellular usage continues to grow, it is prudent for additional policy adaptation to keep pace. Identifying which cellular frequencies may be used to conduct aeronautical navigation functions would also help clear up any confusion as to what should and should not be used.

Technological Considerations

The terrestrial cellular network was never intended for aviation purposes. The network was built using antenna arrays canted toward the ground at angles between approximately 5 and 10 degrees to ensure connectivity for the maximum number of terrestrial users. As described in the Verizon[35] and Appareo[36] reports, RF availability at altitudes relevant to current UAS operations is more than sufficient due to the pervasive propagation patterns of the sidelobe emissions. However, understanding where the network is available with adequate quality of service presents a significant unknown for BVLOS operators. There are several companies, like AirborneRF, attempting to map airspace connectivity using real-world testing and predictive modeling. These data, however, are not yet widely disseminated and have not been used to support FAA or FCC policies.

From previous testing, there are several issues that require additional research, including the following:

- **Physical cell ID (PCI) co-channel interference:** Just as each cell phone has an international mobile subscriber identity (IMSI) identifier, each cell tower emitter/panel has a PCI. However, unlike mobile phones, these PCIs are reused at distributed intervals. Figure 12 illustrates a general concept of how tower sectors are distributed to ensure PCIs never overlap, thus preventing co-channel interference. Main station controller (MSC) sections are divided into base station controllers (BSCs), which control a number of cellular towers or base stations. This system was designed for terrestrial use. Above the horizontal plane of the tower emitter, however, aircraft utilize sidelobe emissions rather than the main lobe and therefore can often "hear" transmissions from multiple sectors simultaneously. In certain scenarios, the aircraft may receive a signal from two towers with the same PCI from different

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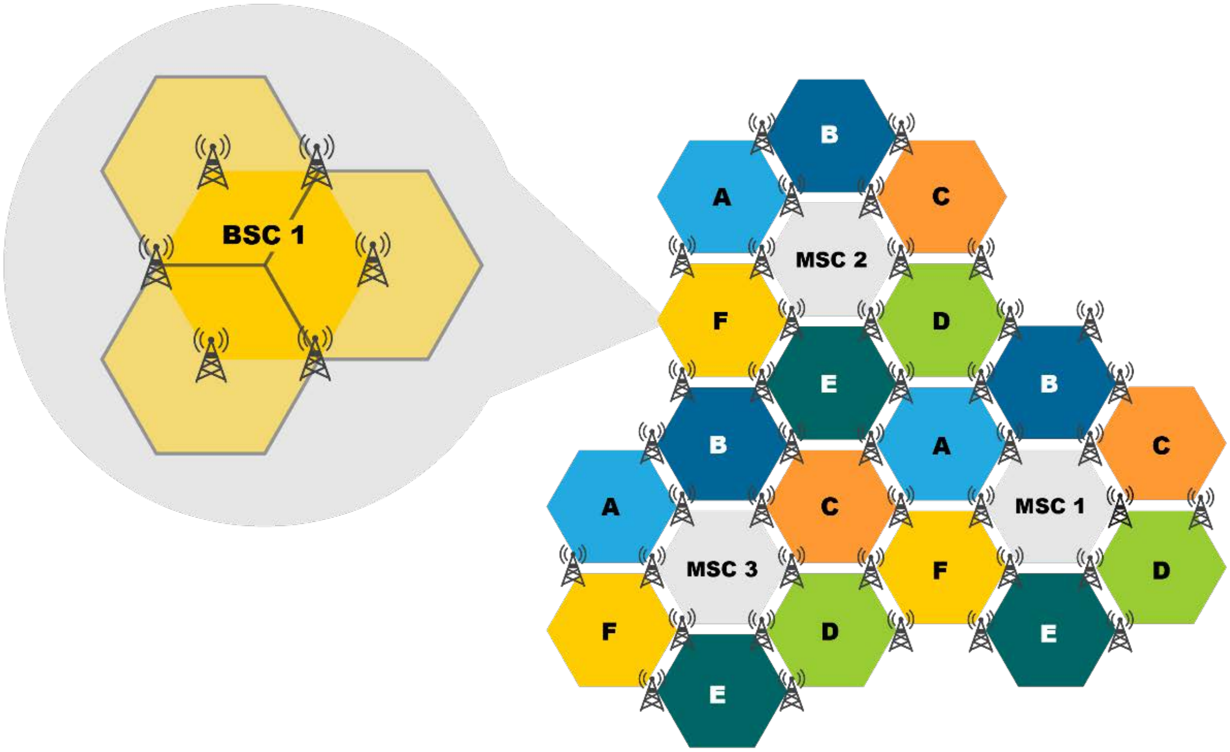
[37] FCC. 2024. *Spectrum Rules & Policies for the Operation of Unmanned Aircraft Systems* (FCC 24-91), paras. 2, 111–150. Accessed 11/12/24: https://docs.fcc.gov/public/attachments/FCC-24-91A1.pdf.

[38] FCC. 2021. *Wireless Telecommunications Bureau Seeks to Refresh the Record on Unmanned Aircraft Systems Use of the 5 GHz Band* (RM-11798). Accessed 11/12/24: https://public-inspection.federalregister.gov/2021-19499.pdf.

sectors. When this happens, co-channel interference may reduce operability and disrupt the C2 uplink or telemetry downlink from the aircraft.

Figure 12. Conceptual layout of a terrestrial cellular network.



Source: HASS COE.

- **Network saturation:** During testing with corresponding MNOs, the network was carefully monitored to ensure there was no impact on terrestrial users. To date, tests have only included a small number of simultaneous aircraft. Additional testing and modeling are required to determine the full effect of hundreds to thousands of aircraft using the network in increasingly active environments. Such testing is especially important in urban environments where UAS and advanced air mobility (AAM) operations will increase relative to the population density.

- **Frequency saturation:** Testing has indicated that the network is sufficient for supporting low throughput operations, which may include C2, electronic conspicuity, remote identification, and telemetry downlinks. Higher throughput operations, such as sensor downlinks of high-resolution video data, have not been sufficiently tested. The Appareo tests indicated that RSRQ values drop at increasing rates relative to altitude. These values are critical to maintain fidelity of the signal. Additional testing is required to corroborate these findings and determine the thresholds for operation types.

Cellular Network: Additional Benefits

The expansive national cellular communications infrastructure offers several potential solutions for UAS integration. UAS functions like C2; sensor downlinks; electronic conspicuity; remote identification; position, navigation, and timing (PNT) resiliency; and cybersecurity may all be improved by leveraging functions inherent to the terrestrial cellular network.

UAS generally determine their position via a GNSS receiver. Often, UAS are equipped with multiple receivers to leverage several GNSS constellations simultaneously, including GPS (United States), Galileo (EU), GLONASS (Russia), and BeiDou (China). Mobile users also leverage multiple GNSS for their location determination via a hardwired receiver in each phone. This connection is what enables traffic applications like Google Maps™ and Waze™. While enabled, the phone constantly transmits its location to the entire network so that anyone else may not only be informed of impending traffic but also the location of individual users, such as those broken down on the side of the road. The same mechanism can be used for aircraft electronic conspicuity. UAS that are already leveraging the cellular network for C2 may instantly upload their real-time telemetry data via a mobile application. Others using the application will have a holistic view of air traffic rather than ground traffic, thus ensuring the ability to detect any other aircraft nearby or even hundreds of miles away. As long as the aircraft connects to the network, proximity is not an issue. By leveraging multiple constellations, PNT resiliency can also be improved. Though it is no small task to spoof or even jam a single GNSS signal, it is incredibly difficult to corrupt multiple transmissions from dozens of geographically separated sources—in this case, GNSS satellites. Additionally, the IMSI number associated with each SIM card or electronic-SIM (eSIM) would act as a remote identifier to assist law enforcement, FAA, and other authorities in determining the identity of any UAS operator. As inherent functions of the cellular network, all these capabilities are currently freely available to a network user and require no additional equipage.

Unlike unlicensed frequencies under 47 CFR Part 15,[28] which have dozens of public uses, cellular networks benefit from licensed frequency spectrums and therefore have greater protections from interference. These frequencies are encrypted by MNOs—128-bit encryption over 4G and 256-bit over 5G networks[39]—thus ensuring secure communication channels for the aircraft. Finally, it may be possible to enable the electronic conspicuity of all aircraft, including manned aircraft, via the cellular network, especially as we potentially evolve toward space-based systems. For pilots, electronic conspicuity may be achieved simply by carrying their cell phone with an app engaged—again, similar to how Google Maps™ and Waze™ operate. From a technical perspective, this networked solution could be available to any aircraft operator in an area with cellular coverage at a near zero cost. Further, the interlacing weave pattern of the sidelobe emissions at operational altitudes (Figure 13) may not only support reliable C2 but also detection and avoidance capabilities for all manned and unmanned aircraft operating outside ATC-serviced areas. For these reasons, it is essential to continue collecting data on the capabilities and limitations of the terrestrial network in various environments and altitudes.

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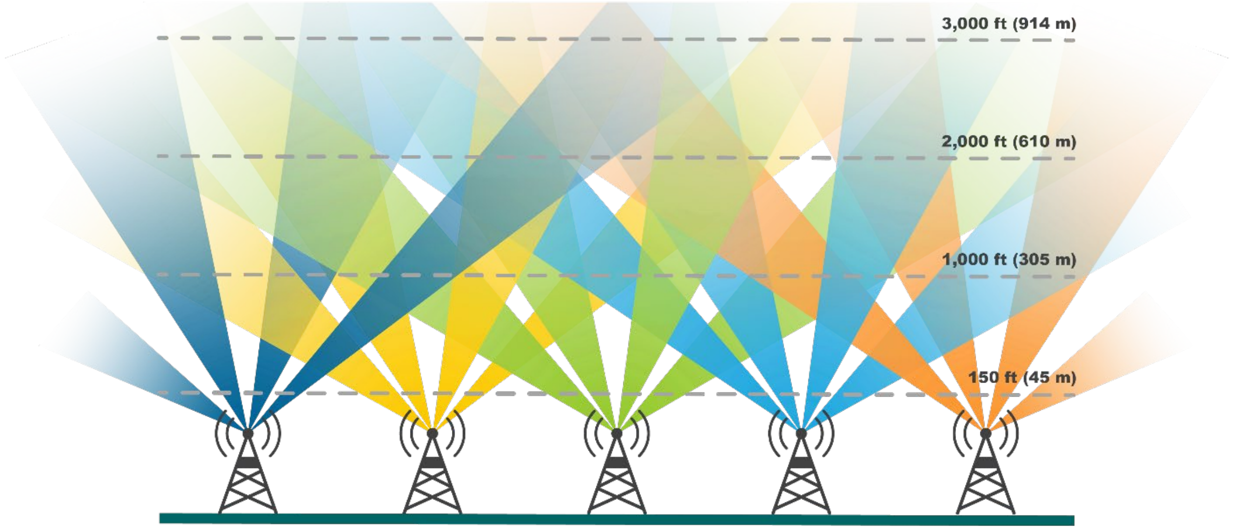
[39] Marty, R. 2020. *Not just speed: 5G will make several security upgrades* [blog post]. Accessed 4/1/24: https://about.att.com/innovationblog/2020/12/5g_security_upgrades.html.

Figure 13. Interlacing weave pattern of sidelobe emissions at operational altitudes.



Source: HASS COE.
Note: As altitude increases, the number of towers within line of sight will increase, but the signal fidelity (signified by the RSRQ value) will decrease. Over the same distance, higher frequencies will attenuate faster than lower frequencies at the same power levels. For example, Band 4 (1700/2100 MHz) will attenuate faster than Band 13 (700 MHz).

Future Applications: Mesh Networking and Nodal Resilience

Approach

Mesh networking leverages a system of many nodes where each node (in this context, each aircraft) communicates with one another, potentially functioning independently of any ground nodes/infrastructure. These networks are generally described as taking one of two forms: full topology, where every node is connected to every other node, and a partial topology, where interconnected nodes are not all directly linked to one another, as depicted in Figure 14. Full mesh networks may offer enhanced resiliency for aircraft PNT functions through nodal validation. In a scenario where dozens of aircraft are interconnected and sharing real-time telemetry data, the network can self-correct if one or two nodes experience jamming, spoofing, or other RF disruptions due to the collective data validation from the neighboring nodes. For a PNT validation use case, some nodes may have very high accuracy inertial navigation systems onboard, which can be used to validate GNSS signals; the mesh network would allow this validation to be shared with all participants. Connections may be established via sidelink peer–peer communications, which enables direct user–user communication without the need for connection to the cellular network. For more information on this technology, reference the 3GPP (i.e., the 3rd Generation Partnership Project).[40]

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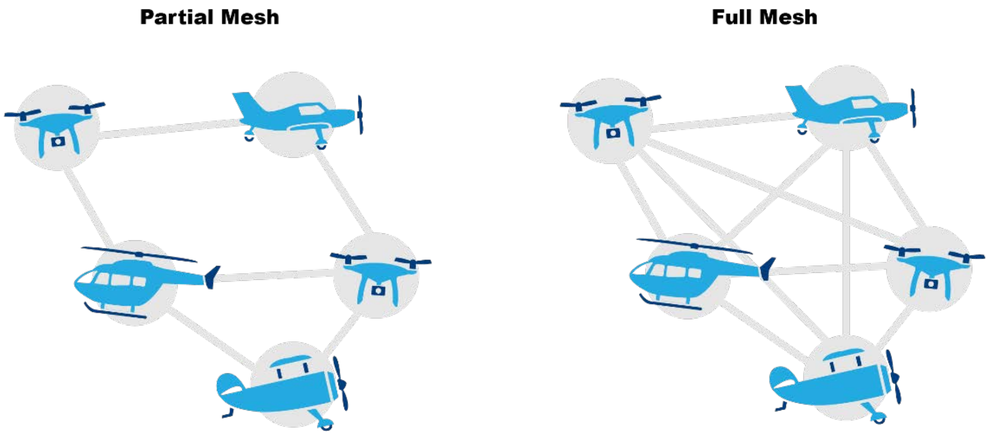
[40] 3GPP. 2024. "NR Sidelink Enhancement in 3GPP Release 17," *Journal of ICT Standardization* 9(2). Accessed 10/21/24: https://doi.org/10.13052/jicts2245-800X.922.

Figure 14. Meshed networks.

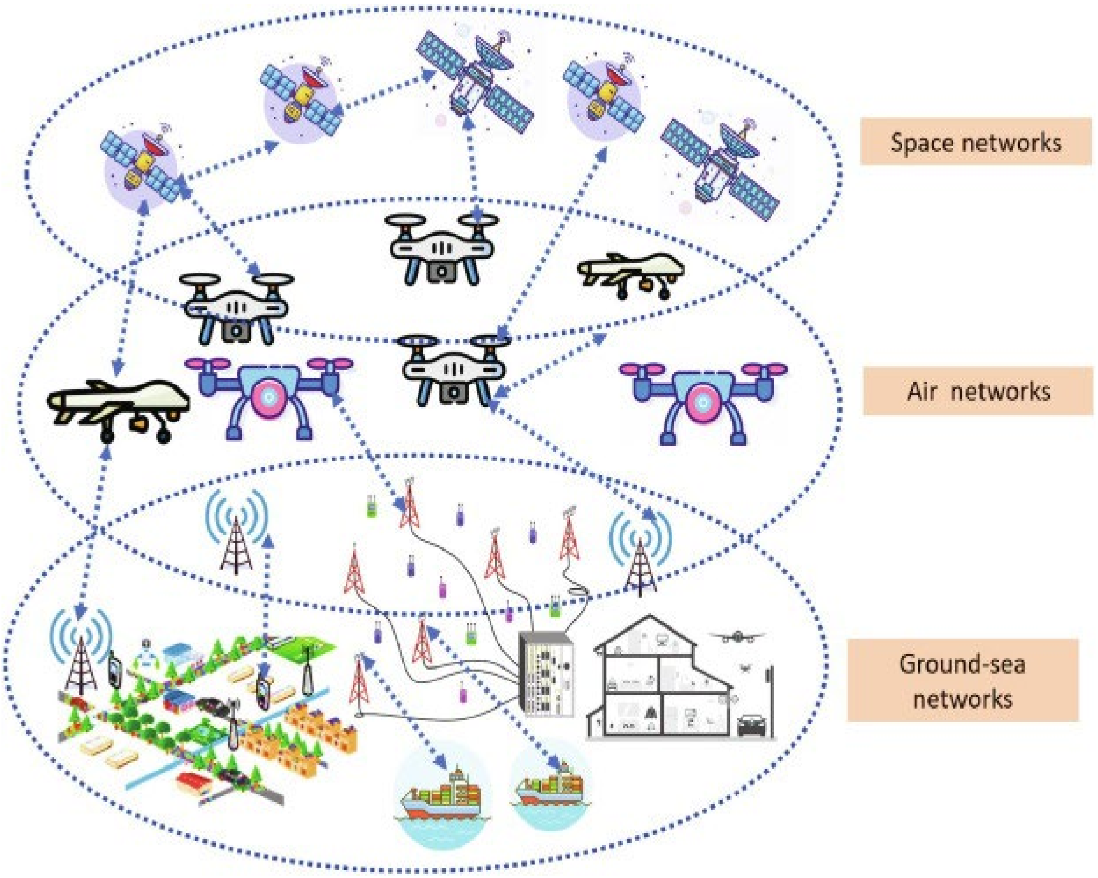


Source: HASS COE.

Achieving redundancy sufficient to assure required levels of safety often means increasing the number of systems involved (e.g., ground sensors plus airborne sensors). A meshed approach, however, allows leveraging self-correcting characteristics of networks operating in parallel, resulting in more efficient and robust performance than serial communication systems where a single nodal error (weak link) could impact a command decision reliant on disparate inputs (e.g., accuracy disparities in more than one detection sensor). Within such an open system framework, techniques like dead reckoning and inertial mapping can also contribute to data correction. Moreover, segmenting networks into defined territories allows for dynamic node adjustment as aircraft enter or exit these areas as may be required by UAS services suppliers under the proposed Unmanned Traffic Management architecture. Applying advanced frequency modulations, such as orthogonal division multiple access (i.e., ODMA) and frequency shift keying (i.e., FSK), can also increase the number of allowable simultaneous users. Finally, applying encryption techniques similar to those used in cellular networks will further improve PNT resiliency and harden the system against jamming and spoofing.

Presently, airborne meshed networks are conceptual and can only become effective as a sole means of deconfliction once the airspace density reaches a saturation point that will ensure enough nodes exist to sustain the system. Absent such “critical mass,” significant benefit can likely be derived from hybrid approaches leveraging mesh networks in areas/times of high traffic density combined with other approaches in less busy areas/times where deconfliction is likely easier. As the world moves toward a space-based cellular network, it is only logical that communication technologies in the aviation environment should evolve as well. Figure 15 illustrates how such a network would not only fit into this overall architecture but enhance its capabilities as a relay system between ground and space.

Figure 15. Integrated ground–sea–air-space 6G network expected.



Source: Hakeem et al. (2022).[41]

European Aviation Conspicuity Efforts

U-Space

Airspace integration need not be bound by national boundaries. Presently, EASA is moving forward with testing the integration of various communications technologies to enable the safe deconfliction of manned and unmanned aircraft across EU airspace. In the *Easy Access Rules for Standardised European Rules of the Air (SERA)*,[42] published in February 2023, SERA.6005 Requirements for Communications, SSR Transponder and Electronic Conspicuity in U-Space Airspace lays out the rules and requirements for aircraft self-identification. As defined in the Official Journal of the European Union, "'U-space airspace' means a UAS

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[41] Hakeem, S., H. Hussein, H. Kim. 2022. "Vision and research direction of 6G technologies and applications," *Journal of King Saud University - Computer and Information Sciences* 34(6a). Accessed 8/7/24: https://doi.org/10.1016/j.jksuci.2022.03.019.

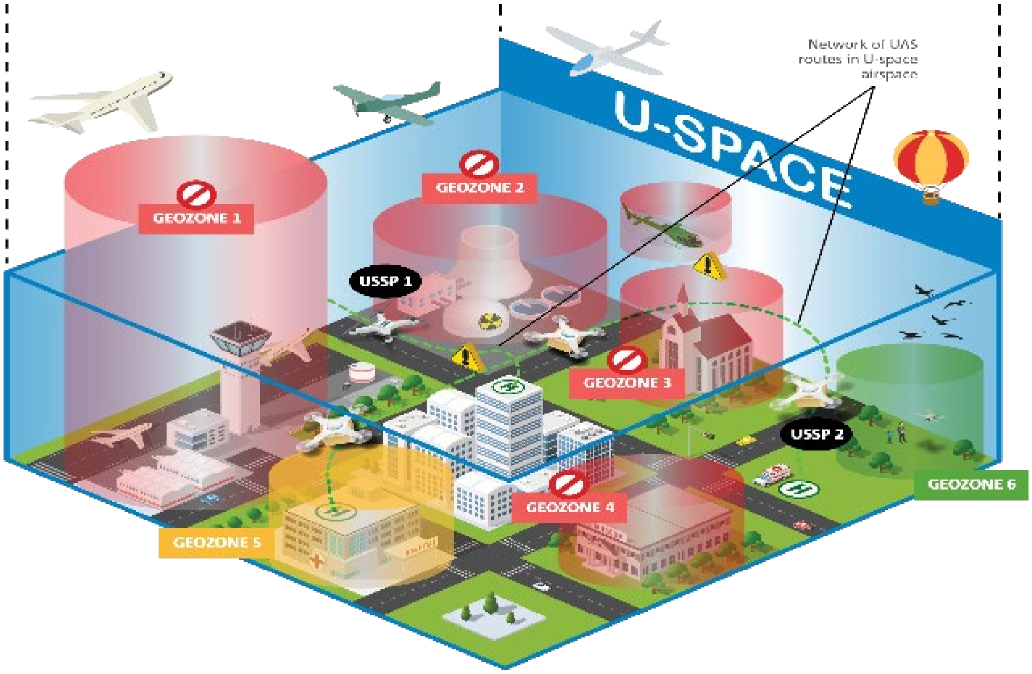
[42] EU. 2023. *Easy Access Rules for Standardised European Rules of the Air (SERA).* Accessed 10/21/24: https://www.easa.europa.eu/en/document-library/easy-access-rules/easy-access-rules-standardised-european-rules-air-sera.

geographical zone designated by Member States, where UAS operations are only allowed to take place with the support of U-space services.”[43] Mandatory services, provided by the U-space service provider (USSP), include UAS flight authorization, network identification, geo-awareness, and traffic information services. It is important to note that U-space regulations do not include UAS passenger-carrying operations as these are presently carried out by manned vertical-takeoff-and-landing-capable aircraft similar to AAM operations in the United States. When these operations shift toward unmanned, EASA will re-evaluate the acceptable levels of safety for U-space operations.

As depicted in Figure 16, U-space encompasses any area designated by the Member State where USSP services are provided. The area may also include any of the following three zones within it:

- **Excluded geo-zones:** UAS operations are not permitted.
- **Restricted geo-zones:** UAS operators need prior authorization before entering.
- **Facilitated geo-zones:** Reserved for low-risk commercial operations and recreational flights.

Figure 16. EU U-space categories.



Source: EASA (n.d.).[44]

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[43] EASA. 2021. *Commission Implementing Regulation (EU) 2021/666 of 22 April 2021 amending Regulation (EU) No 923/2012 as regards requirements for manned aviation operating in U-space airspace*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0666.

[44] EASA. n.d. “Geo-zones – know where to fly your drone | EASA” [webpage]. Accessed 10/21/24: https://www.easa.europa.eu/en/light/topics/geo-zones-know-where-fly-your-drone.

EU U-Space Electronic Conspicuity

When UAS operate in U-space, direct remote identification (DRI) is used to determine the location and identity of the aircraft and its operator. This information is transmitted from the aircraft and is shared with the servicing USSP, neighboring USSPs, and anyone within range who has a receiver like a mobile phone. DRI, however, was implemented to support a security function rather than aerial deconfliction. Like Remote ID in the United States, DRI leverages unlicensed Bluetooth and Wi-Fi transmissions. In an ideal environment, these transmissions may reach their intended target. Unfortunately, atmospheric and environmental conditions are rarely ideal. Further testing is required to determine the capabilities and limitations of these transmissions in operationally representative environments. Leveraging mobile telephony technologies, however, opens a pathway for the EU to enable much more than just DRI. Because the EU does not have a prohibition on aerial mobile telephony, the existing licensed network may be used for C2 and e-conspicuity. Both functions may be enabled through the simple application of an eSIM onboard each aircraft. If the aircraft is within range of a tower, the precise location will be shared across the network. The detection and deconfliction from manned aircraft in U-space can be performed in the same manner.

On April 21, 2021, EASA modified SERA.6005 to state the following:

> *Manned aircraft operating in airspace designated by the competent authority as a U-space airspace, and not provided with an air traffic control service by the ANSP, shall continuously make themselves electronically conspicuous to the U-space service providers.*[43]

To satisfy this requirement, EASA initiated research into its i-Conspicuity and ADS-L (ADS-B Light) concepts. The purposes of these initiatives are to enable integration without the need for airspace segregation and to improve the interoperability of various conspicuity systems:

- **i-Conspicuity:** An umbrella concept encompassing solutions for interoperability, compatibility, and improvements to flight information services.
- **ADS-L:** A minimum standard for designating a transponder signal specifically for manned to unmanned conspicuity. It is further refined into two methods:
  - *ADS-L (SRD-860):* Using a short-range radio device to transmit an ADS-like signal over 860 MHz. This frequency will be used for manned aircraft to make themselves electronically conspicuous to manned and unmanned aircraft.
  - *ADS-L (mobile telephony):* A mobile phone installed with a mapping application will be used to transmit an aircrafts' location via the cellular network. This method does not require any modification to or any equipment installation onboard the aircraft.

In support of the ADS-L mobile concept, European company SafeSky developed a no-cost mobile phone app for GA pilots to share their telemetry data with other app users. To date, they have enlisted more than 70,000 users across the EU GA community.[45] This white paper recommends researching a similar application for use within the U.S. national airspace.

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[45] SafeSky. 2024. "Safesky App | SafeSky" [webpage]. Accessed 10/21/24: https://www.safesky.app/application.

Conclusion

Unmanned aircraft are part of the aviation ecosystem and will continue to grow among and slowly replace various manned aircraft operations. Ensuring their safe integration requires the adoption and adaptation of advanced technologies that will support their vital functions. Data suggest that cellular technologies may support multiple functions, including C2, sensor downlinks, and electronic conspicuity, all while bolstering PNT resiliency and cybersecurity. As discussed, these functions are necessary to ensure detection and deconfliction from manned and other unmanned aircraft during BVLOS operations. UAS are not the only beneficiaries of cellular technologies. Manned aircraft may also improve safety by ensuring flights operating without the benefit of ATC services are more easily detectable to one another. When one considers that "nearly all accidents [MACs] occur at or near uncontrolled airports and at altitudes below 1,000 feet,"[46] the cellular conspicuity option becomes an affordably attractive solution. Applying advanced RF technologies to both manned and unmanned aircraft may not only reduce the loss of life from dangerous professions and emergency situations but also increase productivity across multiple industries. The more rapidly we safely integrate UAS into our national airspace, the sooner we will benefit from their capabilities, present and future.

Summation of Recommendations

Policy/Regulatory Reviews

The following regulations directly impact the ability to successfully implement the electronic conspicuity methods proposed by this paper. A review and potential modification of each may expedite the integration of UAS into the NAS:

- 14 CFR Part 91.225(h)(2):[7] Explore options to allow all UAS to transmit an ADS-B or ADS-B-like signals.
- 14 CFR Part 91.225(d):[7] Explore options for mandating the electronic conspicuity of all manned aircraft in a way that can easily be received by unmanned aircraft.
- 14 CFR Part 91.119(c):[19] Examine minimum safe altitudes for GA aircraft as it relates to UA operations within 500' of structures.
- 47 CFR Part 22.925:[47] Examine the prohibition of the airborne operation of cellular telephones as it applies to UA command and control.

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[46] FAA. 2021. "Chapter 8. Airport Traffic Patterns," *Airplane Flying Handbook* (FAA-H-8083-3C). Accessed 10/21/24: https://www.faa.gov/sites/faa.gov/files/regulations_policies/handbooks_manuals/aviation/airplane_handbook/09_afh_ch8.pdf.

[47] 47 CFR Part 22.925, Prohibition on Airborne Operation of Cellular Telephones. Accessed 11/12/24: https://www.ecfr.gov/current/title-47/chapter-I/subchapter-B/part-22/subpart-H/section-22.925.

Research

Addressing the following research questions will greatly improve our understanding of the national cellular network and its ability to support aviation needs:

- What are the capabilities and limitations of the 4G LTE and 5G networks to support UAS C2 in various environments at operational altitudes? Do millimeter wave frequencies have different sidelobe propagation patterns, especially from femtocells?
- How do the MNO coverage areas compare at various altitudes? Can combined network testing be accomplished?
- What is the feasibility of a universal (multinetwork) eSIM for aviation?
- At what rate do RSRP and RSRQ values decrease as altitude increases in various environments (e.g., urban vs. rural) and can it be predicted?
- How might aviation integration issues be resolved through the application of cellular-based solutions? For example, C2, detect and avoid (DAA), remote identification (RID), and electronic conspicuity. What more can we learn about the reliability, accuracy, and latency of these transmissions?
- What alternative antenna orientations, designs, and power output levels might enable more reliable signals at higher altitudes?
- What are the effects and likelihood of physical cell ID co-channel interference at operational altitudes? What mitigations might be effective?
- Is there a saturation issue with 978 MHz UAT, and if so, what is that limitation?

Appendix. Supplemental Information

The following documents are supplemental sources and information related to this paper:

Nassif, C. 2024. UAS CNPC Testing Metrics Updated April 2021 w 5G [spreadsheet]. https://www.transportation.gov/hasscoe/uas-cnpc-testing-metrics-apr2021.

Verizon. 2022. *Verizon/FAA Memorandum of Agreement Cellular Technologies to Support UAS Activities Report*. https://www.transportation.gov/hasscoe/verizon-faa-moa-final-report.

Verizon. 2022. *FAA/Skyward Memorandum of Agreement (MOA) Bimonthly Report*, March 2022. https://www.transportation.gov/hasscoe/faa-skyward-moa-bimonthly-report-mar2022.

Verizon. 2022. *FAA/Skyward Memorandum of Agreement (MOA) Bimonthly Report*, January 2022. https://www.transportation.gov/hasscoe/faa-skyward-moa-bimonthly-report-jan2022.

Verizon. 2021. *FAA/Skyward Memorandum of Agreement (MOA) Bimonthly Report*, November 2021. https://www.transportation.gov/hasscoe/faa-skyward-moa-bimonthly-report-nov2021.

Appareo. 2022. *Pre-commercialization Effort for Real Time Transport Protocol UAS Video*. https://www.transportation.gov/hasscoe/bAA-02-final-report.

List of Acronyms

AAM	advanced air mobility
ACAS	Airborne Collision Avoidance System
ACAS sXu	system model for small unmanned aircraft
ACAS Xa	base model for the next evolution of TCAS
ACAS Xr	system model for rotorcraft, including advanced air mobility
ACAS Xu	system model for unmanned aircraft
ADS-B	Automatic Dependent Surveillance—Broadcast
ADS-L	ADS-B Light
ADS-R	Automatic Dependent Surveillance—Rebroadcast
AGL	above ground level
ATC	Air Traffic Control
BSC	base station controller
BVLOS	Beyond Visual Line of Sight
C2	command and control
DRI	direct remote identification
EASA	European Union Aviation Safety Agency
EU	European Union
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FIS-B	Flight Information Services
GA	general aviation
GNSS	global navigation satellite system
ICAO	International Civil Aviation Organization
IFF	identify friend or foe
IMSI	international mobile subscriber identity
MAC	midair collision
MNO	mobile network operator
MOA	memorandum of agreement
MSC	main station controller
MSL	mean sea level
NAS	National Airspace System
NITA	National Telecommunications and Information Administration
NMAC	near midair collision
NNA	Non-Network Access
NSS	Network-Supported Services
NTIA	National Telecommunications and Information Administration
PCI	physical cell ID
PIA	Privacy ICAO Address
PNT	position, navigation, and timing
PPM	pulse position modulation
RA	Resolution Advisory
RF	radiofrequency
RSRP	reference signal received power
RSRQ	reference signal received quality
SSR	secondary surveillance radar
sUAS	small unmanned aircraft system

SWAP	size, weight, and power
TA	Traffic Advisory
TCAS	Traffic Collision Avoidance System
TIS-B	Traffic Information Services
UA	unmanned aircraft
UAS	unmanned aircraft systems
UAT	Universal Access Transceiver
USSP	U-space service provider
VFR	visual flight rules