July 17, 2020

Report to Congress under Section 374 of FAA Reauthorization Act of 2018, Public Law 115-254

Unmanned Aircraft Systems Use of Spectrum

DRAFT FOR STAKEHOLDER REVIEW

This page intentionally left blank.

Executive Summary

This report, prepared by the Federal Aviation Administration (FAA) and including valuable input from the National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC), responds to Section 374 of the FAA Reauthorization Act of 2018 (Public Law 115-254), which provides:

> *SEC. 374. SPECTRUM.*
>
> *(a)* ***REPORT****.—Not later than 270 days after the date of enactment of this Act, and after consultation with relevant stakeholders, the Administrator of the Federal Aviation Administration, the National Telecommunications and Information Administration, and the Federal Communications Commission, shall submit to the Committee on Commerce, Science, and Transportation of the Senate, the Committee on Transportation and Infrastructure of the House of Representatives, and the Committee on Energy and Commerce of the House of Representatives a report*
>
> > *(1) on whether unmanned aircraft systems operations should be permitted, but not required, to operate on spectrum that was recommended for allocation for AM(R)S and control links for UAS by the World Radio Conferences in 2007 (L-band, 960-1164 MHz) and 2012 (C-band, 5030-5091 MHz), on an unlicensed, shared, or exclusive basis, for operations within the UTM system or outside of such a system;*
> >
> > *(2) that addresses any technological, statutory, regulatory, and operational barriers to the use of such spectrum; and*
> >
> > *(3) that, if it is determined that some spectrum frequencies are not suitable for beyond-visual-line-of-sight operations by unmanned aircraft systems, includes recommendations of other spectrum frequencies that may be appropriate for such operations.*
>
> *(b)* ***NO EFFECT ON OTHER SPECTRUM****.— The report required under subsection (a) does not prohibit or delay use of any licensed spectrum to satisfy control links, tracking, diagnostics, payload communications, collision avoidance, and other functions for unmanned aircraft systems operations.*

Key Findings

In summary, the key findings in this report are:

(1) on whether unmanned aircraft systems operations should be permitted, but not required, to operate on spectrum that was recommended for allocation for AM(R)S and control links for UAS by the World Radio Conferences in 2007 (L-band, 960-1164 MHz) and 2012 (C-band, 5030-5091 MHz), on an unlicensed, shared, or exclusive basis, for operations within the UTM system or outside of such a system

UAS operations should be permitted[1], but not be required, to use control links (which in this report are called command and control (C2) links) in the L-band and C-band.[2,3]

- UAS operations should be permitted to use the L-band and C-band only on a shared basis, not on an exclusive basis, in accordance with existing rules.[4]
- UAS operations should not be permitted to use the L-band and C-band on an unlicensed basis; i.e., radio devices certified by the FCC for use in unlicensed bands[5] should not be permitted to use the L-band and C-band.[6]
- UAS operations, both within or outside a UTM system, should be permitted to use L-band and C-band for control links.

(2) that addresses any technological, statutory, regulatory, and operational barriers to the use of such spectrum

There are technological, regulatory, and operational barriers, identified in this report, to the use of the allocated L-band and C-band spectrum; no statutory barriers were identified. The barriers for both bands include:

- The need to ensure that spectrum resources are used efficiently to provide equitable access to UAS operations within or outside a UTM system, including mechanisms for dynamically managing frequency assignments and spectrum access.
- The need to mature the proposed concepts for these bands, validate and refine implementation approaches, and address the questions and challenges identified in this report.

There is an additional significant barrier for L-band:

- The need to safely coexist within the L-band that is heavily used by multiple systems that are essential for the safety and regularity of both civil (e.g., commercial) and public (e.g., military) flight operations.[7]

---

[1] Several UAS manufacturers and operators already are making significant use of the C-band. This usage has enabled new UAS operations that previously could not occur, and has demonstrated UAS functionality beyond the manufacturers' and operators' initial expectations. Stakeholders have stated that preservation of C-band for UAS operations is necessary for UAS industry success, particularly for operation of unmanned aircraft beyond the pilot's visual range.

[2] The L-band (960-1164 MHz) and C-band (5030-5091 MHz) cited in Section 374 are allocated by the ITU and FCC for aeronautical mobile (route) services [AM(R)S], which include use for UAS control links.

[3] In the L-band, UAS operations should be permitted if further work determines that safety-of-life aviation functions currently performed in the band can be fully protected and preserved. The finding is qualified in this manner because the barriers for the use of L-band are considered significant, as described in finding (2).

[4] Section 87.41 of 47 CFR states that aviation frequencies are available for assignment on a shared basis only and that they will not be assigned for the exclusive use of any licensee.

[5] Unlicensed bands are used by radio devices that are FCC-certified and operate in accordance with FCC regulations found in 47 CFR 15 and 47 CFR 18. While an FCC-issued license is not required for the device users, operation must comply with various limits such as transmit power and spurious emissions. At the same time, device users have no expectation of protection from radio frequency interference. Thus, no radio link performance guarantees are possible in unlicensed bands.

[6] Such use is not authorized by the FCC and would be contrary to the L-band's and C-band's AM(R)S allocations intended to help ensure flight safety and regularity.

[7] This complexity includes the need to ensure through proper frequency management that the operation of ground and airborne systems currently using the highly congested L-band to help ensure the safety and regularity of manned aircraft flight will not be disrupted by interference from UAS.

3) that, if it is determined that some spectrum frequencies are not suitable for beyond-visual-line-of-sight operations by unmanned aircraft systems, includes recommendations of other spectrum frequencies that may be appropriate for such operations.

All radio frequency (RF) spectrum (including the L-band and C-band federal government spectrum, licensed spectrum, and unlicensed spectrum) could be suitable for operation of unmanned aircraft beyond the pilot's visual line of sight (BVLOS).

- The decision process for the spectrum band selection should take into account the UAS operation's target level of safety and the safety-risk mitigations used to achieve (or exceed) that target.
- Use of unlicensed spectrum in other bands may be unsuitable for some unmanned aircraft (UA) operations, either within or beyond the pilot's visual range, because of potential radio frequency interference (RFI). For BVLOS UAS operations, use of unlicensed spectrum is an increased concern due to the higher dependence on radio services by multiple safety-related UAS functions.[8]
- For UAS operations within or beyond the pilot's visual line of sight, functions for detecting and avoiding other aircraft must not use unlicensed spectrum. That is, radiocommunications and radionavigation functions used for UAS detect and avoid (DAA) capabilities must use licensed or federal government bands with appropriate allocations and regulatory protections for mitigating RFI.
- Stakeholders have supported further investigation into the use of systems and bands used in cellular radio networks providing terrestrial mobile communications services, which may be available for enabling UAS operations in the near term. The feasibility and acceptability of using these systems and bands should be assessed.
- Use of other spectrum bands should be in accordance with FCC and NTIA regulations as well as in accordance with spectrum license holders' requirements and authorizations.

Approach for Stakeholder Consultation

The statute directed the FAA, NTIA, and FCC to submit a report, after consulting with relevant stakeholders, to respond to the questions posed in Section 374.

The FAA has pursued a collaborative approach in the concept development and exploration of alternatives. The FAA consulted with stakeholders to refine preliminary concepts, propose

[8] Section 7.8 of the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management [9] states: "Non-licensed devices, since they operate on a non-interference basis, may not provide sufficient reliability for critical radio communications functions affecting human life or property. Non-licensed devices, however, may provide valuable and unique supplemental or expendable radio communications services where needed. To ensure adequate regulatory protection, Federal entities should rely only on devices with frequency assignments in the Government Master File as principal radiocommunication systems for safeguarding human life or property." Nevertheless, use of unlicensed spectrum for C2 links might be acceptable for some UAS operations in which the safety risks can be sufficiently mitigated by means not dependent on unlicensed spectrum. In such cases, the FAA would rely on those other means for safeguarding human life or property; it would not rely on UAS radio devices operating in unlicensed spectrum.

alternatives, assess their feasibility, and identify potential opportunities and challenges for their realization.

To consult relevant stakeholders during the development of this report, as directed by Congress, the FAA issued a draft overview of the key concepts, including feedback from NTIA and the FCC, for review and comment. Several stakeholders responded to this request by providing written comments on the overview. Following FAA analysis of the comments, the stakeholders were invited to a roundtable meeting where the FAA shed more light on the concepts and approach described in the overview and stakeholders had an opportunity to ask questions and explain their comments. The FAA used the stakeholder inputs, both written and oral, in preparing this report.

The FAA will continue to consult with stakeholders after delivering this report to Congress, as appropriate, on further concept development, implementation, and operations.

Key Principles

The FAA's first principle is to ensure the safety and efficiency of aviation; thus, the safety of manned operations must not be undermined by any changes to spectrum usage supporting UAS operations. Secondarily, the FAA is committed to facilitating safe integration of UAS operations in the national airspace; and to improve spectrum utilization on federal government bands when possible.

The opportunity to allow coexistence of UAS in L-band spectrum used by manned aviation needs to be carefully assessed to ensure that safety of manned aviation will be preserved.

The decision about which radio band(s) could be used for a particular UAS operation depends on multiple factors considered in the safety case for that operation. The safety case key aspects and tradeoffs are discussed in Section 2 of this report.

Whether a UAS operation is VLOS or BVLOS does not determine or dictate what type of spectrum (i.e., government, licensed, or unlicensed) may, must, or must not be used. However, the type of spectrum used does affect the likelihood of disruption of the spectrum-dependent functions. For example, radios operated in unlicensed spectrum are not entitled to regulatory protection against interference from other licensed and unlicensed users in the band. Although FCC device certification rules and standardized protocols help to mitigate RFI, users of unlicensed spectrum must accept any RFI caused by all FCC-compliant devices operating in the band. No matter what type of spectrum is used, appropriate safety-risk mitigations must be in place for the occasions when RFI or frequency congestion disrupts UAS functions that help ensure flight safety and help safeguard human life and property (i.e., safety-related UAS functions[9]).

For all UAS operations (i.e., those within or beyond the pilot's visual line of sight), radiocommunication and radionavigation services used by a UAS DAA capability must use licensed or federal government spectrum that has appropriate allocations and regulatory protections that mitigate RFI. Because the DAA capability is intended to safeguard human life in manned aircraft and

---

[9] A "safety-related" function (also called a "safety-involved" function) is a function whose malfunction or design error has the potential to lead to safety being compromised, either directly or indirectly. A "safety-critical" function is one whose malfunction or design error directly and significantly increases the potential for loss of human life. Safety-critical functions always are safety-related functions, but safety-related functions may or may not be safety-critical functions. Safety-related functions in one context may be safety-critical functions in another context. For example, a UAS C2 link always is safety-critical when the UA is operated in FAA-controlled airspace, but may only be safety-related when the UA is operated outside FAA-controlled airspace.

on the ground and because the DAA capability is relied upon as the principal means of safeguarding human life during periods of lost C2 link, unlicensed spectrum must not be used.

For BVLOS operations, use of unlicensed spectrum for some safety-related UAS functions (except those enabling a DAA capability) might be acceptable if the risks to people and property are very low. For example, use of unlicensed spectrum for command and control of unmanned aircraft flown outside FAA-controlled airspace[10] at very low altitudes in rural areas over large agricultural fields might be acceptable. Although the unmanned aircraft could lose its C2 link because of RFI or frequency congestion, it could have other safety-risk mitigations that do not use radio services. For example, those mitigations could include automatic parachutes and frangible designs that reduce to acceptable levels the maximum kinetic energy the UA could transfer to people or property. For most BVLOS operations, however, the simultaneous disruption of multiple UAS safety-related functions caused by RFI or frequency congestion likely would not meet the FAA's safety requirements and thus likely would necessitate a more reliable type of spectrum (i.e., licensed or federal government).

Improving spectrum utilization in federal government bands is in line with the federal government's objective to facilitate United States (U.S.) economic growth through improved spectrum use.

In summary, the key principles for the proposed concepts are for UAS operators to use the L-band and C-band in ways that do not conflict with incumbent users, and that maintain aviation safety as the highest priority while facilitating further UAS integration in the NAS and improving spectrum utilization when possible.

Concepts of Use

As required by Section 374, this report describes some possible ways the L-band and C-band could be used by UAS and identifies technological, operational, and regulatory barriers potentially hindering such use. The concepts are preliminary and need to be explored, refined, and further coordinated with stakeholders to become viable and evolve to implementation.

In this executive summary, we highlight the key aspects of the concepts at a high level. The body of the report further describes these concepts and provides detail and further insight on potential opportunities and barriers in implementing them.

L-band Concept of Use

L-band (960-1164 MHz) is used extensively for aeronautical radionavigation services (ARNS), and by aircraft surveillance. Due to the importance of the safety functions performed by these systems, previous requests to share this band have been denied by the FAA. To answer the question under Section 374 whether UAS C2 services should be permitted, but not required, in the L-band on a shared or exclusive basis, the FAA examined whether such services could be permitted while at the same time providing the protection needed for radionavigation use.

The concept investigated for the L-band is explained in Section 3, as well as the key technological and operational barriers and opportunities related to implementing that concept. Regulatory barriers are explained in Section 6.2.

[10] "FAA-controlled airspace" means Class A, B, C, D, and E airspace. Although the FAA establishes regulations for aircraft and flight operations in all airspace classes, it does not provide air traffic control services in Class G "uncontrolled" airspace.

For UAS C2 links, L-band use would need to be location- and altitude-specific in order to ensure protection of existing aviation services; that is, if successful, different portions of the band may be available for use at specific locations up to specific altitudes. Most likely, this use would occur at low altitudes such that radio transmission range is limited—mitigating potential interference to incumbent systems. This report refers to areas where UAS C2 link usage would be enabled as "three-dimensional (3D) whitespace" (or in aviation terminology: "service volumes"), as illustrated notionally in Figure ES-1. (See Appendix B for details about this analysis.)

The analysis performed to assess this concept shows that while there may be useful frequencies in certain areas, severe limitations on availability exist across the country. The 1-MHz channels shown as available in a location are most likely not contiguously available at that location. Several additional constraints are expected beyond aspects considered in the analysis performed. Those include the planned FAA expansion in number of DME sites and the size of service volumes, and potential RF congestion with existing military communication system, which has not been assessed. While further analysis would be needed to fully assess those aspects, it is likely that these limitations may make the use of whitespace for UAS C2 impractical for nationwide implementation.

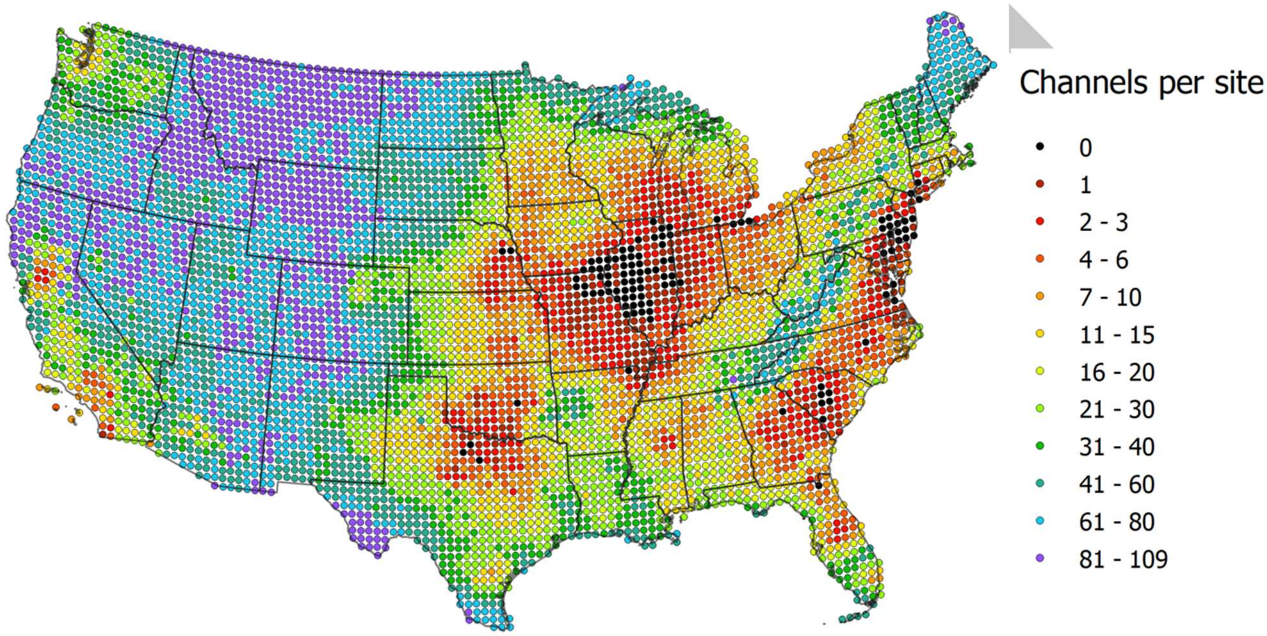

Figure ES-1. Early Estimate of Numbers of 1-MHz DME Channels Potentially Usable for C2 by UA Flying 400 Feet Above Ground Level at Each of 5,496 Sites in the Contiguous U.S.

In addition to the C2 use of L-band, the FAA investigated repurposing a dedicated nationwide channel from its current navigation function for cooperative unmanned aircraft surveillance[11]. Using a new UA surveillance channel, each UA could broadcast its location and other pertinent information needed for unmanned air traffic management and collision avoidance capabilities (UAS to UAS). The capability is similar to those for manned aircraft but would be designed specifically to meet UAS operational needs. The concept is similar to Automatic Dependent Surveillance-Broadcast (ADS-B),

[11] An aeronautical surveillance system is one that "provides the aircraft position and other related information to ATM and/or airborne users" (ICAO Doc 9924 [47]).

where there is real-time position and shared situational awareness, but would be operating on a different channel within the L-band than manned air traffic[12]. Collaborative and contractual partnership with industry would be required to develop such capabilities and infrastructure.

C-band Concept of Use

The concept proposed for the C-band is explained in Section 4, as are the key technological and operational barriers and opportunities related to implementing it. Related regulatory barriers are described in Section 6.3.

C-band (5030-5091 MHz) was formerly used for the Microwave Landing System (MLS), which is no longer in operation. The FAA currently permits C-band use on a temporary basis by UAS operators at specified locations. These temporary authorizations are part of the FAA's forward-looking plan to enable this band's wider use for UAS C2 links.

This band would be used first and foremost for UAS C2 links. As capacity permits, the band could also be used for other UAS functions that contribute to safety of flight (e.g., UA-UA message exchanges for collision avoidance maneuver coordination), and optionally, with an even lower priority and with capacity permitting, also include downlinking of low-bandwidth payload[13] data (e.g., from UAS mission sensors) not necessary for ensuring safety and regularity of flight, as long as such use would not interfere with the safety-related functions using the band.[14] High-bandwidth payload video and other high-bandwidth payload data streams are not recommended within this concept due to their excessive use of this limited aviation spectrum intended to help ensure flight safety and regularity.

Different radio link technologies could be used, and alternative architectures could include both networked and non-networked (i.e., paired-radio) solutions.

For a standalone (non-networked) solution, RTCA currently is evolving its initial C2 Data Link Minimum Operational Performance Standards (MOPS) document, RTCA DO-362 [1], which was developed for a terrestrial-radio solution that supports a low density of UAS and long-range communication.

Networked solutions are expected to be a common need for many UA traveling beyond local distances and at a wide range of altitudes. Ground-based cellular communications network infrastructure and services might support many such UAS operations. Use of these various radio link technologies must be coordinated to avoid performance issues. Ideally, a performance standard would be developed to allow for maximum flexibility of creative network concepts with minimal guidelines that assure no interference between networks that could negatively affect any network's performance.

[12] A UAS surveillance channel should operate separate from those allocated for manned ADS-B (978Mhz Universal Access Transceiver and 1090MHz Extended Squitter)

[13] Regulatory changes in the allocation may be needed to allow spectrum use for UAS functions that are not related to safety or regularity of flight (such as UAS low bandwidth mission sensor data). For further detail see section 6.3.

[14] This concept does not prejudge the FCC's response to the related proposal in the Aerospace Industries Association's (AIA) petition to adopt service rules for UAS command and control in the C-band, RM-11798 (https://www.fcc.gov/ecfs/filing/10209988018431) . In its petition, AIA states the "The commission should restrict the use of the UAS allocation in the 5030-5091 to safety-of-life communications". The concept proposed in this report, if implemented, would expand the scope of usability of the C-band beyond what has been proposed in the AIA petition as a secondary use of the band, when and where the band is available, and as long as not interfering with the primary use for safety-related functions.

The high-level concept for UAS C2 links enabled in several environments is illustrated in Figure ES-2.

In line with the principle to increase spectrum utilization, the potential to use C-band for other UAS functions beyond C2 links should be explored. Such use would increase spectrum utilization by allowing unused capacity, by time and location, to be used for other UAS services. Priority would always be given to C2 links to enable safe UAS operations.

During early stakeholder engagements while developing this report, the FAA raised the possibility of also allowing this spectrum to be used for non-UAS functions in the circumstance of excess capacity. Most stakeholders reacted with concerns related to the need for protected spectrum to be reserved for UAS safety-related functions such as C2. Additionally, stakeholders pointed out that, given the scarcity of spectrum available for UAS, the possibility of excess capacity is extremely remote, and the band will be fully utilized by UAS in the near future. Therefore, the possibility of allowing the C-band to be used for non-UAS functions was not further considered and is not included in the proposed concept for C-band use.

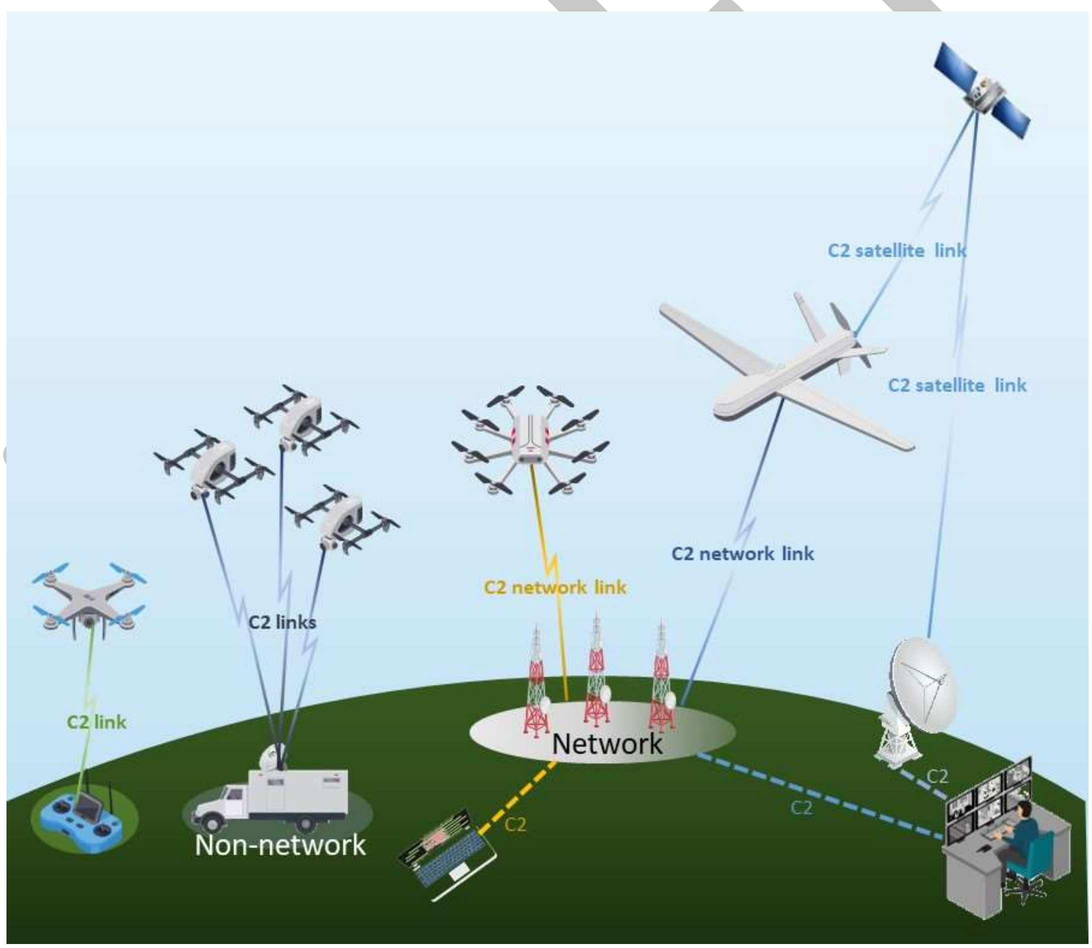

Figure ES-2. High-Level Concept of UAS C2 Links in Several Environments

Other Bands

The L-band and C-band discussed above are not the only options for UAS wireless communications. As described in Section 5, alternatives exist. The choice of appropriate spectrum for a particular UAS operation depends on the safety risks and safety-risk mitigations associated with that operation.

Unlicensed spectrum has a low bar to entry since no one party has exclusive use of the band. At the same time, users of unlicensed spectrum do not have regulatory interference protection, therefore are required to operate with an expectation that RFI and significant sources of radio frequency interference are likely in urban and suburban areas.

Mobile services[15] spectrum, used by terrestrial cellular radio networks, is exclusively licensed and used by an extensively deployed network infrastructure. Stakeholder feedback has demonstrated strong interest in further pursuing the use of commercial cellular bands and networks for UAS services.

Satellite communications spectrum generally is exclusively licensed. Satellite communications networks allow UA to fly nearly anywhere on Earth and still be in communication with the remote pilot. They have a niche for serving UA flying large distances at high altitudes.

Additionally, various vertical markets have licensed niche spectrum for specific purposes that could include UAS services (e.g., railroad and powerline inspections). These alternatives include preexisting radio spectrum licenses (other than cellular) that could be utilized, with appropriate FCC approval, by UAS for specific vertical markets.

Regulatory and Policy Considerations

The FAA is committed to enabling safe UAS operations while sustaining incumbent aviation systems that require use of protected, de-conflicted spectrum. This could include the dynamic sharing of L-band and C-band spectrum provided that incumbent L-band aviation systems and services are adequately protected from interference and provided that UAS C2 links are given the highest service priority in the C-band. National and international spectrum allocations for aviation are intended to safeguard human life, both in aircraft and on the ground. Although UAS are unmanned, there is a need to protect safety of people on manned aircraft, as well as the safety of people on the ground, from hazards presented by UA attributable to loss of the C2 link. Some policy and regulations would need to be revised to realize the concepts described in this report, but to our knowledge there are no statutes that would prohibit them. The FAA is committed to working with industry to develop systems that enable safe UAS operations and at the same time allow for new uses of federal government spectrum.

Recommendations

The FAA plans to continue developing the concepts in this report. We stand ready to work with industry stakeholders as appropriate to mature the proposed concepts, validate and refine

---

[15] The term "mobile service" means a radio communication service carried on between mobile stations or receivers and land stations, and by mobile stations communicating among themselves (47 U.S.C. §§153(33)). The U.S. Table of Frequency Allocations includes mobile service allocations in bands used for commercial mobile radio service (CMRS) and for private mobile radio service (PMRS) (https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf)

implementation approaches, and address the questions and challenges identified in this report and any identified by others.

The next steps for moving forward include:

- FAA's Office of Unmanned Aircraft Systems Integration (AUS), as the designated FAA Office of Primary Responsibility (OPR), will manage the follow-on work related to Section 374 from the aviation perspective. Objectives include:
  - Working with NTIA OPR moving forward, especially on federal licensing process.
  - Working with FCC OPR, especially on integrating non-federal UAS licenses with the national airspace plan.
  - Establishment of safety requirements for UAS use of designated spectrum bands.
  - Establishment of principles to ensure equitable access to designated spectrum bands.

- Orchestration of collaboration between any interested industry stakeholders (inclusive of UAS operators, manned aviation, aerospace manufacturers, UAS service suppliers, communication service providers, air traffic service providers) to provide input to assist in maturing proposed concepts, validating and refining implementation approaches identified in this report. Possible objectives for this stakeholder group could include:
  - Development of concepts of operation and high-level system architecture for each band including rules of engagement; to include mechanisms to dynamically manage frequency assignments to be used by UAS operators and to manage access to spectrum.
  - Validation and documentation of proposed concepts through data from field tests and the results of existing and new studies.

Table of Contents

List of Figures

1 INTRODUCTION

1.1 Objective

This report, prepared by the Federal Aviation Administration (FAA) and including valuable input from the National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC), responds to Section 374 of the FAA Reauthorization Act of 2018 (Public Law 115-254), which provides:

> *SEC. 374. SPECTRUM.*
>
> *(a) REPORT.—Not later than 270 days after the date of enactment of this Act, and after consultation with relevant stakeholders, the Administrator of the Federal Aviation Administration, the National Telecommunications and Information Administration, and the Federal Communications Commission, shall submit to the Committee on Commerce, Science, and Transportation of the Senate, the Committee on Transportation and Infrastructure of the House of Representatives, and the Committee on Energy and Commerce of the House of Representatives a report*
>
> *(1) on whether unmanned aircraft systems operations should be permitted, but not required, to operate on spectrum that was recommended for allocation for AM(R)S and control links for UAS by the World Radio Conferences in 2007 (L-band, 960-1164 MHz) and 2012 (C-band, 5030-5091 MHz), on an unlicensed, shared, or exclusive basis, for operations within the UTM system or outside of such a system;*
>
> *(2) that addresses any technological, statutory, regulatory, and operational barriers to the use of such spectrum; and*
>
> *(3) that, if it is determined that some spectrum frequencies are not suitable for beyond-visual-line-of-sight operations by unmanned aircraft systems, includes recommendations of other spectrum frequencies that may be appropriate for such operations.*
>
> *(b) **NO EFFECT ON OTHER SPECTRUM**.— The report required under subsection (a) does not prohibit or delay use of any licensed spectrum to satisfy control links, tracking, diagnostics, payload communications, collision avoidance, and other functions for unmanned aircraft systems operations.*

It presents concepts for potential use of these bands developed by the FAA with inputs from the FCC and the NTIA. These concepts reflect the primary objective of enabling safe UAS operations while also facilitating United States (U.S.) economic growth through more efficient use of federal government spectrum. The FAA developed these concepts also in consultation with aerospace and wireless communications industries. The FAA welcomes continued collaboration with, and new ideas from, all stakeholders.

Section 374 refers to AM(R)S, an abbreviation for aeronautical mobile (route) services. Spectrum bands allocated to AM(R)S are used for radiocommunication services essential for the safety and regularity of flight (ITU, 2016). Section 374 specifically refers to AM(R)S allocations for L and C bands. The specific frequencies and background is as follows:

- The L-band, in the 960-1164 Megahertz (MHz) range, is used extensively for aeronautical radionavigation services (ARNS) and is also used for aircraft surveillance and military communications. In 2007, the International Telecommunications Union (ITU) revised its Radio Regulations (RR) by adding an AM(R)S allocation to this band. The ITU added this allocation for future digital air/ground communications systems, which permits this band to be used for unmanned aircraft system (UAS) command and control (C2) and other safety-related radio communications.
- The C-band, in the 5030-5091 MHz range, was formerly used for Microwave Landing Systems (MLS). It currently has temporary assignments used by companies exploring this band's use for UAS C2 links. In 2012, the ITU added an AM(R)S allocation to this band specifically for the air/ground radio segment of UAS C2 links.[16]

In common usage, "L-band" and "C-band" encompass wider swaths of the radio frequency (RF) spectrum than the specific sub-bands indicated above. However, in this report these terms mean the two smaller band ranges identified in Section 374.

Subsequent to the allocation actions of the ITU, the FCC added identical allocations in the U.S. Table of Frequency Allocations (FCC, 2019). Since both bands have primary allocations for aviation services, their use in the U.S. is to meet FAA requirements for ensuring the safety and regularity of flight.

Once the FCC, in coordination with the FAA, establishes service rules for access to and use of these bands by UAS operators, the bands would be available.[17] All UAS operations, both public (e.g., government, law enforcement) and civil (e.g., commercial, hobbyist), could use these bands for radionavigation and safety-related UAS radiocommunications (including communication of aircraft surveillance data[18]).

Section 374 poses the question whether UAS operations should be permitted to use these bands on an unlicensed, shared, or exclusive basis, for operations within or outside a UTM system. As used in this document, "band sharing" could occur on networked or non-networked bases as well as on geographic or temporal bases. Use of the L-band and C-band should be on a shared basis among UAS operators since there is insufficient spectrum available to make exclusive frequency assignments for discrete UAS operations, other than in limited numbers and locations for test and evaluation purposes. Furthermore, exclusive frequency assignments are not necessary because nearly all UAS

[16] In 2007 the ITU made an allocation in C-band for the aeronautical mobile-satellite (route) service (AMS(R)S) for satellite communications (SATCOM) links to both manned and unmanned aircraft.

[17] The Aerospace Industries Association and others filed a "Petition To Adopt Service Rules for Unmanned Aircraft Systems Command and Control in the 5030-5091 MHz Band", RM- 11798 (https://www.fcc.gov/ecfs/filing/042644009469). The concepts discussed in this report do not prejudge the FCC decision relating to the AIA petition.

[18] An aeronautical surveillance system is one that "provides the aircraft position and other related information to ATM and/or airborne users" (ICAO Doc 9924 [47]).

operations do not persist indefinitely in time or location. In addition, exclusive licensing of frequencies in spectrum bands allocated for aviation services is not allowed under existing rules.[19]

L-band is used by many existing systems that help ensure aviation safety, including Distance Measuring Equipment (DME), Tactical Air Navigation System (TACAN), Secondary Surveillance Radar (SSR), Automatic Dependent Surveillance – Broadcast (ADS-B), and the Traffic Alert and Collision Avoidance System (TCAS). These and other L-band systems, such as the U.S. military's Joint Tactical Information Distribution System (JTIDS), have location-specific frequency assignments that are deconflicted with adjacent assignments. Since exclusive mobile frequency assignments cannot be made while satisfying the national spectrum policy efficiency objectives, it is necessary that L-band be used on a shared, non-exclusive basis.

Use of either band would require use of FAA-approved or FAA-certified radios built in accordance to government-accepted standards. FAA approval or certification of radios is needed to ensure proper band usage so that all band users have a high likelihood of obtaining the expected radio link performance. Also, this FAA approval or certification helps ensure that radios used in these bands do not interfere with radios used in nearby bands. Radio devices certified by the FCC under 47 CFR 15 or 47 CFR 18 for use in unlicensed bands are not permitted to be used in L-band or C-band. Such FCC certification is focused on compliance with its various technical requirements, such as power, frequency, and bandwidth.[20]

1.2 Approach for Stakeholder Consultation

The statute directed the FAA, NTIA, and FCC to submit a report, after consulting with relevant stakeholders, to respond upon to the questions posed by Section 374.

The FAA has pursued a collaborative approach in the concept development and exploration of alternatives. The FAA consulted with stakeholders to refine preliminary concepts, propose alternatives, and assess their feasibility and potential benefits and challenges. To make sure that relevant external stakeholders were reached, stakeholders were identified using a three-pronged approach:

- The stakeholder self-identified by initiating contact with the FAA.
- The stakeholder was identified by FAA and affiliated subject matter experts.
- The stakeholder was identified by another stakeholder as relevant.

To consult relevant stakeholders during the development of this report, as directed by Congress, the FAA adopted the following process:

- The FAA developed a draft overview of the report, which included feedback from the NTIA and FCC. That overview contained a preliminary description of the concepts being considered for inclusion in the final report. The FAA then issued the overview on October 18, 2019, to relevant stakeholders for review and comment over one month.

[19] Section 87.41 of 47 CFR states that aviation frequencies are available for assignment on a shared basis only and that they will not be assigned for the exclusive use of any licensee.

[20] Although air safety rules are not directly addressed in the FCC equipment approval process, applications for certain bands require FAA concurrence or coordination.

- Several stakeholders responded to this request by providing written comments on the overview. To ensure the stakeholder comments were fully understood all relevant stakeholders were also invited to a roundtable meeting. During the roundtable meeting on January 21, 2020, the FAA shed more light on the concepts and approach in the overview and stakeholders had an opportunity to explain their comments. The FAA used the stakeholder comments, both written and oral comments provided during the roundtable meeting, in preparing this report.
- On November 25, 2019, the FCC initiated a request for public comment regarding Section 374 (FCC, 25 November 2019). The period for public comment closed on January 27, 2020.
- The FAA considered input from the FCC and the NTIA in preparing this report.

1.3 Existing Spectrum Allocations

1.3.1 Existing Allocations

Radio spectrum having the following two aviation service allocations can be used for UAS C2 links:

- The AM(R)S allocation in L-band
- The AM(R)S allocation in C-band[21]

Spectrum outside these bands may be used for UAS C2 links, as long as the operator's safety case for the UAS operation is acceptable (i.e., as long as the FAA approves the UAS operation upon finding the operation's safety-risk level acceptable). The connection between safety-case approval and spectrum choices for a given UAS operation is explained in Section 2.

1.3.2 Allocation History

The international AM(R)S allocation for the 960-1164 MHz band was made by the ITU at the 2007 World Radiocommunication Conference (WRC-07). That allocation was made on the condition that AM(R)S users of the band not interfere with the aeronautical radionavigation services (ARNS) already using the band. UAS C2 terrestrial links are one type of AM(R)S use but were not specifically mentioned in the allocation.

The international AM(R)S allocation for the 5030-5091 MHz band was made at the 2012 WRC (WRC-12). The FCC followed up that action in March 2017 by issuing Report and Order 17-33 to allocate the band in the U.S. for UAS C2 links.[22]

[21] There is also an AMS(R)S allocation in C-band for satellite-based communications.

[22] WRC-07 also granted the AMS(R)S allocation in the 5030-5091 MHz band, also on the condition of non-interference with incumbent radionavigation systems, and with the understanding that satellite-based C2 links are only one type of possible AMS(R)S user.

1.4 Assumptions and Constraints

The following assumptions and constraints guided development of the concepts and potential alternatives.

Assumptions:

- UAS operations will occur at all altitudes, as defined in Appendix F.
- Existing infrastructure and network services provided by the commercial wireless industry may be available and suitable for some UAS operations. Radio coverage and link performance may improve as the wireless industry enhances the cellular networks to better serve aerial users.
- UAS operators are responsible for C2 link provision since C2 links are part of UAS. Because C2 links are integral to UAS and do not connect to the FAA's air traffic control (ATC) system, the federal government will not provide or operate the communications network infrastructure needed to provide them. However, the FAA may impose performance requirements on UAS C2 links, as it does for other NAS users, to help ensure safety.

Constraints driven by key principles:

- Consider possible opportunities for the concepts to advance or complement national spectrum policy.
- Consider possible opportunities for the concepts to advance or complement U.S. 5th Generation (5G) wireless communication initiatives.
- C-band AMS(R)S solutions in the future will need to be assessed for coexistence with any AM(R)S solutions implemented in the C-band.

1.5 Scope and Key Terms

Appendix F, Key Terms, defines the key terms used throughout this report.

This report addresses UAS operations that occur:

- Within the pilot's visual line of sight (VLOS) and beyond it (BVLOS)
- Within radio line of sight (RLOS) and beyond it (BRLOS)
- At all altitudes
- Under ATC provided by the FAA or under UAS Traffic Management (UTM) provided by UAS Service Suppliers (USS)

It addresses all types of radio spectrum, which are described in Appendix F:

- Unlicensed
- Licensed
- Federal government

Definition of the term "control link" for this report:

The following set of safety-related[23] UAS functions is within scope and are included in the term "control links" used in Section 374, subsection (a)(1). These functions definitely use or may use RF spectrum for communications. To varying degrees in various UAS designs and environments, they help ensure the safety and regularity of UAS flight operations:

1. Uplink of telecommand messages from the control station (CS) to the UA.
2. Downlink of UA non-payload telemetry data to the CS.
3. Data exchange between the CS and the UA for the purpose of collision avoidance.
4. UA pilot voice and data communications with air traffic controllers when the UAS is operated within the U.S. ATC system or with USS personnel when operated under the UTM system.
5. Uplink of current data needed for on-board UA geofencing; that is, for the UA to keep itself within or outside specific airspace volumes.
6. Uplink of navaids setting changes and other relevant navigation data from CS to UA.
7. Exchange of information related to hazardous weather, including uplink (for use by the UA), and/or downlink (for use by the remote pilot and potentially by others).
8. Downlink of video from the UA to the CS in some takeoff, landing, or emergency situations, for safety assurance purposes.
9. UA reporting its position to the UA pilot for informed flight control and to other people and systems for aircraft surveillance and collision avoidance (i.e., DAA).
10. UA broadcasting its state vector (e.g., identification, position, altitude, velocity) for informing others, including other UA, pilots of other UA, USS, and ATC, for surveillance of the UA in support of air traffic management and aircraft collision avoidance.
11. UA-to-UA data exchange to coordinate flight maneuvers, including but not limited to maneuvers for:
    - Staying well clear of other UA
    - Avoiding imminent collisions with other UA
    - Sequencing and spacing with other UA.
12. UA receiving navigation data from ground-based navaids (such as multilateration data) to help the UA navigate on its own accord.

A note on C2 terminology: In this report, the term "command and control" (C2) refers to the subset of the functions listed above that involves the exchange of safety-related information between the CS and the UA. C2 excludes functions such as UA broadcast of state vectors (e.g., cooperative

[23] A "safety-related" function (also called a "safety-involved" function) is a function whose malfunction or design error has the potential to lead to safety being compromised, either directly or indirectly. A "safety-critical" function is one whose malfunction or design error directly and significantly increases the potential for loss of human life. Safety-critical functions always are safety-related functions, but safety-related functions may or may not be safety-critical functions. Safety-related functions in one context may be safety-critical functions in another context. For example, a UAS C2 link always is safety-critical when the UA is operated in FAA-controlled (Class A, B, C, D, E) airspace, but might only be safety-related when the UA is operated in uncontrolled (Class G) airspace.

surveillance, in item 10), UA-UA links (e.g., for aircraft DAA purposes, item 11) or UA navigation data communications (item 12). Those functions are discussed separately when appropriate.

Therefore, functions 1 to 9 are part of C2. Functions 10 to 12, although needed for ensuring safety and regularity of flight, are not part of C2.

Additionally, the term C2 in this report is roughly equivalent in scope to the term used by the ITU and RTCA, which is Control and Non-Payload Communications (CNPC) (ITU Radiocommunication Sector, December 2009).

Functions not included in the term "control link"

The following UAS functions require use of RF spectrum but are not needed for ensuring the safety and regularity of flight. Therefore, they are outside the scope of the inquiry under subsection (a)(1) of the Section 374. They are discussed in this report as non-safety-related UAS functions, where relevant.

- Remote control of mission sensors on the UA (i.e., sensors not needed for UA flight control and thus not safety related).
- Downlinking data from mission sensors on the UA (i.e., the UA payload).
- Downlinking of video streams from mission sensors (i.e., UA payload video)
- Broadcasting information needed for remote identification of the UA, for homeland security or law enforcement purposes.

2 SPECTRUM SELECTION FOR SAFETY ASSURANCE

UAS may use many radio spectrum bands, subject to the requirements and constraints imposed under existing law by the band allocations and by entities licensed to use them for private or commercial purposes. Most UAS safety-related functions may use federal government spectrum allocated for aeronautical services, licensed spectrum, or unlicensed spectrum. However, as explained below, functions that enable UAS DAA capabilities must not use unlicensed spectrum. Although federal government aeronautical bands are well suited for safety-related UAS functions, use of other bands is permitted as long as the required overall safety level for the UAS operation can be achieved. Other potential bands include licensed spectrum allocated by the ITU and FCC for mobile services[24] and, for some low-risk UAS operations and non-safety-critical UAS functions, unlicensed spectrum.

2.1 UAS Safety Case

The decision about which radio band(s) is/are appropriate to be used for a UAS operation depends on multiple factors. From the FAA's perspective, safe UAS operations in the national airspace is paramount. Key factors that contribute to a UAS operation's safety include:

- Pilot training and experience
- UAS safety features, such as the capability to detect and avoid (DAA) other aircraft
- UA design and construction, including the UA's weight, materials, and frangibility
- UA flight altitudes and speeds
- UA flight procedures, including procedures executed in the event of a lost C2 link
- The airspace in which the UA flight occurs, and the types and numbers of other aircraft operating within that airspace
- The susceptibility of people and property on the ground to injury or damage from the UA.

UAS C2 link performance is an important factor in the UAS operation's safety. However, C2 link performance requirements are not absolute; they must be determined in full consideration of the potential safety hazards and the safety-risk mitigations in place. For example, highly automated UA with high-performing, on-board DAA capabilities may not require robust C2 links. Also, a small UA operated in Class G airspace (in which FAA does not provide ATC services) over a large, sparsely populated agricultural area with very few unsheltered people on the ground vulnerable to injury from the UA, a poorly performing C2 link may suffice. For such an extremely low-risk UAS operation, a C2 link implemented in an unlicensed band, which has no guarantee of radio link performance, might suffice to achieve the operation's required safety level.

The radio band used for the C2 link can influence radio link performance given the protection and non-interference requirements associated with the band. In addition to the radio band, other factors influence radio link performance. These additional factors include radio design and implementation, communications network design and implementation, and management of band access. For example, a well-managed mobile service band used by a well-designed, well-managed network serving well-

[24] The term "mobile service" means a radio communication service carried on between mobile stations or receivers and land stations, and by mobile stations communicating among themselves (47 U.S.C. §§153(33)). The U.S. Table of Frequency Allocations includes mobile service allocations from bands used for commercial mobile radio service (CMRS) and for private mobile radio service (PMRS) (https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf)

regulated mobile radios might provide radio link performance sufficient for UAS operations in urban areas. The resulting radio link performance potentially could be higher than the performance achievable with aviation-specific networks using bands that have AM(R)S or AMS(R)S allocations.

Under existing law and practice, the determination of appropriate radio bands or band allocations for safety-related UAS functions is made on a case-by-case basis. The UAS operation's safety case both accounts for and drives UAS functionality requirements and subsystem performance requirements. The performance requirements for each UAS subsystem, including the C2 link, is determined through a holistic analysis of safety risks, considering all potential safety hazards and all safety-risk mitigations in play. As long as the required overall safety level for a UAS operation can be achieved and sustained, any UAS C2 link system implementation could prove acceptable to the FAA whether the system uses unlicensed, licensed, or federal government spectrum. For UAS operations in FAA-controlled airspace, however, the C2 link changes from safety-related to safety-critical because it is the principal function relied upon by the pilot to maneuver the UA in response to air traffic controller directives. (If the C2 link is the only means of communications between the pilot and air traffic controller, it is safety-critical for this reason too.)

The FAA applies general principles and guidelines when determining spectrum requirements for UAS operations. For example, unlicensed spectrum should only be used for safety-related (i.e., not safety-critical) UAS functions in low-risk UAS operations outside FAA-controlled airspace. Because any number of users could be using the same unlicensed band simultaneously in close proximity, the performance of the radio links cannot be guaranteed. In one analytic study (Box, Globus, Snow, & Monticone, October 2018) about using unlicensed bands for C2 links in low-altitude UA operations, significant limitations on the radio link range (with acceptable link performance) were discovered. Depending on the radio frequency, the needed C2 link availability, the UA altitude, the UA receiver sensitivity, the geographic location, the ground environment (urban or suburban), and the signal propagation model, the maximum link distance ranged from a few meters to tens of kilometers. As modeled, the radio link performance results were reduced significantly in the presence of RFI. Based on this analysis, a UAS operator would need to assume a C2 link in an unlicensed band could be lost and hence would need to implement safety-risk mitigations to ensure the UAS operation's required safety level can be sustained during periods of lost C2 link.

2.2 Relevance of BVLOS to Spectrum Selection

The question of whether the UA is operated within or beyond the pilot's visual line of sight (VLOS or BVLOS) is relevant in assessing the operation's safety, but it does not determine or dictate what type of radio spectrum (i.e., government, licensed, or unlicensed) is appropriate for that operation. However, the spectrum type does affect the likelihood of disruption of spectrum-dependent safety-related UAS functions. Appropriate safety-risk mitigations must be in place for the occasions when RFI or frequency congestion disrupts safety-related functions.

Unlicensed spectrum is the type of spectrum most susceptible to unintentional RFI. The FCC regulations that govern radio devices using unlicensed spectrum (47 CFR Part 15 and Part 18) state that RFI must be expected and accepted. Radios operated in unlicensed spectrum have no regulatory protection against RFI from other licensed and unlicensed users operating in the band. Although FCC rules for device certification and standardized protocols help mitigate RFI, users of unlicensed spectrum must accept any RFI caused by FCC-compliant devices in the band.

In contrast, licensed and federal government spectrum have regulatory protections tailored to their allocations. Nonetheless, users of such spectrum may still experience RFI. Hence, UAS operators would need to consider the possibility of RFI-induced disruption to spectrum-dependent, safety-related functions. Based on those considerations, operators must establish mitigations to maintain the UAS operation's required safety level during such disruptions.

In BVLOS UAS operations, detecting and avoiding other aircraft can be much more challenging than it is in VLOS operations. The pilot requires information about other aircraft operating near the UA, and the UA might need a DAA capability to automatically avoid collisions with aircraft and obstacles without pilot involvement (e.g., in the event of lost C2 link). The aircraft surveillance information needed for the pilot's or UA's situational awareness can be provided in several ways, including the use of ground-based or UA-based sensors such as radars.

When radar technology is used onboard UA for DAA purposes, it must use spectrum allocated for aeronautical radionavigation services. Licensed spectrum may be used to implement UA-based DAA-related functions that do not use radar technology, for example spectrum allocated for mobile services such as cellular vehicle-to-vehicle communications. In all cases, UAS radiocommunication and radionavigation functions that enable a DAA capability must not use unlicensed spectrum. Because the DAA capability is intended to safeguard human life in manned aircraft and on the ground and because the DAA capability is relied upon by the FAA as the principal means of safeguarding human life during periods of lost C2 link, use of unlicensed spectrum is prohibited.

2.3 Current Uses of Spectrum for UAS Operations

Today, UAS operators and manufacturers are using a variety of spectrum bands for their UAS operations and UAS research and development activities. This use is described briefly here.

Although current UAS operations primarily are VLOS, the demand for BVLOS operations is increasing and hence the demand for radio spectrum needed to enable BVLOS operations is increasing. The FAA has supported and will continue to support the research and development of UAS BVLOS solutions through temporary and experimental frequency assignments.

- Operations of small UAS (whose gross takeoff weight is less than 55 pounds) under 14 CFR 107, which implies the existence of a C2 link, typically use unlicensed spectrum bands. Such operations must be within the remote pilot's visual range, must occur in daylight or twilight, stay below 400 feet AGL or higher if the UA remains within 400 feet of a structure, remain in uncontrolled (Class G) airspace, not exceed 100 miles per hour (87 knots), not fly over people, and not be operated from a moving vehicle. Furthermore, the remote pilot is limited to controlling a single UAS. Although the presumption is that most such UAS operations are relatively low risk, a 55-pound aircraft flying at 100 miles per hour 5 ft AGL could be quite lethal. From a safety perspective, use of unlicensed spectrum is not appropriate for such high-risk Part 107 operations, especially in geographic areas in which frequency congestion could be high.
- About 80% of the UAS operations under the FAA's UAS Integration Pilot Program (IPP) use unlicensed bands, and about 20% use licensed terrestrial cellular radio bands that have mobile services allocations. However, a large number of the operations that use unlicensed bands are

likely to transition to use of licensed bands allocated for mobile services. This transition is driven by the challenges encountered in using unlicensed bands, and the FAA's guidance to use other bands that can support more reliable C2 links.

- Several companies are using their own licensed spectrum for their UAS C2 links.
- There are 247 active UAS-related frequency assignments in the C-band[25]. Some of these assignments are experimental licenses for UAS research and development, and some are temporary licenses for initial business operations in strictly limited geographic areas and time periods. The FAA has not approved any permanent C-band frequency assignments[26].

[25] These represent frequency assignment applications approved by the FAA and forwarded to NTIA for its assignment or coordination

[26] This band is not available for permanent frequency assignments. Service rules have not been set for the C-band yet.

3 CONCEPT FOR USE OF L-BAND

Existing incumbent federal government services and operations present a substantial barrier to use of this band. Due to the importance of the aeronautical radionavigation systems that rely on it, previous requests to share this band have been denied by the FAA due to the need to provide continued, un-impacted operation of equipment used to ensure flight safety. To answer the question under Section 374 whether UAS C2 services should be permitted, but not required, in the L-band on a shared or exclusive basis, the FAA examined whether such services could be permitted while providing the protection needed for radionavigation use.

The FAA has used a collaborative approach to develop potential concepts and explore alternatives. The concepts discussed here, as well as the potential opportunities and barriers, consider comments from stakeholders that helped refine preliminary concepts for the use of the whitespace spectrum for UAS C2 and also the possibility of reserving a nationwide channel for cooperative UAS surveillance in the L-band. Policy considerations for the use of this band are discussed in Section 6 of this report. The FAA plans to continue assessing feasibility for this concept, while affording higher priority to work on the C-band, which is discussed under section 4. The FAA stands ready to advise and assist interested stakeholders, as appropriate, on further concept development, implementation, and operations.

3.1 L-band Concept

The key principle for the proposed concept is for UAS operators to use this spectrum in ways that will not conflict with existing incumbents and preserve safety as the highest priority, while increasing spectrum utilization when possible.

The existing L-band users are summarized below:

- Aeronautical navigation aids (Distance Measuring Equipment [DME] and Tactical Air Navigation System [TACAN]), required for safe manned-aircraft operations
- Aircraft surveillance systems[27] (Secondary Surveillance Radar [SSR] and Automatic Dependent Surveillance Broadcast [ADS-B]) and collision avoidance[28] (Traffic Alert and Collision Avoidance System [TCAS]) systems, also required for safe manned-aircraft operations
- A military communication system[29] variously called Joint Tactical Information Distribution System (JTIDS), Multifunctional Information Distribution System (MIDS), or Link 16, which operates in this band on a non-interference basis under a Memorandum of Agreement (MOA) with the Department of Transportation (DOT).[30]

[27] These include SSR and ADS-B systems.

[28] Specifically, the TCAS and the future Airborne Collision Avoidance System X (ACAS X).

[29] JTIDS and MIDS are components of Link 16, which is a highly survivable radio communication system that uses spread-spectrum technology (a form of radio communications in which the transmitted signal's frequency is intentionally varied, resulting in wideband, noise-like signals that are hard to detect, intercept, or demodulate).

[30] The terms of the DOT-DoD agreements for JTIDS operations in the 960-1215 MHz band are described in Section 4.3.17 of the NTIA's "Manual of Regulations and Procedures for Federal Radio Frequency Management" (Sep-2017 revision).

The FAA's uses of this band for navigation and surveillance for airborne manned aircraft are primarily based on fixed-location ground sites for reception from and transmission to such aircraft. FAA's uses typically involve signals at medium to high power levels. The hypothesis for the use of this band by UAS is that there are opportunities for additional use of the band at low altitude. UAS would employ lower power transmissions on frequencies used only by distant ground transceivers (and hence not by nearby aircraft).

3.1.1 Use of L-band Whitespace for UAS C2

For UAS C2 links, L-band use would be location- and altitude-dependent; that is, different portions of the band may be available for use at specific locations up to specific altitudes. Most likely, this use would be restricted to small UAS (sUAS) flying at low altitudes such that radio transmission range is limited—mitigating potential interference to incumbent systems. This report refers to locations where UAS C2 link usage would be permitted as "three-dimensional (3D) whitespace" (or in aviation terminology: "service volumes").

In this concept, the FAA would establish the required spectrum protection criteria to ensure safety of incumbent operations in this band, and would provide electronic maps that define where available frequencies are spatially located. Such electronic maps would be updated regularly and on demand by the FAA as changes in the existing systems occur, increasing or decreasing the frequencies available for UAS as a result. UAS operators would have to take into account changes in available frequencies when planning UAS operations.

The FAA has performed a preliminary analysis (see Appendix B) to assess the feasibility of using L-band 3D whitespace for UAS C2. The analysis was performed on a grid of 5,946 points, spaced roughly 20 nautical miles (nmi) apart, across the contiguous United States (CONUS). An automated simulation tool estimated the number of 1-MHz DME channels potentially usable at each of the 5,946 sites without undue risk to existing DME, TACAN or other receivers anywhere in the country.

Figure 3-1 graphically depicts the results of the analysis. The color of each circular dot represents the number of DME channels estimated to be usable by a 1-watt UA C2 transmitter flying 400 feet above terrain at the site at the center of the circle. The observed variations in channel usability result mainly from local variations in the numbers of nearby DMEs and TACANs and from the shielding effects of terrain. Channel usability at points between the selected sites undoubtedly differs somewhat from that at the sites themselves, but the relative consistency of dot colors for adjacent sites indicates that nearby points tend to have similar amounts of available whitespace.

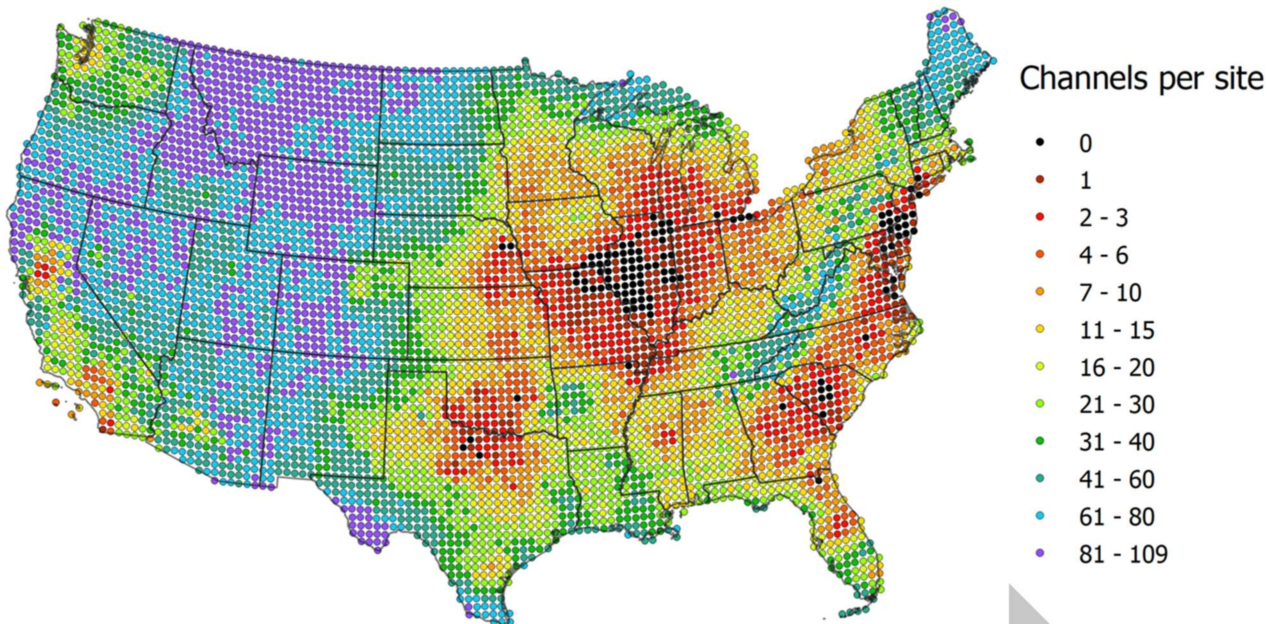

Figure 3-1. Early Estimate of Numbers of 1-MHz DME Channels Potentially Usable for C2 by UA Flying 400 Feet Above Ground Level at Each of 5,496 Sites in CONUS

USS, as described in the FAA's UTM concept (FAA, 2020), would need automated methods to allocate and manage allowed UAS frequencies on an as-demanded basis. Any allocations found to cause interference to existing aviation and military systems would be withdrawn from consideration by modifying the FAA mapping database to prevent interference recurrence. The reason for the interference would be examined with a view to modifying or "fine tuning" the withdrawn allocation to enable its return to UAS use. Additionally, unforeseen needs related to special aviation or military circumstances may also trigger updates to the map database reflecting changes in the availability of frequencies for UAS use. These needs may be temporary or permanent, and modifications would remain in place for the duration of the need.

The analysis performed to assess this concept shows that while there may be useful frequencies in certain areas, severe limitations on availability exist across the country. Furthermore, even where multiple frequencies are shown as available, they refer to 1-MHz channels, which are most likely not contiguously available at a location. The analysis reflects the current assignment of DME channels, but DME expansion is expected to increase the number of DME sites and the size of service volumes, therefore reducing potential availability of whitespace. Additionally, a large proportion of the channels shown as potentially usable in Figure 3-1 overlap with the bands also utilized by the JTIDS (Link-16) system. Potential RF congestion with UAS and JTIDS systems has not been assessed in this initial study and could present additional constraints for the use of whitespace for UAS. While further analysis would need to be performed, it is likely that these limitations may make the use of whitespace for UAS C2 impractical for nationwide implementation.

3.1.2 Nationwide Channel for UAS Cooperative Surveillance

An additional component of this concept supports cooperative UA surveillance. As discussed in Section 3.2.1, cooperative aircraft surveillance is the concept that aircraft carry equipment that either broadcasts information about the aircraft or is interrogated by ground radars and may reply with information such as the altitude and a unique identifier for the aircraft. A dedicated nationwide L-band channel would be repurposed from its current navigation function. Using this channel, each UA would broadcast its location and other pertinent information needed for cooperative UAS surveillance and collision avoidance capabilities (UAS to UAS).

These capabilities are similar to those for manned aircraft (SSR, ADS-B, and TCAS) where there is real-time position and shared situational awareness, but they would be designed specifically to meet UAS operational needs and would be operating on a different channel within the L-band. Suitably equipped UA would receive broadcasts from nearby manned aircraft and UA, and if requested manned aircraft could receive broadcasts from nearby UA (e.g., public-service helicopters). FAA ATC could, if requested, receive information about UA operating near terminal airspace. A USS could receive information about manned aircraft needed to ensure safe UA operation by providing that information to the UA. Appendix D presents this concept in greater detail.

Such a system could help address issues relating to separation assurance and collision avoidance among UA for BVLOS UAS operations. Industry has questions about the feasibility of a designated nationwide channel to enable such capabilities. Further study with federal government and industry will help define the concept further. Industry support and commitment to develop, evaluate, test and deploy such a system is required.

The concepts proposed here for L-band, comprising the use of whitespace spectrum for UAS C2 and reserving a nationwide channel for cooperative UAS surveillance, would increase both the use and the utility of L-band spectrum. The L-band whitespace would provide aeronautical spectrum, where available, for C2 links for low-altitude UAS operations. A nationwide cooperative UA surveillance channel would help enable a UAS detect and avoid capability, which is essential for enabling BVLOS UAS operations. Additionally, utilizing the whitespace spectrum in an ongoing, continuously updated and coordinated manner could help ensure continued availability of the L-band spectrum, which is needed for manned-aircraft navigation and surveillance functions.

3.1.3 Federal Government Role

As to the use of L-band whitespace spectrum for UAS C2, the FAA would not deploy or operate any communications network, nor would it manage day-to-day band use. However, related regulatory functions would remain with FAA, NTIA, and FCC. For the FAA, these functions include development of UAS C2 link performance requirements, protection of L-band for incumbent aviation users, and UA operational approvals based on safety cases prepared by UAS operators.

To protect the incumbent systems and services, the FAA would determine requirements and constraints on UAS use of L-band. The FAA also would electronically publish up-to-date 3D whitespace maps; that is, frequencies available within designated regions of low-altitude airspace.

With respect to the nationwide broadcast channel for cooperative UA surveillance, the FAA would identify the potential frequencies to be used. Additionally, the FAA would need to coordinate with industry and global partners on developing a new, unique identification method for UA surveillance. A new surveillance identification method is outside the scope of the remote identification (Remote ID) concepts and requirements, as it is intended for traffic management functions and not identification functions. A unique identification is required to enable a receiver to distinguish and track aircraft for UA traffic management, necessary for aviation safety. Current ICAO addresses are not sufficient, as the expected large number of UAS could quickly exceed the number of unique addresses possible in the current method. It is recommended that the new surveillance identification be interoperable with as many NextGen air traffic management systems as possible. UAS Remote ID is outside this report's scope.

3.1.4 Industry Role

Industry would need to deploy new networks or modify existing networks to enable C2 links where needed for sUAS BVLOS operations. Industry would develop an approach, and if needed, a system, for managing sUAS C2 link frequency assignments. Such a capability would use the electronic maps of 3D whitespace published by the FAA.

Industry would need to design, develop, deploy, and operate the C2 link systems, including the radios on the UA, and the networks and radios on the ground.

If this band were to be used for a cooperative UA surveillance capability, industry would collaborate with the FAA to develop the standards, design and manufacture the aircraft components, obtain FAA certification of the aircraft components, and install and operate the aircraft components per FAA requirements.

3.2 Potential Opportunities and Barriers

3.2.1 Incumbent Systems and Services

Several federal government systems and services already operate in L-band. A careful consideration of barriers to using L-band for UAS requires a comprehensive exploration of current uses. A full explanation of the details of each system is beyond this report's scope, but this report provides an overview of the incumbent systems and frequency allocations.

The 960-1164 MHz band is part of a larger band, 960-1215 MHz, that has served the ARNS for several decades. Figure 3-2 depicts the global frequency allocation and assignment structure of this larger band. ARNS systems operating throughout the 960-1215 MHz band include the civilian DME system, the U.S. military TACAN system, and a Russian navigation system not compliant with ICAO standards and not used in the U.S.

DME, invented in the 1950s, is a navigational aid that measures the distance between the aircraft and a known ground location. The concept is that the pilot or aircraft automation knows its approximate location accurately enough to use a table lookup to identify nearby DME station frequencies and locations. Then interrogation pulses are broadcast from the aircraft for receipt by a nearby ground transceiver. Upon receipt of the interrogation pulse, the ground beacon returns pulses on a different but paired channel. The aircraft can compute the difference between the transmit and reply pulse times and infer its distance from the DME site.

GPS is the principal means of navigation for most aircraft in the U.S. However, GPS signals are only transmitted at 40 watts, from satellites over 12,000 miles away. This low power is an inherent vulnerability, so an alternative navigation system is required for safety. DME is currently the FAA's primary alternative navigational aid for civil aircraft. By interrogating multiple DME stations, a modern civil aircraft can accurately determine its geographic location in a manner independent of GPS. To improve navigation resiliency, the FAA's NextGen DME program is currently deploying additional DME sites. As currently envisioned, this deployment will include over one hundred new DME stations, principally around major metropolitan areas to support air carrier operations into the largest airports in CONUS.

TACAN is a military navigation system with the same specification as DME for distance measurement, but it also provides azimuth information. This additional function allows a military aircraft to determine its position relative to a TACAN station by combining the distance, the azimuth, and the known location of the station.

The adjacent 1164-1215 MHz band has a primary allocation for the radionavigation-satellite service (RNSS). This allocation is used by GPS, the European Galileo system, and other foreign satellite navigation systems. Any RNSS system that provides global coverage, such as GPS and Galileo, is called a global navigation satellite system (GNSS). ICAO takes a broader view and defines GNSS as the global collection of satellite navigation systems, augmentation systems, and airborne equipment.

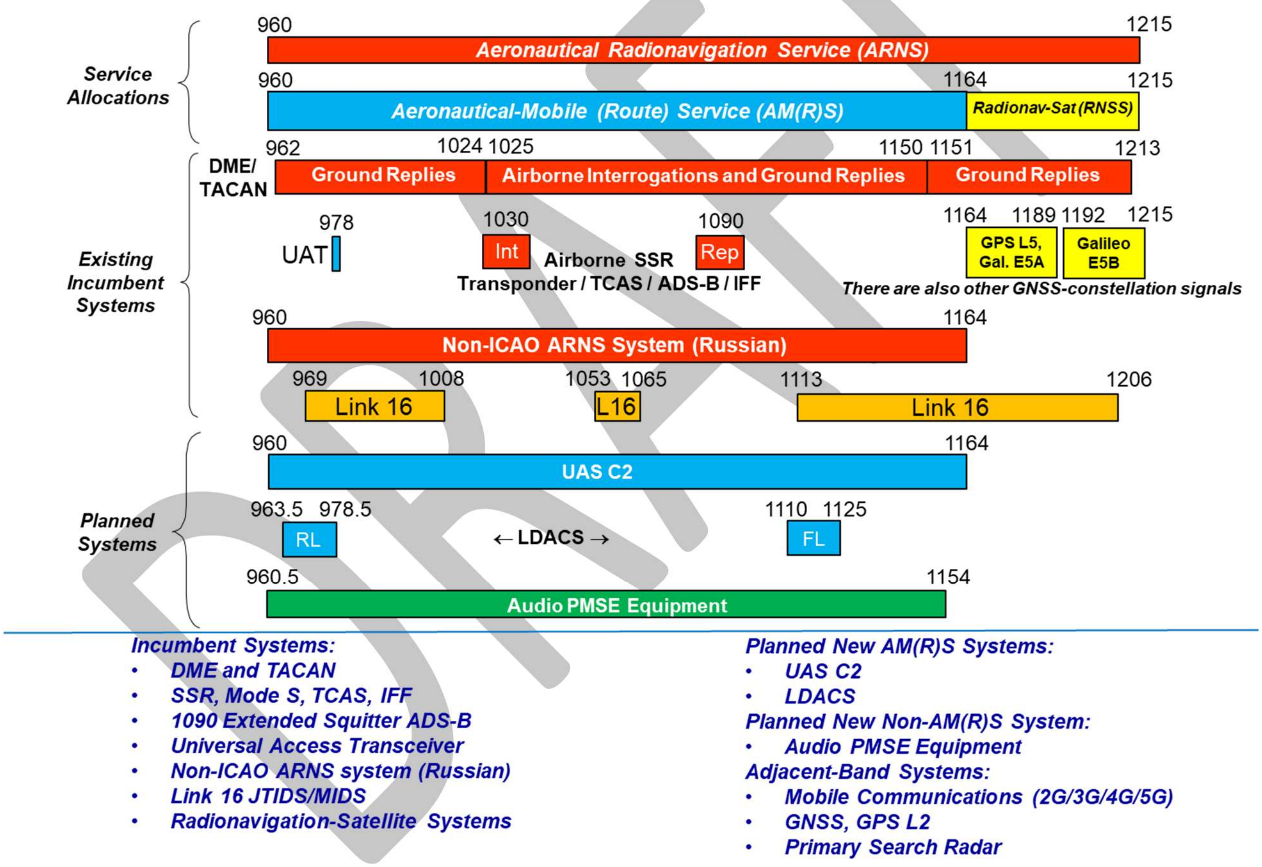

Figure 3-2. Systems and Services in the 960-1215 MHz Band

For many decades, cooperative aircraft surveillance (in which the aircraft electronically participate in the surveillance function) for ATC has been provided by SSRs, which interrogate aircraft transponders on 1030 MHz. The transponders reply on 1090 MHz. Similar transponders also are used in the aircraft-based TCAS and in the U.S. military Identification Friend or Foe (IFF) system. These three systems (SSR, TCAS, and IFF) require interference protection across the 1021-1039 MHz and 1081-1099 MHz sub-bands.

ADS-B is another means of providing cooperative aircraft surveillance for ATC. It has been required in certain airspace volumes since January 1, 2020. In ADS-B, aircraft regularly broadcast their GPS-derived positions without prompting by interrogations. ADS-B uses two data links on separate frequencies. The Universal Access Transceiver (UAT) link operates on 978 MHz, and the Mode-S Extended Squitter (ES) link operates on 1090 MHz. The Mode-S ES ADS-B link is designed to coexist with SSRs and TCAS, which also operate on 1090 MHz.

The U.S. military JTIDS and MIDS, also known as Link 16, operate within this band on 51 hopping channels with carrier center frequencies spaced 3 MHz apart. The center frequencies of the channels are in three sub-bands: fourteen in the 969-1008 MHz sub-band, five in the 1053-1065 MHz sub-band, and thirty-two in the 1113-1206 MHz sub-band. By design, Link 16 is jam-resistant, so its performance is not impaired by non-hostile systems operating in these sub-bands. Appendix C describes the Link 16 system in more detail and explains how UAS C2 links in the L-band whitespace could coexist with Link 16 operation.

Figure 3-3 depicts use of the 960-1215 MHz band by ground-based transmitters in the U.S., as listed in an unclassified 2019 frequency-assignment database. Most of these transmitters belong to DME and TACAN beacons, which are ground-based. Not shown in the figure is frequency use by airborne DME and TACAN interrogators, JTIDS transmitters, systems operating at 1030 or 1090 MHz, and certain non-DME/TACAN transmitters using "fractional-MHz" frequencies such as 1017.23 MHz.

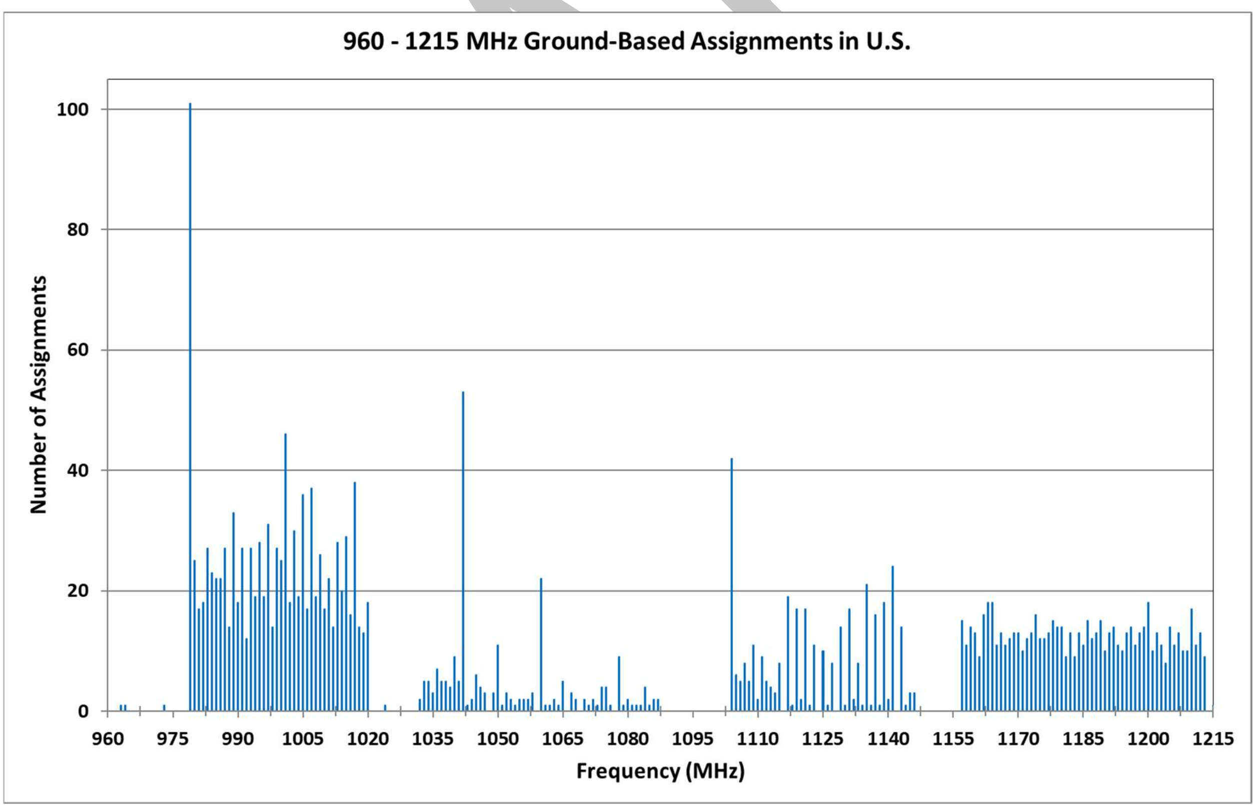

Figure 3-3. Ground-Based 960-1215 MHz U.S. Frequency Assignments in 2019

AM(R)S is a radiocommunication service dedicated to the safety and regularity of flight. Since 2007, AM(R)S has had a primary allocation in the 960-1164 MHz band, subject to the requirement of non-interference with the ARNS. FAA has worked with RTCA in the U.S. to define standards for UAS C2 links in this band. ICAO is also defining standards in Europe for forward link (FL) and reverse ink (RL) of the L-Band Digital Aeronautical Communications System (LDACS) for ATC communications. In the U.K., but not in the U.S., a non-AM(R)S communications system for Programme Making and Special Events (PMSE) is used for UAS operations.

3.2.2 Potential Technological Opportunities and Barriers

L-band is particularly valuable for many applications due to propagation characteristics. L-band radio links have a high enough frequency to provide significant data-transfer capacity, while still being able to penetrate most structures. Many cellular communication services in operation today use spectrum near the DME band (although not in the 960–1164 MHz band addressed in this report) because of these attributes. While DME was state-of-the-art when it was invented in the 1950s, modern signaling methods allow for much more efficient use of spectrum. With the FAA's current spectrum protection methods, DME fully uses its spectrum band in congested locations such as New York City. However, there is significant unused DME spectrum in less-congested locations such as North Dakota.

Current DME spectrum-protection guidelines conservatively assume an interfering signal is of equal power and has similar signal characteristics. That is, the guidelines are designed to protect DME stations against interference from other DME stations. The guidelines restrict not only signals on the same channel, but also signals on adjacent channels.

Some of the incumbent systems require dedicated spectrum that is protected against interference from the adjacent DME channels. Systems such as ADS-B UAT that use spectrum adjacent to DME channels show that it is feasible to use adjacent channels in a non-interfering way. Similarly, JTIDS is designed to operate by hopping among multiple frequencies, which makes it more secure and interference resistant. JTIDS is permitted to operate in L-band on a non-interfering basis. During times of national emergency, JTIDS use of the band can be prioritized over other users.

A potential barrier to the use of whitespace spectrum is the fact that the highest density of navigation aids and corresponding use of L-band spectrum occur around major airports, which constrains the likelihood of safely using this spectrum for UAS in those areas. Those are also typically the most densely populated areas. Feasibility analysis should be performed to fully assess these environments.

Given the rapid development of the UAS industry and the existing spectrum demand for UAS, the report focuses on ways to enable coexistence of UAS in the L-band in the shortest time frame. Changes to existing avionics and systems that could release more spectrum for UAS use typically take long periods to implement, due to the need to replace or redesign aviation electronics that have a significantly longer lifecycle. Concepts that do not require significant changes to the incumbent systems (such as the whitespace approach) have the possibility of being implemented in a much shorter timeframe.

Some far reaching opportunities to increase L-band availability are discussed below, but it is beyond this report's scope to provide further depth in this area, because they require much longer periods to implement.

- The evolution of ground-based navigation systems to provide a robust backup for Global Positioning System (GPS)-based navigation could make more L-band spectrum available for

UAS use. Opportunities in this category are longer-term and may require significant investment to be implemented. They include:

- Synchronizing the timing of all Distance Measuring Equipment (DME) stations and transmitting a time message in addition to the current DME transmissions. Aircraft with conventional DME equipment would not be affected, but aircraft with new DME equipment would passively receive the signal. Removing the need for aircraft to interrogate the DME stations would, over time, reduce the demand for DME spectrum and hence make L-band spectrum available for other uses.
- Implementation of a modernized long-range navigation (LORAN) system might allow for the complete divestment of all current Very-High Frequency Omnidirectional Range (VOR) and DME systems in the NAS, which would make their spectrum available for other uses. However, doing so would necessitate costly and lengthy avionics equipage changes across the commercial and general aviation aircraft fleets. This aircraft equipage transition would likely have to be driven by FAA rulemaking.
- Other Alternative Position, Navigation and Timing (APNT) technologies that are being explored by both the private and public sector.[31]

- There may be additional far reaching opportunities for L-band use based on dynamically sensing the spectrum and identifying specific areas of availability. However, assuring safety of the incumbent system would pose additional challenges to implementing such solution, as simply sensing (even if perfect) does not guarantee that the signal is not about to be utilized in the next moment. While sensing the channels could be used in combination with whitespace databases as a method to increase safety assurance in the whitespace approach, sensing alone is not considered a safe method in itself.

3.2.3 Potential Operational Opportunities and Barriers

While GNSS has become the primary means of air navigation, it has shortcomings. Because the signal originates from satellites powered by solar arrays, it is inherently a very low-power signal and thus radio interference is a concern. Aircraft position determination by triangulation using multiple DME stations is the current alternative form of navigation to GNSS for aircraft at high altitudes and in the U.S.'s busiest terminal areas.

To fully protect air carrier operations from the threat of interference with GNSS, the FAA's NextGen DME program is currently planning to deploy new DMEs to provide complete high altitude en-route coverage and terminal coverage to the 62 largest airports in CONUS. This program deployed two new DMEs in 2019 and is expected to deploy an additional five DMEs in 2020 and more in the following years. In total, the program plans to activate more than 100 new DME sites, most of which would be located around major metropolitan areas further restricting the use of the band from UA. In addition, as part of this program, the service volume of a large portion of the existing DME sites will be expanded. All these changes will further reduce the available channels shown in Figure 3-1, particularly in major urban areas, further restricting the use of the band for UA.

Besides the upcoming expansion of the DME system, other changes that affect 3D whitespace availability are expected on an ongoing basis. Because of changes in manned-aircraft traffic demand

[31] https://insidegnss.com/11-firms-chosen-to-demonstrate-gps-backup-technologies/

and routes, navigation aids undergo periodic re-planning of coverage and hence require retuning of frequency channels. These ongoing changes would result in a need to regularly update the electronic 3D whitespace maps; they underlie the dynamic nature of spectrum availability for UAS C2 use.

Considering that those changes are completely tied to the national airspace system operations, it would be challenging for UAS operators to independently identify available L-band spectrum. An automated system managed by the FAA to identify the available spectrum would be preferred. This automated system of identifying and mapping available L-band spectrum could be designed, developed, and deployed by the FAA.

A capability would also be needed for actively determining spectrum utilization in order to monitor interference and ensure protection to navigation systems. This system would require automated recognition of interference and action to resolve that interference (e.g., by updating the 3D whitespace maps). Such a system would also assess spectrum utilization by UAS.

The initial cost and resources needed to develop such an automated system have a direct correlation to the system's timely availability and wide distribution. While concepts may be tested and developed in the short term, a gradual rollout may be required as demand dictates and resources permit, to avoid a longer delay in establishing the nationwide capability. Stakeholders' feedback on this concept have pointed to the complexity and difficulty to implement, and that it may take years to make it operational.

Compared with C-band, L-band propagation has lower losses in non-line-of-sight conditions, such as in the presence of buildings and trees. Hence, L-band would work well for UA flown at low altitudes where ground clutter is at play. Additionally, L-band frequencies have less loss in signal strength than C-band frequencies, which means they offer greater C2 link coverage ranges for the same amount of power. Hence, if L-Band is used for a network solution, fewer ground communication sites would be needed to provide comparable radio coverage.

Stakeholders have expressed concern about protecting incumbents from potential interference with unmanned aircraft systems. Some support continued investigation and testing of unused DME spectrum using new technologies so long as it does not interfere with safe manned aircraft operations.

4 CONCEPT FOR USE OF C-BAND

For the C-band the FAA has also used a collaborative approach to develop concepts and explore alternatives for the C-band. The concept discussed here, as well as the potential opportunities and barriers, considers comments from stakeholders that helped refine preliminary concepts for the use of this band. Policy is included in Section 6 of this report. The FAA plans to continue and prioritize work in the C-band. The FAA stands ready to advise and assist interested stakeholders, as appropriate, on further concept development, implementation, and operations.

The FAA recognizes industry concerns that access to the C-band is urgently needed on a more routine basis. For this reason, while not providing a comprehensive plan for future use of the C-band in this report, we plan to prioritize work on the C band (over L-band developments) for future work.

4.1 C-band Concept

4.1.1 Use of C-band for UAS with Priority for C2

For C-band, there are no long-term incumbents.[32] The FAA has supported the reservation of C-band for UA use internationally via the ITU WRC process (ITU Radiocommunication Sector, December 2009) (ITU Radiocommunication Sector, November 2011), which resulted in provisions in the international spectrum-allocation tables enabling UAS use of this band. At this point, the FAA sees no need to restrict access to C-band to certain types of UAS operations, but notes the priorities for use listed below.

In this concept, the C-band would be used solely for UAS control links (defined in Section 1.5 as control link functions between the control station (CS) and the unmanned aircraft (UA)), with priority for C2 functions. As capacity permits, the band could also be used for other safety-related UAS control link functions (e.g., broadcasting and UA-UA messages for collision avoidance), and optionally, with a lower priority and capacity-permitting, also include low bandwidth payload data (e.g., mission sensors) not needed for ensuring the safety and regularity of flight[33], as long as such use would not interfere with the safety-related functions using the band. High bandwidth payload video and other high bandwidth payload data streams are not practicable within this concept due to their excessive use of this spectrum intended for functions that help ensure the safety and regularity of flight.

BRLOS operation of UA depends on a network for C2 link connectivity. C-band is a contiguous frequency range available nationwide. Therefore, a nationwide C2 network may be easier to implement in C-band where there is a significant amount of contiguous spectrum available nationwide. This is a strong advantage compared to the L-band, described in the previous section, in which geographical gaps exist in availability at every frequency, creating challenges to achieving contiguous nationwide coverage).

Currently, the C-band frequencies are allocated for the now-retired MLS. This MLS allocation is currently codified in 47 CFR 300, which references NTIA's *Manual of Regulations and Procedures for Federal Radio Frequency Management* (NTIA, Revision of the September 2015 Edition, September 2017)[34]. The FAA recommends that NTIA modify this manual to remove all references to MLS.

In the U.S., this band currently is used for UAS C2 links in a preliminary, temporary manner. The purpose of this preliminary use is to promote exploratory UAS C2 link development to inform future regulation and standards development. The FAA has proposed a possible channel plan for UAS C2 link use and has enabled testing between 5040 and 5050 MHz to maintain a 10-MHz margin of safety against potential interference to future GPS receivers in the 5010–5030 MHz band.

C-band will work well for medium altitudes (i.e., above local ground clutter, such as buildings and trees), where aircraft would fly mostly within RLOS to network towers. UAS flying at medium altitudes will encounter every type of manned aircraft, so systems will be needed to deconflict flight

[32] A limited number of temporary licenses exist for experimental UAS operations.

[33] Regulatory changes in the allocation may be needed to allow spectrum use for UAS functions that are not related to safety or regularity of flight (such as UAS low bandwidth mission sensor data). For further detail see section 6.3.

[34] The MLS allocation is also mentioned in the U.S. Table of Frequency Allocations, footnote US444

paths and avoid collisions. UAS missions above 400 ft AGL continue to be identified and refined. They include local linear infrastructure inspection and local aerial survey, as described in RTCA DO-377 (RTCA, March 2019). Additionally, some UAS package delivery operations may use airspace above 400 ft AGL, but generally will operate below 1000 ft AGL. The Urban Air Mobility (UAM) concept of a flying city taxi for transporting people and cargo short distances is envisioned to use airspace between 1000 and 3000 ft AGL.

Architectures for implementing C2 radio links can include terrestrial non-networked and networked, satellite-based, aircraft-based (e.g., via UA or balloons used as network nodes), or any combination thereof. Some of these alternatives are illustrated in Figure 4-1.

The concept proposed for use of the C-band encompasses different C2 link solutions and technologies, depending on the type of operation and required range of communications. The vision includes a partition of the band across non-networked (or paired) and network solutions.[35] The amount of spectrum for each type of use is not defined at this point.

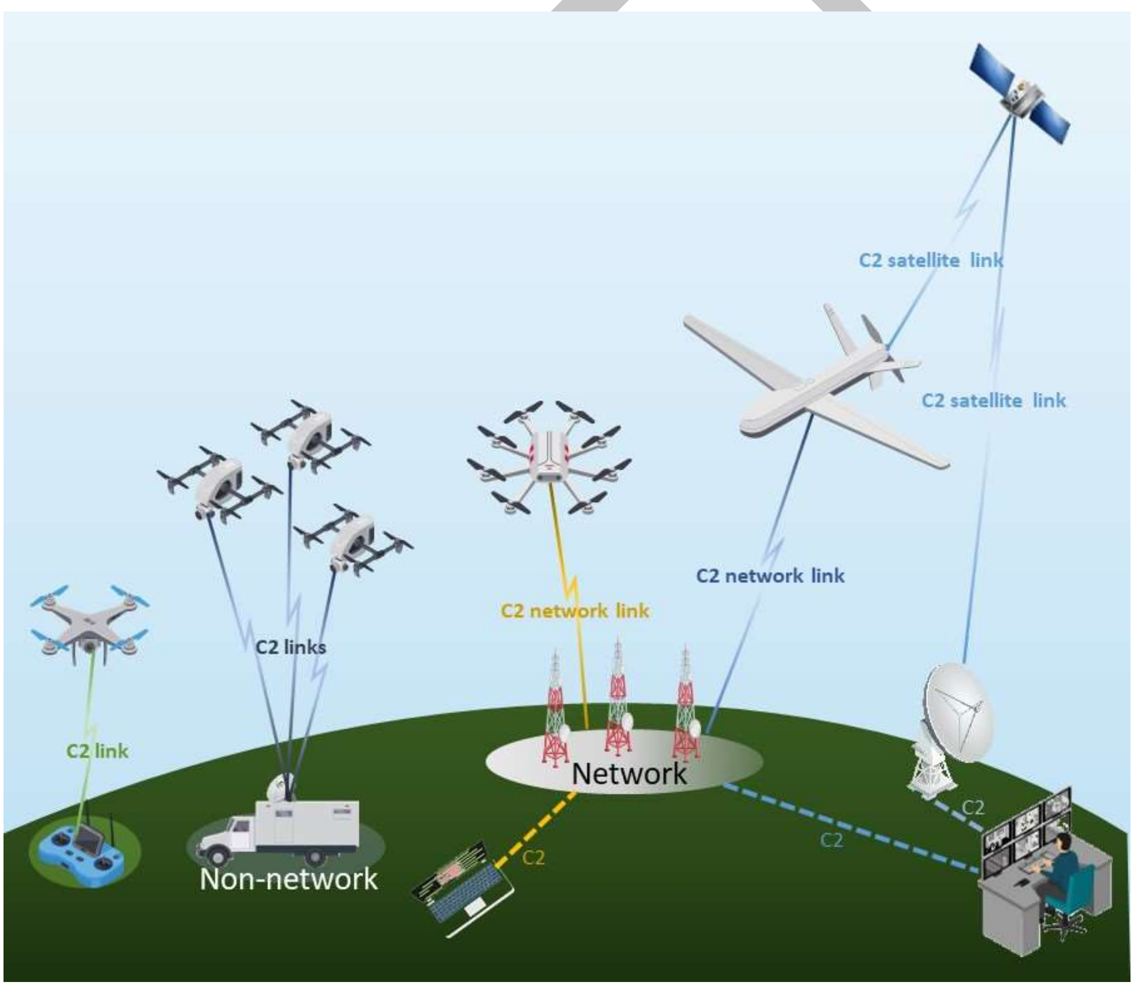

Figure 4-1. High-Level Concept of UAS C2 Links in Several Environments

[35] Satellite links are not within this report's scope.

With a non-networked solution, the UA operates within radio line of sight (RLOS) of the control station, i.e., there is a single, direct radio link between the UA and its control station. This allows operation in BVLOS because radio signals often can travel way beyond the pilot's visual range and, depending on the radio frequency (RF) used, sometimes can travel through and around obstacles. Atmospheric conditions may shorten or lengthen a radio link's range. However, it does not allow long distance travel as it is likely that the UA would move beyond the range of coverage of a single control station. They can be a good fit for low, medium, and high-altitude local operations.

For the paired solution, RTCA is currently evolving its initial C2 Data Link Minimum Operational Performance Standards (MOPS) document, RTCA DO-362 (RTCA, September 2016), which was developed for a terrestrial-radio solution that supports a low density of UAS long-communication ranges. The FAA has incorporated by reference the RTCA DO-362 MOPS into its Technical Standard Order (TSO)-C213, *Unmanned Aircraft Systems Control and Non-Payload Communications Terrestrial Link System Radios* (FAA, 9 March 2018). Section 4.2.2.1 details characteristics of this solution and how it is evolving.

Networked operations allow transitioning (handoff) the communication link from one ground station to another within the network. Networked solutions are expected to be a common need for many UA traveling beyond local distances and at a wide range of altitudes. Terrestrial-based networks are likely a good fit for low to medium-altitude operations. High altitude, long distance operations are likely best served by satellite networks.

A potential option for networked UAS C2 is the use of commercial cellular network infrastructure, operating in this band for UAS C2 link service. The use of the existing cellular network infrastructure could accelerate UAS BVLOS operations by improving the economic feasibility of providing the needed C2 network services. Existing network infrastructure could potentially have C-band services added to their existing services.

The wireless industry and the UAS community are currently exploring the use of existing cellular networks and standards (e.g., LTE and 5G) to support the communications needs of sUAS at low altitudes. Research, development and flight-testing activities for sUAS at low altitudes are ongoing. This topic is further discussed in Appendix E, which describes existing work exploring the feasibility of current cellular network infrastructure to serve UAS. Additional work is needed to understand feasibility of using cellular network infrastructure to operate in C-band providing C2 services to UAS at low and medium altitudes throughout the NAS.

Approval processes would be needed to ensure that communications services being offered have acceptable performance characteristics. Since C2 link performance depends on factors related to the network design and implementation, the network's offered communications services should meet minimum performance levels to operate those services. Performance factors include expected coverage and availability at desired UA operating volumes, as stated in a UAS operator's safety case to be approved by the FAA.

The C-band concept is in line with the operational, functional, and system views of the C2 Link System defined by RTCA Special Committee (SC)-228 in its C2 Data Link White Paper Phase 2 (RTCA, September 2017). One of the C2 Link System options is a network of terrestrial radio stations providing coverage over a wide geographic area for enabling BVLOS UAS operations.

In this concept, the data backhaul connections[36] and radio towers used in commercial cellular networks would support UAS operations in C-band. Use of this existing commercial cellular infrastructure combined with the availability of C-band spectrum could significantly expedite implementation of a nationwide commercial UAS C2 network.

Allowing use of C-band for other UAS functions beyond C2:[37] During consultation some stakeholders supported considering the feasibility of using the C-band for other safety-related and non-safety-related UAS functions (beyond C2). Doing so would potentially advance the goals of the national spectrum policy and presidential initiatives[38] to improve spectrum utility. The rationale for exploring this option would be to increase spectrum utility by allowing any unused channel capacity to be used for other functions, while giving service priority to UAS C2 functions. This could be enabled both for networked and non-networked scenarios, as long as the communications provider allows the automatic management of priorities for different UAS functions, automatically and dynamically shifting resources across functions based on criticality, as needed. The band would be used first and foremost for UAS C2 links. As capacity permits, the band also could be used for other UAS functions critical to safety of flight (e.g., UA-UA messages for collision avoidance), and optionally, with a lower priority and capacity permitting, include low-bandwidth payload data (e.g., mission sensors) not related to the safety and regularity of flight, as long as such use would not interfere with UAS safety-related functions using the band. High-bandwidth payload video and other high-bandwidth payload data streams are not recommended acceptable under this concept due to their excessive use of this safety-critical spectrum.

Not-allowing use of C-band for non-UAS users: During early engagements while developing this report, the FAA raised to stakeholders the possibility of allowing this spectrum to be used also by non-UAS users in the circumstance of excess capacity after satisfying the demands for UAS services. A cellular network provider would need to configure its systems to allocate network resources dynamically to other users when the band is lightly loaded by UAS use, and back to UAS services as soon as their demand increases. Several stakeholders have strongly reacted with concerns related to the need for protected spectrum to be reserved for safety-critical UAS functions. Additionally, stakeholders pointed out that, given the scarcity of spectrum available for UAS and the increasing number of UA systems and proposed applications, the possibility of excess capacity is extremely remote, and the band will be fully utilized by UAS in the very near future. Therefore, the possibility of allowing the use of this band by non-UAS users was not retained for further consideration in this report and is not included as part of the proposed concept.

---

[36] In a telecommunications network, the backhaul connections are the intermediate links between the core (backbone) network and the small subnetworks at the network's edge. In a cellular network, backhaul connections are used to link radio (cell) towers to the core (backbone) network.

[37] This concept does not prejudge the FCC's response to the related proposal in the Aerospace Industries Association's (AIA) petition to adopt service rules for UAS command and control in the C-band, RM-11798 (https://www.fcc.gov/ecfs/filing/10209988018431) . In its petition, AIA states the "The commission should restrict the use of the UAS allocation in the 5030-5091 to safety-of-life communications". This concept, if implemented, would expand the scope of usability of the C-band beyond what has been proposed in the AIA petition as a secondary use of the band, when and where the band is available, and as long as it does not interfere with the primary use for safety-related functions.

[38] https://www.ntia.doc.gov/category/national-spectrum-strategy

4.1.2 Federal Government Role

The FAA will work with NTIA and FCC to establish the regulatory framework for operations in the band. The framework might also define the potential evolution of these regulations over time (e.g., proportion to potentially partition for network and non-network operations) based on actual use and expected demand within the band.

The FAA would not operate any network or manage day-to-day spectrum use of these bands.

The FAA's primary responsibilities would be related to establishing safety-risk-based performance requirements that, in light of a given UAS operation, level of flight automation, lost-C2-link procedures and other aspects of the safety-case, would help UAS operators determine the required C2 link performance (RTCA, March 2019).

The FAA would establish the minimum communications service performance requirements for networks to start operating in C-band and providing radio services for UAS C2 links. The FAA also would establish certification processes to ensure these performance requirements are met.

The FAA would have an oversight role to ensure the band is used according to the interference protection rules for UAS C2 links, and to ensure that the network's minimum communications service performance requirements are met.

If the use of the C-band for non-safety-related UAS functions is pursued, the FAA would inform the rules for levels of priority given to UAS C2 links relative to non-safety-related uses. The UAS C2 link priority would be based on the degree to which the safety of a given UAS operation depends on the C2 link performance. The FAA also would identify ways for industry to provide evidence of compliance with those rules. That evidence may be achieved through design-based compliance, (i.e., evidence that the system is designed in a way that will automatically behave in compliance with the rules).

4.1.3 Industry Role

Industry would define the paths to be further explored for non-networked and networked solutions, technologies and systems to be supported, and associated demand. These plans will inform the FAA's position, to be coordinated with FCC and NTIA, related to the definition and evolution of partition of this band across network and non-networked solutions.

The availability of equipment for the different standards, and the market evolution and actual use will depend on commercial interests beyond the scope of this report. Therefore, the vision is for this flexibility to be maintained initially to allow both solutions to evolve in parallel.

Non-networked solutions need to evolve (and work is ongoing in that direction, as described in Section 4.1.1) to increase spectral efficiency and allow higher user density.

For networked solutions, cellular standards are evolving to support UAS use, as described in Appendix E. In order to leverage cellular infrastructure to operate on C-band, industry would need to modify their existing cellular networks to enable UAS C2 links on C-band, providing sufficient performance to meet the expected UAS operations safety cases. The use of C-band may result in demand for industry to add network infrastructure to meet desired coverage and performance levels.

Industry would develop an approach, and a system if needed, for managing channel assignments for UAS operations. The capability would need to include initial frequency assignment and the automatic transfer of C2 links between operators as needed.

If a priority approach is pursued to allow service to non-safety-related UAS functions in addition to C2, industry would also need to establish and provide evidence (for FAA certification) of the means to guarantee that priority would be given to safety-related UAS C2 functions over non-safety-related functions at all times.

4.2 Potential Opportunities and Barriers

4.2.1 Incumbent Systems and Services

The 5030-5091 MHz C-band is part of a larger frequency band, 5000-5150 MHz, that is used for a variety of radiocommunication and radionavigation systems and services as shown in Figure 4-2. UAS C2 links that use the 5030-5091 MHz band must do so in a manner that will not result in interference to or from other systems operating within the band or in the adjacent 5000-5030 MHz and 5091-5150 MHz bands.

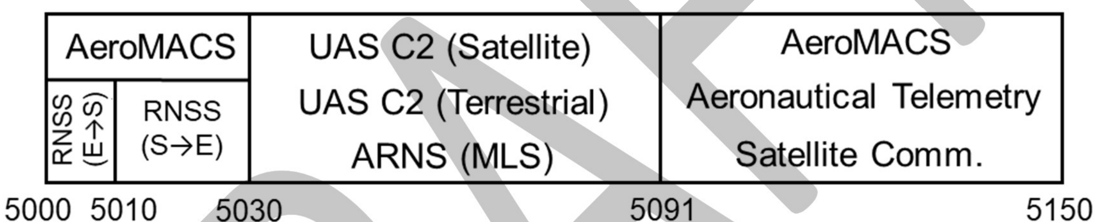

Figure 4-2. Systems and Services in the 5000-5150 MHz Band

The Aeronautical Mobile Airport Communication System (AeroMACS) is a relatively recent AM(R)S system currently being deployed by the FAA that serves as a broadband wireless network for the airport surface. It supports communications for air traffic services and aeronautical operational control of taxiing aircraft and other surface vehicles. AeroMACS is authorized by the FAA to operate in the 5000-5030 and 5091-5150 MHz bands.

The 5000-5010 MHz sub-band is also allocated to the Earth-to-space (E→S) segment of planned future RNSS links intended to improve GNSS performance and availability. The space-to-Earth (S→E) segment of these or other RNSS links has its allocation in the 5010-5030 MHz sub-band.

Under FCC regulations and the NTIA Manual [10], the 5030-5091 MHz band is currently allocated to three separate services: microwave landing systems (MLS), AMS(R)S for future UAS C2 satellite links that will carry pilot/UA messages via satellite relays, and AM(R)S for UAS C2 terrestrial data links that will carry such messages via paths within the Earth's atmosphere. All MLS in the U.S. have been retired. MLS would have provided a radionavigation service at towered airports but was superseded by the widespread use of augmented GPS, in conjunction with legacy systems such as instrument landing systems (ILS), to provide precision landing guidance for aircraft.

4.2.2 Potential Technological Opportunities and Barriers

4.2.2.1 Standalone (Non-Networked) C2 Links

Soon after WRC-12 granted the 5030–5091 MHz AM(R)S allocation in 2012, RTCA established Special Committee (SC)-228 on Unmanned Aircraft Systems, whose initial tasking included the development of standards for non-networked terrestrial UAS C2 data links. In 2016 the committee published the resulting MOPS document, DO-362 (RTCA, September 2016).

DO-362 stipulates time-division duplexing (TDD) to preclude interference among collocated UAS C2 ground-station transmitters and receivers. To prevent "near-far" interference between C2 links whose signal paths differ drastically in length (which can result from a distant desired transmitter being overwhelmed by a strong signal from a nearby undesired transmitter, even when different frequencies are used), DO-362 recommends a minimum 10-nmi separation between C2 ground stations used for takeoff/landing (e.g., at airports) and those used to control UA in en route airspace. FAA TSO-C213 (FAA, 9 March 2018), which is based on the MOPS and was issued in 2018, strengthened that restriction by mandating a 10-nmi minimum separation between any two DO-362-compliant C2 ground stations, even if both are takeoff/landing or both en route. This 10-nmi minimum separation constraint significantly limits the density of UAS that would be allowed to utilize C-band with this solution in a certain area and is seen by industry as a barrier for adoption. This solution would not utilize spectrum efficiently or scale sufficiently to match the demand of the UAS industry.

Soon thereafter, SC-228 began work on an updated standard (DO-362A) that will reduce the minimum separation between C2 ground stations. The improved design achieves that result by means of altitude-dependent power control of airborne transmitters, elevation-plane beam-shaping of ground-based UAS C2 transmitting antennas, and much lower C2-transmitter output noise levels. DO-362A is due to be published in 2020.

SC-228 currently is working with the National Aeronautics and Space Administration (NASA) in NASA's efforts to design a satellite-based UAS C2 link that will utilize the 5030–5091 MHz AMS(R)S[39] allocation while maintaining compatibility with the DO-362A terrestrial system in the same band. The NASA design uses a TDD frame structure compatible with that of DO-362A and will be able to operate throughout the 5030–5091 MHz band, as will the DO-362A system, without mutual interference.

SC-228 has also issued a Minimum Aviation System Performance Standards (MASPS) document, DO-377 (RTCA, March 2019), which partially consists of requirements for the use of networks to support UAS C2 radios, whether or not those networks will use DO-362-compliant radios.

4.2.2.2 Networked C2 Links Using Cellular Technology

The FAA has identified key potential technological barriers related to the concept for use of C-band for UAS operations. The challenges center on the feasibility of establishing viable cellular standards, both well-established (e.g., 4th Generation [4G]/Long Term Evolution [LTE]) and new (e.g., 5G) to assure aviation safety. In other words, there is a need to determine whether such systems can deliver

[39] The AMS(R)S allocation in the C-band is out this report's scope. Coexistence of the AMS(R)S and the AMRS uses of the C-band will need to be assessed in the future.

the performance levels required for safe UAS operations and to prioritize the use of the band for C2 functions over non-safety-related functions. Specific questions include:

1. Can systems based on cellular standards (LTE, 5G) meet UAS C2 link performance requirements needed to ensure that UAS operations will satisfy the FAA's safety assurance requirements?
2. At what altitudes can those systems meet those performance requirements?
3. Can LTE and/or 5G provide priority of service-level agreements for different UAS communication streams (different functions)?
4. Can network base-station handoffs be handled reliably for typical UAS missions expected in mid-altitudes?

Although beyond the scope of this report, a similar set of questions applies to the communications needed for future UAM aircraft, with respect to their communication link performance requirements, priority management for UAM operations (compared to that of non-UAM unmanned systems), handoff, traffic isolation, and prioritization.[40]

Compared with L-band, propagation in C-band suffers more severe losses in non-line-of-sight conditions, such as low-altitude UA flying below local clutter of buildings and trees. However, C-band will work well for medium altitudes (i.e., above local ground clutter), where UA would fly mostly within RLOS of network towers. Initial tests have shown favorable results regarding UA range and altitude. Additionally, C-band frequencies have increased path loss (even when in line of sight) compared to frequencies in lower bands. This range disadvantage, combined with the limited coverage at low angles, may require a larger number of ground communication sites to support connectivity in transit operations (compared to what would be needed with current commercial cellular frequencies that operate in lower bands).

Therefore, while existing cellular infrastructure could be leveraged and start benefiting UAS operations early on in this band, networks may need to increase in ground-station density (densification) if high levels of link availability were needed for the UAS operation to meet the required safety level. Although multiple tests have been performed with cellular networks serving UAS, most of them have targeted low-altitude operations and utilizing current cellular frequencies. To address questions 1 and 2 above, further assessments are needed to understand performance at medium altitudes, using C-band, for different types of UAS operations.

Recent improvements in the standards for 5G networks and radios include advanced features[41] needed to enable cellular networks to support large-scale UAS operations. Those new standards could resolve issues relating to prioritization of UAS C2 streams (question 3 above). These issues have to be fully assessed (including testing) to obtain definitive answers.

In addition to the technological questions concerning use of cellular networks, more work is needed to assess the potential for non-cellular technologies to also operate in this band as well as the potential for them to be used by UAS. Some of the issues include:

---

[40] All still need to be determined.

[41] Such advanced features include network slicing, further enhancements to quality of service mechanisms, and 3D beamforming [44] [45].

- Should the 5030–5091 MHz band be partitioned to allow part of it to operate non-network types of radios (e.g., TSO-C213) and part of it to be allowed for cellular network use?
- How will the frequency assignment function be provided for TSO-C213 radio links?

More work is needed to assess the potential for a partitioning approach to allow non-network and network solutions to operate in this band. Some of the issues include:

- How should the 5030–5091 MHz band be initially partitioned to allow part of it to operate non-network types of radios (e.g., TSO-C213) and part of it to be allowed for cellular network use?
- If the two partitions were to operate in the same area, can TSO-C213 radios coexist on the same tower with cellular radios without causing or suffering interference?

4.2.3 Potential Operational Opportunities and Barriers

The amount of spectrum needed by C2 systems depends heavily on the necessary data rates of the individual UAS, which in turn depends on factors such as:

- The number of C2 control messages that the control station (CS) must uplink to the UA
- The rates at which on-board sensor data must be downlinked to the pilot for sufficient situational awareness needed for safe remote control
- The number of possible aircraft collision threats that must be tracked simultaneously, and the number that must be flagged for consideration by the pilot
- Whether pilot/ATC voice messages must be relayed via the C2 link, or if some other operationally acceptable method for pilot-controller voice communications is available
- Whether video downlinking is necessary for adequate pilot situational awareness (as during takeoff and landing, or when searching for a place to ditch a UA), and if so, at what resolution
- The technology used by the C2 link (since some are more spectrally efficient than others).

Those factors will vary by UA size (small or large) and their environments (ranging from busy airports to high-altitude airspace during good weather). The requirements of higher-altitude UA should be carefully considered. Higher-flying UA have lines of sight to more ground stations, thus tying up more spectrum and ground resources.

Overall bandwidth requirements for a nationwide C2 system should be estimated in order to assess how much spectrum should be reserved for C2. This can be done by computer simulations that consider:

- Expected data traffic profiles per aircraft (e.g., typical data message exchanges, regularity, and message sizes) for different types of operations
- Anticipated geographical distributions of UA for various altitudes, operation types and categories of aircraft, and expected growth over time
- Expected communications performance requirements for different types of operations and safety-risk profiles.

The better understanding of spectrum needs for UAS C2 as described above will allow a more refined assessment of the eventual opportunity to serve UAS under this band. Cellular network coverage is aligned with population density. So, if the existing network infrastructure were to be utilized, UA would fly point to point following population transit routes. Expansion of UA routes away from population corridors will be driven by economic factors including infrastructure cost and value of direct flight.

As additional open areas, the FAA needs to conduct significant work to refine, validate, and implement this concept. Some of the key questions include:

- What are the alternatives to establish a business model for access to communications service providers (e.g., lease or charge fees for spectrum use)?
- How should bandwidth be allocated (partitioned) across non-networked and networked solutions?
- How should bandwidth be allocated to network service providers (e.g., on a competitive basis by region)?
- What should the key requirements for communication service providers be to start offering service within a region utilizing this band?

5 OTHER BANDS

Section 374(a)(3) states that: "if it is determined that some spectrum frequencies are not suitable for beyond-visual -line-of-sight operations by unmanned aircraft systems, includes recommendations of other spectrum frequencies that may be appropriate for such operations." The suitability of spectrum for UAS functions is not determined by whether the UA is operated within or beyond the pilot's visual line of sight, but instead is determined through a holistic analysis of the UAS operations' safety risks and the safety-risk mitigations needed to gain FAA approval for the operation (see Section 2).

Both L-band and C-band are considered suitable for BVLOS UAS operations (see Sections 3 and 4). It is also well settled that the spectrum bands allocated for aviation services are not the only options for UAS wireless communications. Other alternatives exist, and as noted above and discussed further in Section 2, the choice of what spectrum is appropriate for a given UAS operation depends on the associated safety risks and the safety-risk mitigations. Unlicensed spectrum must not be used by functions enabling UAS DAA capabilities, but its use for UAS C2 links in low-risk UA operations outside FAA-controlled airspace might be acceptable.

Several stakeholders maintained in their comments that Section 374 requires that the report identify potential spectrum alternatives to the L and C bands. Although Section 374 text only requires the identification of alternatives if L and C bands were considered not suitable for BVLOS operations (which is not the case, as described in the paragraph above), the stakeholders urged the federal agencies to address use of other spectrum as an immediate solution, because in their view it will take many years to develop workable regulatory and operational solutions for the L and C bands. Some of these stakeholders specifically advocated use of commercial wireless networks, which use licensed spectrum allocated for mobile services.

Several bands are in use today or being pursued for UAS C2. The vast majority of small UAS (commonly called drones) operating today are using frequency bands in unlicensed spectrum. Unlicensed spectrum has a low bar to entry since no one party has exclusive use and no operator license is needed. Cell phone spectrum is exclusively licensed and is used by an extensive, deployed cellular network infrastructure. Satellite communications, which use several spectrum bands allocated for such service, is the gold standard for world-wide coverage but has limitations for low-angle, low-altitude service. Additionally, various vertical markets have licensed special niche spectrum for specific purposes that could include UAS wireless communication services. Some examples of frequency bands and band allocations that industry has pursued for enabling UAS operations are briefly described below.

5.1 Unlicensed Bands

Several bands in unlicensed spectrum are allocated for unlicensed national information infrastructure (UNII) services, including for example wireless local area networks (WLAN) implemented using WiFi technology. And, several bands are allocated for industrial, scientific, and medical (ISM) services, including for example garage door openers, wireless doorbells, and radio frequency identification (RFID) for item tracking. In addition, several bands are allocated for unlicensed personal communications services (UPCS), including for example wireless microphones and wireless baby monitors. Some frequencies have multiple allocations, which makes it difficult to say which allocations are being used for which services.

Today, most civil (i.e., non-public) UAS use unlicensed bands for functions that use radio frequency communications, particularly for C2 links. A concern regarding UAS use of unlicensed spectrum, especially for safety-related functions, is also what makes unlicensed spectrum so popular: anyone can use it. Although the radio devices are non-licensed, they must be FCC-certified in accordance with 47 CFR 15. (ISM equipment and use also must be in accordance with 47 CFR 18.)

The lack of active radio frequency management means there is no way to assure that users of these bands will not create enough radio interference to deny service to other users of the same bands. The non-licensed radio devices are each individually power-constrained, but there is no regulatory limit on the number of users simultaneously using the band. For example, large public events have planned and tested a drone show demonstration only to find that on the day of the event the large number of users of WiFi hotspots and Bluetooth devices make it impossible for the drones to operate.[42]

Currently, most consumer drones use the 900 MHz band for C2 links to avoid conflicts with WiFi radio usage. In addition, the lower frequency enables better radio signal penetration through obstacles and improved signal transmission range versus the 2.4 GHz band used for Wi-Fi and Bluetooth.

For most small UAS operated in the U.S. within the pilot's visual line of sight and that not near large public gatherings, unlicensed bands work reasonably well for C2 links. Unlicensed bands provide a low-cost option for both manufacturers and consumers to use UAS for many purposes. It is when UA are operated in high-risk environments, such as in urban areas or over people, that the threat of completely legal interference from other consumer devices operating in the same unlicensed band becomes a serious concern. As discussed in Section 2, the UAS operation's safety case must account for all the safety risks and all the safety-risk mitigations (such as using licensed or federal government spectrum instead of unlicensed spectrum) at play. Also as discussed in Section 2 and in this section, unlicensed spectrum must not be used by functions enabling DAA capabilities in either VLOS or BVLOS UAS operations.

5.2 Mobile Services Bands

The other very large consumer-facing wireless technology that nearly everyone uses is cell phones. Mobile services[43] spectrum in this document refers to spectrum allocated for cellular telephony. The FCC licensed these bands to cellular telephony service providers for land-based use, and cellphone towers were designed specifically to provide service to the customers on the ground and in buildings. Because of this, current cell phone reception is usually designed and optimized for ground level and buildings level. However, the majority of small UAS business concepts involve drones flying at low altitudes and there is opportunity to use cellular networks for enabling UAS operations.

When the FCC originally licensed these bands, there was no intended use for aviation, UAS, or other non-terrestrial uses. Given advancing emerging technologies, the FCC may need to review rules, allocations, and licenses for the use of these bands. The FAA has indicated that cellular telephony bands have the potential to meet the safety requirements for some UAS operations, considering those

[42] "When Drones attack. Triathlete discovers the hazards of drones in public spaces.", The Conversation, April 7, 2014. https://theconversation.com/when-drones-attack-triathlete-discovers-the-hazards-of-drones-in-public-spaces-25341

[43] The term "mobile service" means a radio communication service carried on between mobile stations or receivers and land stations, and by mobile stations communicating among themselves (47 U.S.C. §§153(33)). The U.S. Table of Frequency Allocations includes mobile service allocations in bands used for commercial mobile radio service (CMRS) and for private mobile radio service (PMRS) (https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf)).

bands are licensed, protected and deconflicted. Most of the major U.S. cell phone service providers and major U.S. cellular equipment manufacturers have done flight evaluations on the performance of using existing cellular technology for drone communication and found it works well at less than 1,000 ft above ground level. Additionally, the developing 3GPP standards for 5G are working to improve service for aerial users, including small UAS. The standards have accommodations for high-priority services with assured delivery of data, as well provisions to address the needs of airborne users (Flynn, 2019). Appendix E provides further insight on the usability of cellular technology and evolving LTE systems for that purpose, as well as references to related studies.

5.3 Satellite Communications Bands

Military and other public UAS operations typically use satellite communication networks that use spectrum bands having an allocation for mobile satellite services. This allows UA to fly anywhere on Earth and still be in communication with the remote pilot. It is likely that large civil UAS (typically over 2,500 lbs.) that desire long ranges (typically over 1,000 miles) would also use satellite communication. While significantly more expensive than the other options discussed here, only satellite offers a service with the possibility of worldwide coverage. The futuristic concept of an unmanned large, heavy cargo aircraft flying halfway around the world would likely rely on satellite communications.

5.4 Other Licensed Spectrum

The possible uses of UAS have been shown to extend to nearly every industry and civil government level in the economy. Many of these entities have preexisting radio spectrum licenses that could be used, with appropriate FCC approval, for UAS operations in these specific vertical markets. An example of this is BNSF Railway that was able to use spectrum reserved for railroad operations to fly UA for railroad inspections. As drone applications expand there may be other opportunities to use existing spectrum licenses for UAS.

6 REGULATORY AND POLICY CONSIDERATIONS

This section discusses regulatory and policy considerations, including the legal framework for spectrum management, and regulation and policy for L-band, C-band, and other bands.

6.1 Legal Framework

Wireless communications in the U.S. are regulated pursuant to the Communications Act of 1934. The Communications Act established the FCC and created a dual organizational structure in the U.S. for spectrum management. As shown in Figure 6-1, NTIA and the FCC share responsibility for managing the nation's radio spectrum resources in the public interest. NTIA manages spectrum and assigns frequencies to federal stations, while the FCC has regulatory authority, including licensing, over non-federal stations. NTIA and the FCC under U.S. law allocate and assign spectrum. All spectrum allocations in the U.S. result from agreements between NTIA and the FCC (NTIA).

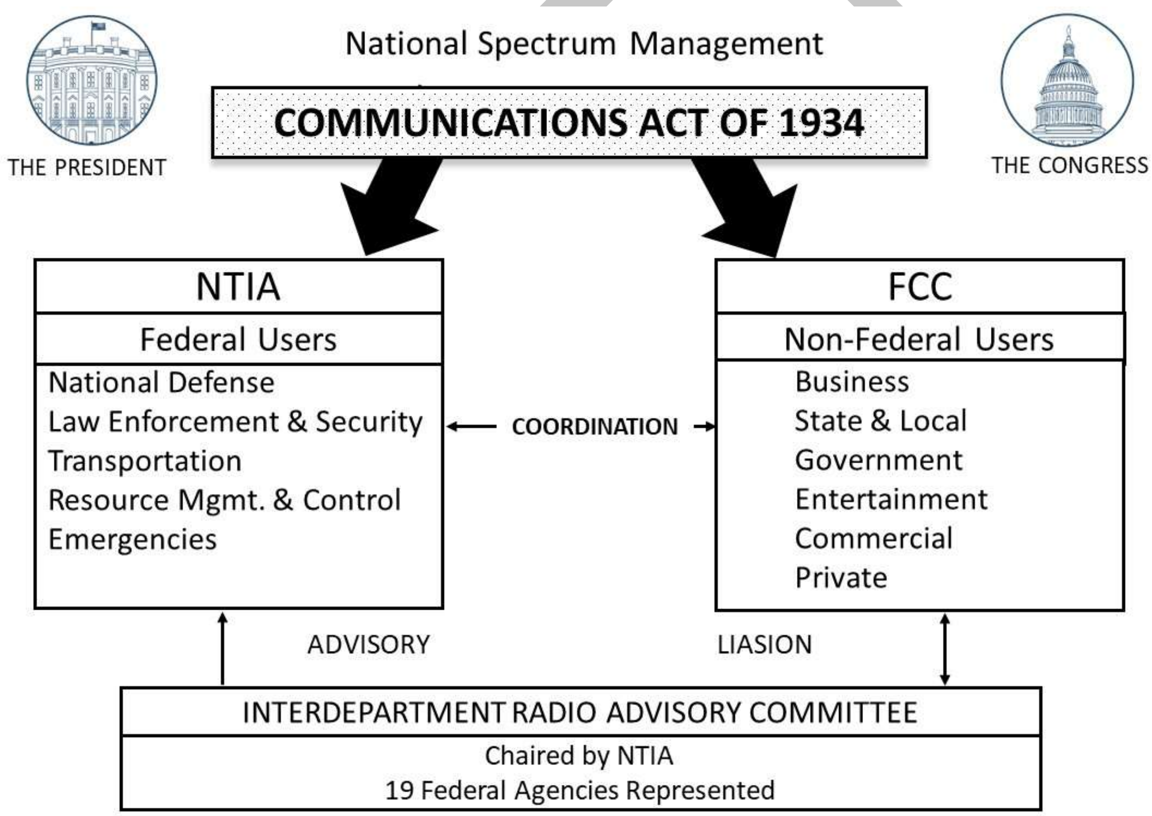

Figure 6-1. U.S. Spectrum Management

The Interdepartment Radio Advisory Committee (IRAC) is an advisory committee to NTIA comprised of federal agency spectrum managers (Nebbia). A new spectrum allocation for a private entity exclusively assigned for use by the federal government must be coordinated through the IRAC. Use of bands with allocations for shared federal and non-federal services must be coordinated between NTIA and the FCC.

In preparing this report concerning spectrum for UAS operations, the FAA is mindful of the policies underlying legislative and executive branch mandates to identify and assess spectrum bands for possible repurposing. In 1993, Congress directed the reallocation of federal spectrum to meet changing requirements and the growing demands for wireless services.[44] Over the next few decades, Congress enacted laws to establish a framework to encourage sharing and reallocation of federal spectrum. This included the Spectrum Relocation Fund (SRF) to provide federal agencies with cost reimbursement.[45]

Congress further refined the tools available for NTIA and the federal agencies to explore repurposing of federal spectrum bands with the Middle Class Tax Relief and Job Creation Act of 2012 and the Spectrum Pipeline Act of 2015.[46] The Spectrum Pipeline Act appropriated funds for federal agencies to conduct studies to improve the efficiency and effectiveness of their spectrum use to make it available for auction. This allowed federal agencies proposing spectrum "Pipeline Plans" to recover directly from auction proceeds the costs associated with sharing spectrum or relocating their radiocommunications systems for commercial wireless purposes. The Spectrum Pipeline Act also required NTIA and the FCC to identify certain amounts of federal and non-federal spectrum for repurposing.

Most recently, in 2018 the Making Opportunities for Broadband Investment and Limiting Excessive and Needless Obstacles to Wireless (MOBILE NOW) Act of 2018 required the identification of spectrum for repurposing as well as studies and reports related to spectrum repurposing in specific frequency bands and spectrum bands meeting certain criteria or amounts.[47]

Over the past two decades, the White House has issued directives concerning efficient use of spectrum. In 2017, the Presidential Memorandum for the Secretary of Transportation on *Unmanned Aircraft Systems Integration Pilot Program*, established the UAS Integration Pilot Program with a policy objective of "using radio spectrum efficiently and competitively" (White House, 2017). In 2018, the White House made spectrum policy a top priority, issuing the *Presidential Memorandum on Developing a Sustainable Spectrum Strategy.* The Presidential Memorandum calls for the development of a comprehensive, long-term National Spectrum Strategy. One goal of the National

---

[44] Title VI of the Omnibus Budget Reconciliation Act of 1993 required that the Secretary of Commerce identify at least 200 megahertz of spectrum below 5 GHz used by the Federal Government for reallocation to new spectrum-based technologies. *See* Pub. L. No. 103-66, Title VI, 107 Stat. 312, 380 (1993). In response, NTIA published a plan identifying twelve bands and a reallocation schedule for each. *See* NTIA, Spectrum Reallocation Final Report, NTIA Special Publication 95-32 (Feb. 1995) Title III of the Balanced Budget Act of 1997 (Budget Act) required the FCC to identify 15 megahertz from the 1990-2110 MHz band for assignment by competitive bidding, but also provided a process for spectrum substitution to protect incumbent federal systems from interference if "the President determines such spectrum cannot be reallocated due to the need to protect incumbent Federal systems from interference, and that allocation of other spectrum (A) better serves the public interest, convenience, and necessity, and (B) can reasonably be expected to produce comparable receipts." *See* Pub. L. No. 105-33, Title III, 111 Stat. 251, 258-270 (1997).

[45] Congress enacted the Commercial Spectrum Enhancement Act in 2004 (Title II of Public Law 108-494), creating the SRF and setting the stage for the initial Advanced Wireless Service (AWS) auction of the 1710-1755 MHz band (AWS-1).

[46] Middle Class Tax Relief and Job Creation Act of 2012, Pub. L. No. 112-96, Title VI, Subtitle G, 126 Stat. 156, 245-255 (Feb. 22, 2012); Spectrum Pipeline Act of 2015, Pub. L. No. 114-74, Title X, 129 Stat. 584, 621-624 (Nov. 2, 2015) .

[47] MOBILE NOW Act, Division P, (pp. 750-768) of the Consolidated Appropriations Act of 2018, Pub. L. No. 115-141, H.R. 1625, available at https://www.congress.gov/115/bills/hr1625/BILLS-115hr1625enr.pdf (MOBILE NOW Act).

Spectrum Strategy is to "increase spectrum access for all users, including on a shared basis, through transparency of spectrum use and improved cooperation and collaboration between federal and non-federal stakeholders."[48] It is also intended to improve the utility of spectrum use as effectively as possible. "It is the policy of the United States to use radiofrequency spectrum (spectrum) as efficiently and effectively as possible to help meet our economic, national security, science, safety, and other federal mission goals now and in the future." The Presidential Memorandum further states: "The United States Government shall continue to look for additional opportunities to share spectrum among Federal and non-Federal entities" (White House, 2018).

The remainder of this section describes the regulatory and policy concerns that pertain to use of both the 960-1164 MHz and 5030-5091 MHz bands for UAS operations. Subsections 6.2 and 6.3 address additional regulatory and policy concerns specific to the 960-1164 MHz and the 5030-5091 MHz bands, respectively. Subsection 6.4 discusses potential open questions related to other bands.

The 960-1164 MHz and 5030-5091 MHz bands are allocated internationally and nationally for aeronautical purposes: AM(R)S (radiocommunication services for safety and regularity of flight, primarily along national and international civil air routes) and ARNS (radionavigation services). The U.S. allocations pertain to federal and non-federal use of the bands for aviation services. AM(R)S use of the band is limited to internationally standardized systems (FCC, 2019), (NTIA, Revision of the September 2015 Edition, September 2017).

The FAA seeks to collaborate as appropriate with industry to create new spectrum access opportunities for UAS operations. These opportunities would be mutually beneficial and advance both federal statutory missions and the goals of the Presidential Memorandum and national spectrum policy. Ideally, they would also support federal initiatives incentivizing federal agencies to reallocate and share spectrum for commercial wireless purposes. The FAA is committed to working with industry to develop systems that enable safe UAS operations.

Spectrum is allocated for use under international law by the International Telecommunication Union Radiocommunication Sector (ITU-R). Every three to four years, the ITU's World Radiocommunication Conference (WRC) reviews and revises the ITU Radio Regulations, an international treaty governing the use of radio frequency spectrum.

6.2 L-band Regulation and Policy

In the proposed concept for the L-band, the FAA is exploring the viability of shielding incumbent systems and services that require use of protected, deconflicted spectrum while allowing coexistence of UAS C2 users in this spectrum to enable safe UAS operations. National and international aeronautical spectrum allocations are designed to protect people in manned aircraft. Although UA currently carry no people, there is a need to protect people on the ground from hazards such as the loss of C2 communications between the remote pilot and the UA. The L-band spectrum UAS coexistence approach would increase spectrum utility in this band under strict conditions that maintain NAS safety.

[48] Presidential Memorandum, Section 4(a).

A new spectrum allocation for a private entity in a portion of L-band exclusively assigned for use by the federal government must be coordinated through the IRAC. The FAA's role is to protect incumbent operations. In this band, federal systems using spread-spectrum techniques for terrestrial operations may be authorized as long as they do not cause harmful interference to ARNS systems.

The FAA would not deploy or operate any communications network, nor would it manage day-to-day band use. However, related regulatory functions would remain with FAA, NTIA, and FCC. For the FAA, these functions include development of UAS C2 link performance requirements, protection of L-band for incumbent aviation users, and UA operational approvals based on safety cases prepared by UAS operators.

6.3 C-band Regulation and Policy

This section addresses regulatory and policy matters pertaining to using the C-band, specifically the 5030-5091 MHz sub-band. The C-band does not have any incumbents other than a few closely controlled temporary licenses enabled by the FAA.

WRC-12 and the FCC took actions to support UAS operations in the 5030-5091 MHz band. Based on the U.S. WRC-12 proposal, the FCC's WRC-12 Notice of Proposed Rulemaking (NPRM) noted that this band "would be appropriate to satisfy the terrestrial, line-of-sight, spectrum requirements for command and control of UAS in non-segregated airspace" (FCC, March 2017).

As noted by ICAO, "WRC-12 also adopted (footnote No. 5.443C) a new complementary terrestrial allocation to the AM(R)S in 5030-5091 MHz, again limited to internationally recognized systems. This band was therefore internationally recognized as the band to be used for the implementation of UA links for safety and regularity of flight via both terrestrial and satellite systems (Wambeke, June 2018)." Updates will be needed to the 2018 TSO-C213, *Unmanned Aircraft Systems Control and Non-payload Communications Terrestrial Link System Radios*, to reflect determinations of this ongoing work by RTCA (FAA, 9 March 2018).

The concept proposed for C-band includes the possibility of serving, as a lower priority, UAS functions that are not needed to help ensure the safety and regularity of flight (such as payload and mission sensors). Additional uses of the spectrum, beyond those specified in the FCC National Table of Frequency Allocations,[49] may be authorized to meet additional needs. These additional uses must be in the national interest and consistent with national rights and international obligations. While there is no regulatory barrier to providing spectrum access for UAS safety and regularity of flight (as per allocation primary purpose), regulatory changes may be needed to allow spectrum use for UAS functions that are not needed to help ensure the safety or regularity of flight (such as low-bandwidth, mission-sensor data). High-bandwidth payload video and other data streams are not recommended within this concept due to their excessive use of this spectrum intended for ensuring the safety and regularity of flight. This concept must be implemented in a manner consistent with safe and efficient use of the navigable airspace under 49 United States Code (USC) §40103 (b). Required changes in allocation, depending on type of operations, are illustrated below.

[49] Available here: https://www.fcc.gov/engineering-technology/policy-and-rules-division/general/radio-spectrum-allocation

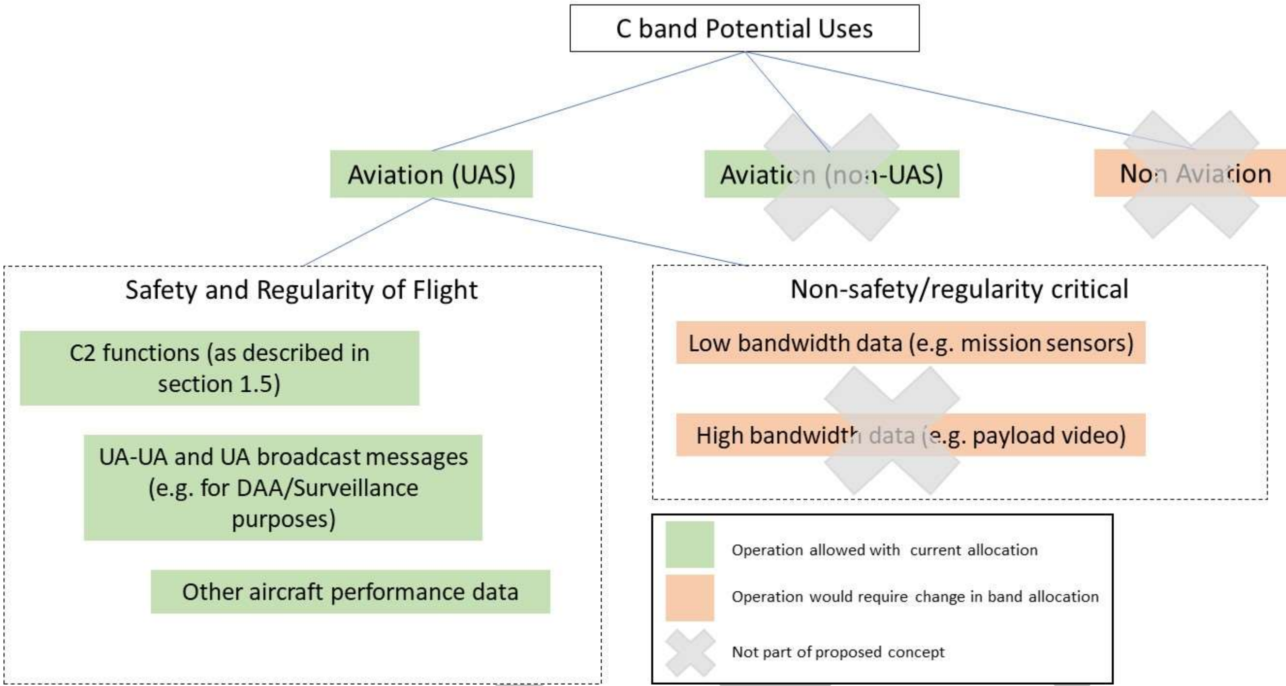

Figure 6-2. Required changes in allocation for C-band depending on type of operations

If changes in allocation are to be pursued to support secondary use of this band for UAS uses not related to safety and regularity of flight (excluding high-bandwidth data streams), the FAA suggests this be undertaken in a phased approach, so as not to delay UAS operations using C2 in this band.

In addition to the allocations described in Section 4.2.1, C-band also is allocated internationally and nationally for AMS(R)S (the aeronautical mobile-satellite (route) service) for communication for safety and regularity of flight, primarily along national and international civil air routes. Although there are no plans to use AMS(R)S in the U.S. in the near future, SC-228 is currently working with NASA on efforts to design a satellite-based UAS C2 link that would utilize the 5030–5091 MHz AMS(R)S allocation while maintaining compatibility with the DO-362A terrestrial system in the same band. Other countries are also conducting compatibility and sharing studies for UAS C2 satellite communications (SATCOM), which could be used at higher altitudes, in this band.

Use of bands with allocations for shared federal and non-federal services like C-band for air route communications services (AM(R)S) must be coordinated between NTIA and the FCC.

There are additional rules for this band. Unwanted adjacent-band emissions from AM(R)S in this band must be limited to protect RNSS system downlinks in the lower adjacent band. For aeronautical mobile-satellite service, national administrations must coordinate in advance with other administrations to use non-geostationary (GEO) networks, other GEO-non-GEO networks, and terrestrial stations. Coordination is based on frequency overlap and visibility, if there is not a power flux-density hard or trigger limit (ITU).

Under this allocation, MLS currently has priority over other uses of the band. However, MLS is not used in the U.S. because the FAA decommissioned and removed all MLS stations. The last operational MLS system in the U.S. was decommissioned over a decade ago. Therefore, this rule is more relevant internationally than in the U.S. The FAA is working with NTIA to remove text from

U.S. regulations prioritizing MLS use of the band. In particular, the IRAC could take the action to delete footnote US 444 (NTIA, Revision of the September 2015 Edition, September 2017), (FCC, 2019) and incorporate this redaction in the next revision of 47 CFR 300, which references NTIA's *Manual of Regulations and Procedures for Federal Radio Frequency Management*.

FAA and FCC regulations of wireless communications and necessary to protect UAS operations, life, and property would be necessary under this approach. The FCC table of frequency allocations would require modification accordingly. Development of standards, operational scenarios, and UAS is ongoing, and rules for communications in this band need to be flexible to account for emerging technologies and requirements. However, regulation beyond these requirements could stifle investment and innovation and should be avoided.

C-band spectrum must be protected from radio frequency interference since it would be used by safety-related UAS functions. Some of these functions may be safety-critical because the UA may be large, may operate at high altitudes, and may fly at high speed – all of which would increase the potential risk of significant property damage and loss of human life. Therefore, licensing on a primary basis would be required, either by person, by fleet, or by rule. The preference is by rule in order to maximize the number of users and minimize the cost and management overhead associated with licensing. Also, equipment would require certification under 47 CFR Part 87, Aviation Services, to include UAS C2 and other UAS functions.

Given the possible large number of users and the “pop-up” nature of many missions, a dynamic frequency assignment process allowing use of a channel only for the duration of the mission will be required. This could be integrated in the request to fly the mission by a proponent to an independent frequency assigner. The expectation is that the system would be automated, to the extent that the appropriate regulations and availability could be verified.

6.4 Other Bands

Large fleets of commercial operators flying UA BVLOS over people and property may require use of licensed or federal government spectrum. However, highly automated UA flight may someday reduce the dependency on C2 links for safeguarding human life and property. If and when UAS operations reach this advanced level of automation, the FAA could revisit safe use of unlicensed spectrum in these cases.

As part of the feedback received from stakeholders, there is a strong desire from UAS operators to be allowed to utilize existing commercial licensed cellular bands for UAS systems. There is also a strong push by the cellular industry (represented in stakeholder feedback) for permission to offer services to UAS immediately in existing commercial cellular networks.

While cellular networks might be able to meet safety-related performance requirements to support high-risk UAS operations, there are potential regulatory and operational barriers. These concern whether these operations are allowed in those mobile services bands, up to what altitude, and whether their use would disrupt (by causing interference to) other users in different locations, domains or adjacent bands.

Stakeholders submitted comments urging that these bands are made available for UAS use.

As discussed previously, the FCC is the regulator here. The FAA’s role in this question is to advise the FCC to assure safety of aviation operations (including incumbent systems and UAS operations if approved in this band). Cellular bands have the potential to meet the safety case for some UAS operations, assuming the cellular bands are licensed, protected and deconflicted. From the safety perspective the FAA would not object to FCC rules permitting UAS operations to use commercial licensed bands authorized as long as they would not cause harmful interference to ARNS systems and that they meet safety-risk requirements for UAS operation approval, based on the operation safety case.

For commercial cellular networks to provide anything other than exclusive service to UAS C2, FCC regulations would likely need to be changed to require priority for UAS C2 links.

7 SUMMARY AND RECOMMENDATIONS

In summary, the key findings in this report are:

(1) on whether unmanned aircraft systems operations should be permitted, but not required, to operate on spectrum that was recommended for allocation for AM(R)S and control links for UAS by the World Radio Conferences in 2007 (L-band, 960-1164 MHz) and 2012 (C-band, 5030-5091 MHz), on an unlicensed, shared, or exclusive basis, for operations within the UTM system or outside of such a system

UAS operations should be permitted[50], but not required, to operate their control links (which in this report are called command and control (C2) links) in L-band and C-band spectrum.[51,52]

- UAS operations should be permitted to use the L-band and C-band only on a shared basis, not on an exclusive basis, in accordance with existing rules.[53]
- UAS operations should not be permitted in the L-band and C-band on an unlicensed basis, i.e., radio devices licensed by the FCC for use in unlicensed bands[54] should not be permitted to use the L-band and C-band.[55]
- UAS operations, both within or outside a UTM system, should be permitted to use L-band and C-band for their control links.

[50] Several UAS manufacturers and operators already are making significant use of the C-band. This usage has enabled new UAS operations that previously could not occur; and has demonstrated UAS functionality beyond the manufacturers' and operators' initial expectations. Stakeholders have stated that preservation of C-band for UAS operations is necessary for UAS industry success, particularly for operation of unmanned aircraft beyond the pilot's visual range.

[51] The L-band (960-1164 MHz) and C-band (5030-5091 MHz) cited in Section 374 are allocated by the ITU and FCC for aeronautical mobile (route) services [AM(R)S], which enables their use for UAS control links.

[52] In the L-band, UAS operations should be permitted only if further work determines that safety-of-life functions currently performed in the band can be fully protected and preserved. The finding is qualified in this manner because the barriers for the use of L-band are considered significant, as described in finding (2).

[53] Section 87.41 of 47 CFR states that aviation frequencies are available for assignment on a shared basis only and that they will not be assigned for the exclusive use of any licensee.

[54] Unlicensed bands are used by radio devices licensed by the FCC under 47 CFR 15. Although those regulations limit transmit power and spurious emissions, there are no mechanisms to manage the spectrum's use. Thus, no radio link performance guarantees are possible.

[55] Such use is not authorized by the FCC and would be contrary to the L-band's and C-band's AM(R)S allocations intended to help ensure flight safety and regularity.

(2) that addresses any technological, statutory, regulatory, and operational barriers to the use of such spectrum

There are technological, regulatory, and operational barriers, identified in this report, to the use of the allocated L-band and C-band spectrum; no statutory barriers were identified. The barriers for both bands include:

- The need to ensure that spectrum resources are used efficiently to provide equitable access to UAS operations within or outside a UTM system, including mechanisms for dynamically managing frequency assignments and spectrum access.
- The need to mature the proposed concepts for these bands, validate and refine implementation approaches, and address the questions and challenges identified in this report.

There is an additional significant barrier for L-band:

- The need to safely coexist within the L-band that is heavily used by multiple systems that are essential for the safety and regularity of both civil (e.g., commercial) and public (e.g., military) flight operations.[56]

3) that, if it is determined that some spectrum frequencies are not suitable for beyond-visual-line-of-sight operations by unmanned aircraft systems, includes recommendations of other spectrum frequencies that may be appropriate for such operations

All radio frequency (RF) spectrum (including the L-band and C-band federal government spectrum, licensed spectrum, and unlicensed spectrum) could be suitable for operation of unmanned aircraft beyond the pilot's visual line of sight (BVLOS).

- The decision process for the spectrum band selection should take into account the UAS operation's target level of safety and the risk mitigations used to achieve (or exceed) that target.
- Use of unlicensed spectrum in other bands may be unsuitable for some unmanned aircraft (UA) operations, either within or beyond the pilot's visual range, because of potential radio frequency interference (RFI). For BVLOS operations this is an increased concern due to the higher dependence on radio services for multiple safety-related functions.[57]
- For UAS operations within or beyond the pilot's visual line of sight, functions for detecting and avoiding other aircraft must not use unlicensed spectrum. That is, radiocommunications

[56] This complexity includes the need to ensure through proper frequency management that the operation of ground and airborne systems currently using the highly congested L-band to help ensure the safety and regularity of manned aircraft flight will not be disrupted by interference from UAS.

[57] Section 7.8 of the NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management [9] states: "Non-licensed devices, since they operate on a non-interference basis, may not provide sufficient reliability for critical radio communications functions affecting human life or property. Non-licensed devices, however, may provide valuable and unique supplemental or expendable radio communications services where needed. To ensure adequate regulatory protection, Federal entities should rely only on devices with frequency assignments in the Government Master File as principal radiocommunication systems for safeguarding human life or property." Nevertheless, use of unlicensed spectrum for C2 links might be acceptable for some UAS operations in which the safety risks can be sufficiently mitigated by means not dependent on unlicensed spectrum. In such cases, the FAA would rely on those other means for safeguarding human life or property; it would not rely on UAS radio devices operating in unlicensed spectrum.

and radionavigation functions used for UAS DAA capabilities must use licensed or federal government bands with appropriate allocations and regulatory protections for mitigating RFI.

- Stakeholders have supported further investigation into the use of systems and bands used in cellular radio networks providing terrestrial mobile communications services, which may be available for UAS operations in the near term. The feasibility and acceptability of using these systems and bands should be assessed.
- Use of other spectrum bands should be in accordance with FCC and NTIA regulations as well as in accordance with spectrum license holders' requirements and authorizations.

7.1 Recommendations

The FAA plans to continue developing the concepts in this report. We stand ready to work with industry stakeholders as appropriate to mature the proposed concepts, validate and refine implementation approaches, and address the questions and challenges identified in this report and any identified by others.

The next steps for moving forward include:

- FAA's Office of Unmanned Aircraft Systems Integration (AUS), as the designated FAA Office of Primary Responsibility (OPR), will manage the follow-on work related to Section 374 from the aviation perspective. Objectives include:
    - Working with an NTIA OPR moving forward, especially on federal licensing process
    - Working with FCC OPR, especially on integrating non-federal UAS licenses with the national airspace plan
    - Establishment of safety requirements for UAS use of designated spectrum bands.
    - Establishment of principles to ensure equitable access to designated spectrum bands.

- Orchestration of collaboration between any interested industry stakeholders (inclusive of UAS operators, manned aviation, aerospace manufacturers, UAS service suppliers, communication service providers, air traffic service providers) to provide input to assist in maturing proposed concepts, validating and refining implementation approaches identified in this report. Possible objectives for this stakeholder group could include:
    - Development of concepts of operation and high-level system architecture for each band including rules of engagement; to include mechanisms to dynamically manage frequency assignments to be used by UAS operators and to manage access to spectrum.
    - Validation and documentation of proposed concepts through data from field tests and the results of existing and new studies.

7.2 Key Open Areas

There is significant work needed to further refine, validate, and implement the proposed concepts. Some of the key open areas include:

With respect to L-band:

- Further assess feasibility of using the L-band whitespace for UAS C2 without interfering with existing systems and assess the possibility of clearing a nationwide L-band channel to be dedicated for a cooperative UAS surveillance broadcast service. These assessments need to be done taking in consideration planned expansion of the DME system.

With respect to C-band:

- Mature the C-band concept to address band partitioning across networked and non-networked solutions; and, how frequency assignments and licensing process will be managed in each of those cases.
- Assess how the C-band can be partitioned (e.g., fixed-band partition or varying geographically and over time), how those partitions can evolve to address current and future needs, and how to adequately protect users in each partition against mutual interference, including assessing co-location of radios and guard band requirements.
- Assess compatibility of potential coexistence of satellite-based C-band (AMS(R)S) UAS-C2 link solutions with the ground-based C-band (AM(R)S) systems to be utilized in each partition.
- Define the frequency assignment function for the non-networked solutions for TSO-C213 links; including the level of automation required and the roles and responsibilities related to implementation and management.
- Determine performance requirements acceptable for non-networked and networked UAS C2 operations, including coverage, handoff, and availability. Where cellular standards (e.g., LTE, 5G) are used in these partitions, determine the altitude strata where those systems can offer service to UAS. Determine the process for licensing of cellular services in the band.
- Determine whether UAS functions that are not part of C2 (e.g., payload sensors, UA-UA data exchange) may be served within the same sub-band partition (for networked or non-networked scenarios); and, ensure that the systems can automatically provide priority of service-level agreements for different UAS communication streams to allow prioritization of safety-related functions.

8 References

[1] RTCA, "Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS) (Terrestrial) (DO-362)," September 2016.

[2] ITU, "Radio Regulations, Edition of 2016," 2016. [Online]. Available: http://www.itu.int/pub/R-REG-RR-2016. [Accessed October 2019].

[3] FCC, "Online Table of Frequency Allocations," 7 May 2019. [Online]. Available: https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf. [Accessed October 2019].

[4] FCC, "Wireless Telecommunications Bureau and Office of Engineering and Technology Seek Comment on Unmanned Aerial System Operations in the 960-1164 MHz and 5030-5091 MHz Bands, Pursuant to Section 374 of the FAA Reauthorization Act of 2018 GN Docket No. 19-356," Washington DC, 25 November 2019.

[5] ITU Radiocommunication Sector, "Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace," ITU-R M.2171, December 2009.

[6] F. Box, L. Globus, R. Snow and L. C. Monticone, "Spectrum Planning for Command and Control Links of Unmanned Aircraft Systems, MTR 150186R1," MITRE Corporation, McLean, VA, October 2018.

[7] FAA, "Unmanned Aircraft System (UAS) Traffic Management (UTM) Concept of Operations V2.0," FAA, 2 March 2020. [Online]. Available: https://www.faa.gov/uas/research_development/traffic_management/media/UTM_ConOps_v2.pdf. [Accessed 22 May 2020].

[8] ITU Radiocommunication Sector, "Compatibility study to support the line-of sight control and non-payload communications link(s) for unmanned aircraft systems proposed in the frequency band 5 030-5 091 MHz," ITU-R M.2237, November 2011.

[9] NTIA, "Manual of Regulations and Procedures for Federal Radio Frequency Management (Redbook)," Revision of the September 2015 Edition, September 2017.

[10] RTCA, "Minimum Aviation System Performance Standard (MASPS) for C2 Link Systems Supporting Operations of Unmanned Aircraft Systems in U.S. Airspace (DO-377)," March 2019.

[11] FAA, "TSO-C213: Unmanned Aircraft Systems Control and Non-Payload Communications Terrestrial Link System Radios," 9 March 2018.

[12] RTCA, "Command and Control (C2) Data Link White Paper Phase 2 (WP-4)," September 2017.

[13] K. Flynn, "Unmanned Aerial Systems over 5G," 18 November 2019. [Online]. Available: https://www.3gpp.org/technologies/keywords-acronyms/2090-unmanned-aerial-systems-over-5g. [Accessed March 2020].

[14] NTIA, ""Who Regulates the Spectrum"," [Online]. Available: https://www.ntia.doc.gov/book-page/who-regulates-spectrum. [Accessed 7 June 2019].

[15] K. B. Nebbia, "The Interdepartment Radio Advisory Committee," NTIA.

[16] White House, "Presidential Memorandum for the Secretary of Transportation on Unmanned Aircraft Systems Integration Pilot Program," 2017.

[17] White House, "Presidential Memorandum on Developing a Sustainable Spectrum Strategy for America's Future," 25 October 2018. [Online]. Available: https://www.whitehouse.gov/presidential-actions/presidential-memorandum-developing-sustainable-spectrum-strategy-americas-future/. [Accessed October 2019].

[18] FCC, "Report and Order, ET Docket No. 15-99," Washington, DC, March 2017.

[19] N. V. Wambeke, "Remotely Piloted Aircraft Systems Panel (RPASP)," ICAO, Montreal, June 2018.

[20] ITU, "ITU Radio Regulatory Framework for Space Services," [Online]. Available: https://www.itu.int/en/ITU-R/space/snl/Documents/ITU-Space_reg.pdf. [Accessed October 2019].

[21] ITU Radiocommunication Sector, "Aeronautical Mobile (Route) Service Sharing Studies in the Frequency Band 960-1164 MHz," ITU-R M.2235, November 2011.

[22] RTCA, "Minimum Operational Performance Standard (MOPS) for Airborne Distance Measuring Equipment (DME) Operating Within the Radio Frequency Range of 960–1215 MHz," RTCA DO-189, Section 2.2.11 (Receiver Susceptibility to CW Interference), September 1985.

[23] DoD, "Chairman of the Joint Chiefs of Staff Instruction: Link-16 Spectrum Deconfliction (CJCSI 6232.01E)," 21 September 2012.

[24] FAA, "14 CFR Part 91.225 Automatic Dependent Surveillance-Broadcast (ADS-B) Out Equipment and Use," ECFR, 28 May 2010. [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?node=se14.2.91_1225&rgn=div8. [Accessed 6 March 2020].

[25] R. M. Guterres, G. L. Orrell, R. C. Strain and S. R. Jones, "ADS-B Surveillance System Performance with Small UAS at Low Altitudes," in *AIAA SciTech Forum*, 2017.

[26] R. M. Guterres, S. R. Jones, S. V. Massimini and R. C. Strain, "ADS-B Surveillance in High Density SUAS Applications at Low Altitudes," in *International Symposium on Enhanced Solutions for Aircraft and Vehicle Surveillance Applications*, Berlin, 2016.

[27] ATIS, "“Use of Cellular Communications to Support Unmanned Aerial Vehicle (UAV) Flight Operations”," August 2019. [Online]. Available: https://access.atis.org/apps/group_public/download.php/48760/ATIS-I-0000074.pdf. [Accessed February 2020].

[28] 3GPP, "Study on Enhanced LTE Support for Aerial Vehicles (Release 15), 3GPP TR 36.777 V15.0.0," December 2017. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3231. [Accessed October 2019].

[29] I. Gheorghisor, A. Chen, L. Globus, T. Luc and P. Schrader, "Modeling and Simulation for Reliable LTE-Based Communication in the National Airspace System," 2019 USA/Europe ATM R&D Seminar, June 2019.

[30] S. Muruganathan, X. Lin, H. Maattanen, J. Sedin, Z. Zou, W. Hapsari and S. Yasukawa, "An Overview of 3GPP Release-15 Study on Enhanced LTE Support for Connected Drones," June 2019. [Online]. Available: Available at: https://arxiv.org/ftp/arxiv/papers/1805/1805.00826.pdf. [Accessed February 2020].

[31] 3GPP, "“New WID on Enhanced LTE Support for Aerial Vehicles,”," December 2017. [Online]. Available: https://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_78/Docs/RP-172826.zip. [Accessed February 2020].

[32] 3GPP, "Unmanned Aerial System (UAS) support in 3GPP," [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3545. [Accessed February 2020].

[33] 3GPP, "Study on application layer support for Unmanned Aerial Systems (UAS)," [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3588 . [Accessed February 2020].

[34] GUTMA, "LS from GUTMA: Liaison statement from GUTMA to 3GPP's TSG SA #85 plenary meeting," September 2019. [Online]. Available: https://www.3gpp.org/ftp/tsg_sa/TSG_SA/TSGS_85/Docs/SP-190859.zip. [Accessed February 2020].

[35] ATIS, "LS from ATIS: Liaison Statement on UAV Progress in 3GPP," September 2019. [Online]. Available: https://www.3gpp.org/ftp/tsg_sa/TSG_SA/TSGS_85/Docs/SP-190871.zip. [Accessed February 2020].

[36] FAA, "UAS Integration Pilot Program," [Online]. Available: https://www.faa.gov/uas/programs_partnerships/integration_pilot_program/ . [Accessed February 2020].

[37] FAA, "UTM Pilot Program (UPP)".

[38] CTIA, "Comments of CTIA in Response to FCC Public Notice GN Docket No: 19-356," December 2019. [Online]. Available: https://ecfsapi.fcc.gov/file/12260080421626/191226%20CTIA%20Comments%20on%20UAS%20PN.pdf. [Accessed February 2020].

[39] FAA, "Unmanned Aircraft System Traffic Management (UTM)," FAA, 01 February 2019. [Online]. Available: https://www.faa.gov/uas/research_development/traffic_management/. [Accessed 15 February 2020].

[40] NASA, "UTM," NASA, 4 September 2019. [Online]. Available: https://utm.arc.nasa.gov/index.shtml. [Accessed 15 February 2020].

[41] Government Printing Office, "CFR Title 47 Part 15 - Radio Frequency Devices," [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?SID=a109eee12e0b72e720948176dbbb3be3&mc=true&node=pt47.1.15&rgn=div5. [Accessed October 2019].

[42] ATIS, "“Support for UAV Communications in 3GPP Cellular Standards"," October 2018. [Online]. Available: https://access.atis.org/apps/group_public/download.php/42855/ATIS-I-0000069.pdf. [Accessed February 2020].

[43] M. Davis, F. Xue, R. Arefi, J. Bai and S. Yeh, "Aerial Cellular: What Can Cellular Do for the UAVS With and Without Changes to Present Standards and Regulations," in *AUVSI XPONENTIAL 2019 Proceedings*, May 2019.

[44] X. Lin, J. Li, R. Baldemair, J.-F. Cheng, S. Parkvall, D. C. Larsson, H. Koorapaty, M. Frenne, S. Falahati and A. Grovlen, "5G New Radio: Unveiling the Essentials of the Next Generation Wireless Access Technology," IEEE Communications Standards Magazine, 2019.

[45] A. Banchs, D. M. Gutierrez-Estevez, M. Fuentes, M. Boldi and S. Provvedi, "A 5G Mobile Network Architecture to Support Vertical Industries," IEEE Communications Magazine, 2019.

[46] ICAO, "Doc 9924: Aeronautical Surveillance Manual, Second Edition," ICAO, Montreal, Canada, 2017.

[47] ICAO, "Doc 9718: Handbook on Radio Frequency Spectrum Requirements for Civil Aviation - Second Ediiton," ICAO, Montreal, Canada, 2018.

9 Acronyms and Abbreviations

Acronym	Definition
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
ACAS X	Airborne Collision Avoidance System X
ADS-B	Automatic Dependent Surveillance-Broadcast
AeroMACS	Aeronautical Mobile Airport Communication System
AGL	Above Ground Level
AIA	Aerospace Industries Association
AM(R)S	Aeronautical Mobile (Route) Service
AMS(R)S	Aeronautical Mobile-Satellite (Route) Service
ARNS	Aeronautical Radionavigation Service
ATC	Air Traffic Control
ATM	Air Traffic Management
BRLOS	Beyond Radio Line of Sight
BS	Base Station
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CFR	Code of Federal Regulations
CJCSI	Chairman of the Joint Chiefs of Staff Instruction
CMRS	Commercial Mobile Radio Service
CNPC	Control and Non-Payload Communications
CPDLC	Controller Pilot Data Link Communications
CS	Control Station
CTIA	Cellular Telecommunications Industry Association
CW	Continuous Wave
dB	Decibel
DHS	Department of Homeland Security
DME	Distance Measuring Equipment

Acronym	**Definition**
DO	Document
DoD	Department of Defense
DOT	Department of Transportation
EMC	Electromagnetic Compatibility
ES	Extended Squitter
ET	Engineering & Technology
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDR	Frequency Dependent Rejection
FL	Forward Link
ft	Feet
GEO	Geostationary
GHz	Gigahertz
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICAO	International Civil Aviation Organization
IFF	Identification Friend or Foe
ILS	Instrument Landing System
IMT	International Mobile Telecommunications
IOT	Internet of Things
IPP	Integration Pilot Program
IRAC	Interdepartment Radio Advisory Committee
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
JTIDS	Joint Tactical Information Distribution System
km	Kilometer
LDACS	L-band Digital Aeronautical Communications System
LORAN	Long Range Navigation
LTE	Long Term Evolution

Acronym	Definition
MASPS	Minimum Aviation System Performance Standard
MHz	Megahertz
MIDS	Multifunctional Information Distribution System
MLS	Microwave Landing System
MOA	Memorandum of Agreement
MOPS	Minimum Operational Performance Standard
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
nmi	Nautical Mile
NPRM	Notice of Proposed Rulemaking
NR	New Radio
NTIA	National Telecommunications & Information Administration
OPR	Office of Primary Responsibility
PMR	Professional/Private Mobile Radio
PMSE	Programme Making and Special Events
PNT	Position, Navigation, and Timing
R&D	Research and Development
RF	Radio Frequency
RFI	Radio Frequency Interference
RFID	Radio Frequency Identification
RL	Reverse Link
RLOS	Radio Line of Sight
RM	Rulemaking
RNSS	Radionavigation-Satellite System
RPASP	Remotely Piloted Aircraft System Panel
RSRQ	Reference Signal Received Quality
SATCOM	Satellite Communications
SC	Special Committee
SSR	Secondary Surveillance Radar
sUAS	Small Unmanned Aircraft System

Acronym	Definition
SV	Service Volume
TACAN	Tactical Air Navigation
TCAS	Traffic Alert and Collision Avoidance System
TDD	Time-Division Duplexing
TDMA	Time Division Multiple Access
TR	Technical Report
TSO	Technical Standard Order
U.S.	United States
UA	Unmanned Aircraft
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UAT	Universal Access Transceiver
UK	United Kingdom
UNII	Unlicensed National Information Infrastructure
UPCS	Unlicensed Personal Communications Services
US&P	United States and Possessions
U.S.C.	United States Code
USS	UAS Service Supplier
UTM	UAS Traffic Management
VHF	Very-High Frequency
VLOS	Visual Line of Sight
VOR	Very-High Frequency Omnidirectional Range
WLAN	Wireless Local Area Network
WP	Work Package
WRC	World Radiocommunication Conference

APPENDIX A – COMMAND AND CONTROL LINK PERFORMANCE CRITERIA

UAS C2 links must meet the performance levels stated in the UAS operator's safety case and approved by the FAA. The metrics associated with those criteria depend on many factors, including among others the size of the UA, the environment in which the UA will operate, and whether humans are aboard the UA as passengers. Performance concerns must be factored into the safety-risk assessment for each applicable use case.

Key metrics for quality of service include latency, availability, and continuity. All three of those metrics strongly affect the ability of the UAS to respond in a timely fashion to pilot commands and to external safety threats such as an imminent collision. Numerical values for the metrics depend on the acceptable risk level and on the degree to which message delays can threaten UAS mission success. RTCA DO-377 [10] provides quantitative guidance on various key performance criteria in a variety of situations.

A.1 Key Performance Metrics

A.1.1 Latency

Latency is the time delay between initiation of a C2 message at the control station or on the UA, and its successful reception at the other end of the C2 link. Low latencies are particularly important during takeoff and landing, and in other situations where pilots may have to respond quickly to adverse changes in the environment. Depending on UAS mission and flight phase, maximum acceptable latencies may range from as little as 155 milliseconds to well over one second.

A.1.2 Availability

Link availability is the probability that the C2 link will be functioning properly at the beginning of a transaction between the pilot and UA. Availabilities greater than 99.99% are needed for air traffic control and safety-related UAS functions in many circumstances. For UAS, availability requirements depend on the importance of the C2 link in the context of the safety requirements for a given mission, UA type, speed, and nature of operation.

A.1.3 Continuity

Link continuity is the probability that the C2 link, if available at the beginning of a transaction, will continue to function properly until the end of the transaction. Typically, the stringency of continuity requirements is similar to those of availability requirements in a given situation. The duration of C2 link outages is also of concern. Long interruptions tend to degrade UAS performance and safety more seriously than short ones.

A.2 Electromagnetic Compatibility

Every C2 link must be able to coexist (i.e., function without causing harmful interference) in the spectrum with other C2 links in its vicinity.

A.2.1 Co-site Electromagnetic Compatibility

Co-site compatibility is the ability of a C2 link transmitter to operate successfully without causing harmful interference in its own collocated receiver or in the receiver of other RF equipment on the same aircraft or in the same ground station. Two important methods of protecting a C2 link against self-interference are frequency-division duplexing (in which the uplink and downlink operate on different frequencies) and time-division duplexing (in which they take turns transmitting on a single frequency and so cannot mutually interfere). Electromagnetic compatibility of multiple systems can be achieved by time-sharing or by filtering of signals operating in different channels or bands, to prevent mutual interference.

A.2.2 Inter-site Electromagnetic Compatibility

Inter-site compatibility is the ability of a C2 link to operate successfully without degrading the performance of other systems (C2 or non-C2) that are not collocated with the C2 link's transmitter. This can be achieved through careful spectrum management, which can be accomplished by traditional frequency assignment techniques or (in newer systems) by real-time or near-real-time frequency management.

APPENDIX B – L-BAND THREE-DIMENSIONAL WHITESPACE ANALYSIS

The objective of the L-band whitespace analysis is to ascertain the feasibility of operating UAS C2 links in parts of the 960-1164 MHz frequency band and in portions of the NAS without interfering with other aviation systems already using the band. The term “whitespace” refers to the pockets of airspace where such noninterfering C2 operations could take place at one or more L-band frequencies.

Two key radionavigation systems are tunable at one-megahertz increments from 962 MHz to 1213 MHz: Distance Measuring Equipment (DME) and Tactical Air Navigation (TACAN).

Three specific frequencies are reserved for surveillance systems: 978 MHz for the Universal Access Transceiver (UAT), and 1030 and 1090 MHz for secondary surveillance radar (SSR), the Traffic Alert and Collision Avoidance System (TCAS), and the military Identification Friend or Foe (IFF) system. Certain other systems such as simulators, testers, and trainers also operate in the band and must be considered in determining where whitespace exists. ADS-B uses two data links on separate frequencies. UAT on 978 MHz, and the Mode-S Extended Squitter (ES) link, which operates on 1090 MHz. The Mode-S ES ADS-B link is designed to coexist with SSRs and TCAS, which also operate on 1090 MHz.

Certain segments of the band seem generally unsuitable for C2 operations because of the difficulty of preventing RFI, regardless of geographical location. The 960-977 MHz sub-band is reserved for TACAN on ships, whose locations are unpredictable; 978 MHz is used only by UAT; and 979 MHz is heavily used by certain DME test equipment. C2 operation within the 1021-1039 MHz and 1081-1099 MHz sub-bands would pose too great a risk of adjacent-channel interference to SSR and TCAS receivers. The need to protect GPS L5 receivers in the adjacent 1164-1189 MHz band against RFI requires significant restrictions on the output powers of aeronautical radios operating above 1127 MHz. Those restrictions tighten as frequency increases, and above 1140 MHz they become too severe for most C2 uses. That leaves the following sub-bands as whitespace candidates:

- 980-1020 MHz
- 1040-1080 MHz
- 1100-1140 MHz (with diminished usability above 1125 MHz).

Figure B-1 depicts the DME operation, in which a DME interrogator aboard an aircraft exchanges pulsed radio signals with a DME beacon on the ground. Each interrogation elicits a reply from the beacon. Two separate frequencies, separated by 63 MHz, are involved: one for the downlink from the interrogator to the ground-based beacon, and the other for the beacon-to-interrogator uplink. The DME-equipped aircraft uses the time lag between transmitting the interrogation and receiving the reply to determine the distance to the beacon, which helps the pilot to determine the aircraft’s location. TACAN operates similarly, except that its beacons also have a means for ascertaining the azimuth of the interrogator and reporting the azimuth back to the aircraft.

Using a Flight Management System (FMS) computer, air carrier aircraft can compute their current positions via the integration of two or more DMEs. This alternate form of area navigation provides a safe backup to the risk of GPS interference.

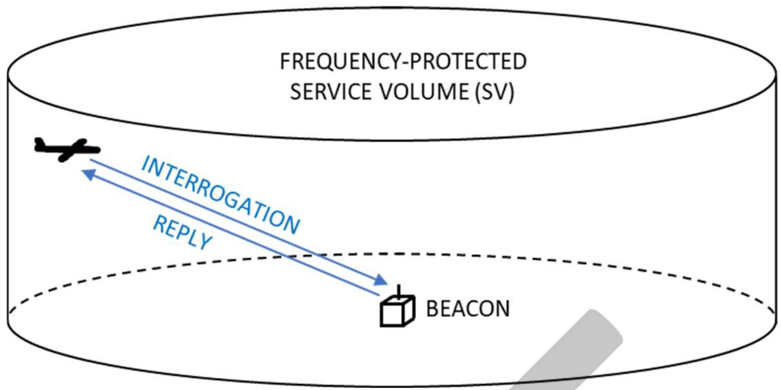

Figure B-1. DME Operation

Each DME or TACAN beacon has a defined frequency-protected service volume (SV) and can reply almost simultaneously to every interrogating aircraft within that SV. The NextGen DME program is currently working to greatly expand the low-altitude SV of most of the existing and future DME sites to provide a more resilient navigation system for CONUS. Most of these SV expansions should occur by 2022. Frequencies have been assigned to the network of DME and TACAN beacons across the country in such a way that signals emitted by any given beacon and its airborne interrogators will not interfere with those of any other beacon or interrogator, provided that the interrogators remain within the SVs of the beacons on whose downlink frequencies they are transmitting.

A whitespace analysis requires determining whether a C2 signal emitted by the UA at a given frequency will be strong enough when it enters the receiver of any DME interrogator or beacon to degrade that receiver's operation. If it is, the UA SV (or some of it) is outside the whitespace for that frequency, and so the frequency should not be used there for C2.

Figure B-2 shows a notional example of potential C2-to-DME interference. Following good spectrum-management practice, we conservatively assume that the UA and both DME-equipped aircraft are positioned at the points in their respective SVs that minimize the possible RLOS distance and thus maximize the likelihood of RFI. In this hypothetical example, the UA transmitter is close enough to cause interference to both DME-equipped aircraft and to the beacon serving DME SV 1. DME SV 2 is far enough from the UA to be shielded sufficiently by the curvature of the earth and/or by intervening terrain such as hills and mountain ridges, which are not shown in Figure B-2. (We also assume in this example that the C2 ground station is inside the UA SV and has an effective isotropically radiated power no greater than that of the airborne C2 transmitter. If those conditions were not met, it would also be necessary to identify separately any possible interference paths from that ground station to the DME-equipped aircraft and beacons.)

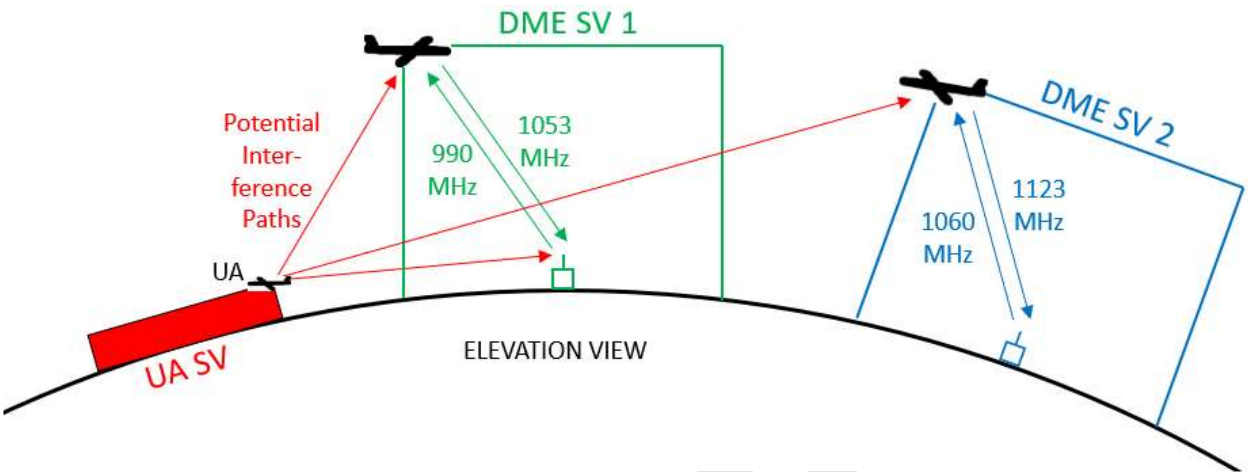

Figure B-2. Potential Interference Paths from a UA C2 Transmitter to DME Receivers

Power calculations are necessary to determine whether RFI is possible. The following rule expresses a general requirement for protecting a radionavigation system such as DME or TACAN against undesired radio signals such as C2 transmissions:

$$P_{ru} = P_{tu} + G_{tu} - L_{fu} - L_{au} + G_{ru} - L_{rc} - X - F(\Delta f) + M_a + F_m \leq T, \qquad \text{(B-1)}$$

where

P_{ru} = Effective on-tune C2 signal power, in dBm (decibels [dB] referred to one milliwatt), that enters the DME or TACAN receiver.

P_{tu} = C2 transmitter power in dBm.

G_{tu} = Gain of C2 transmitting antenna toward the DME or TACAN receiver in dBi (dB referred to the gain of a lossless isotropic antenna); for airborne transmitters, this is likely to be 2–5 dBi.

L_{fu} = Free-space propagation loss in dB along the RLOS path = 20 log ($f D_u$) + 37.8 dB.

f = Signal frequency in MHz.

D_u = Worst-case (minimum) distance (nmi) of the UA from the DME or TACAN receiver.

L_{au} = Excess path loss (dB), from terrain, buildings, or foliage, in addition to free-space loss. This is computed by means of a rough-earth propagation-loss calculation model such as the one described in ITU-R Recommendation P.2001.

G_{ru} = Gain (in dBi) of the DME or TACAN receiving antenna toward the C2 transmitter, in dBi (9.1 dBi for TACAN beacon antennas; otherwise 5.4 dBi [21]).

L_{rc} = DME or TACAN antenna-to-receiver cable loss (typically 2.5 dB).

X = cross-polarization loss (dB); this is zero if the C2 transmitter uses the same polarization as DME and TACAN but could be 3 dB or more if it does not.

$F(\Delta f)$ = frequency-dependent rejection (FDR), by the DME or TACAN receiver, of a C2 signal whose frequency is separated by Δf MHz from the receiver's tuned frequency. This is expressed in decibels and depends on the C2 transmitter's emission spectrum, the frequency selectivity of the DME or

TACAN receiver, and the amount of off-tuning Δf. As an example, Figure B-3 shows the FDR for one class of C2 transmitters and one class of DME airborne receivers.

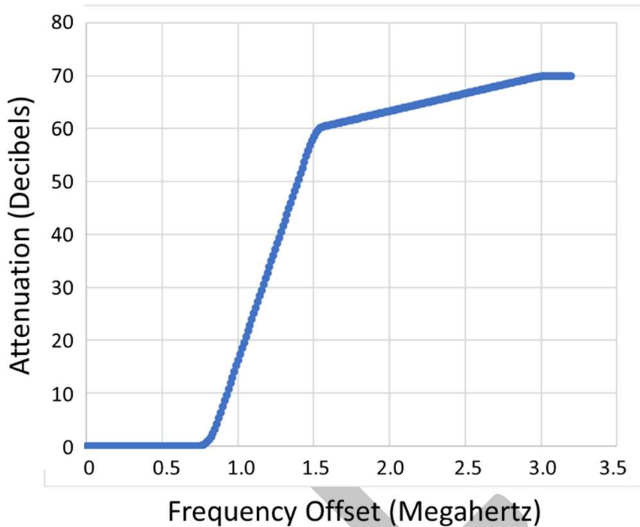

Figure B-3. Example of Frequency-Dependent Rejection of C2 Signals

M_a = Aviation safety margin (dB); the International Civil Aviation Organization (ICAO) often recommends a margin of 6 dB for safety-critical systems.

F_m = Multiple-equipment factor (dB), which may be needed to allow for possible additive effects of multiple undesired C2 signals entering a single receiver.

T = Receiver's interference threshold (dBm). This is the maximum value of P_{ru} that the receiver can tolerate without degradation of its performance. If the undesired signal is continuous-wave (CW), i.e., non-pulsed, then $T = -99$ dBm for DME airborne receivers [22]. Recent test data suggest that TACAN airborne receivers are more susceptible than DME ones to CW RFI, with $T = -108$ dBm.

Solving (B-1) for D_u yields the minimum distance that is needed between the C2 transmitter and the DME or TACAN receiver to protect the receiver against interference when a RLOS exists:

$$D_u \geq 1.23 \text{ x } 10^{-5} \text{ antilog } (0.05(P_{tu} + G_{tu} - L_{au} + G_{ru} - L_{rc} - X - F(\Delta f) + M_a + F_m - T)). \qquad \text{(B-2)}$$

As an example, suppose that for a given pair of C2 and DME/TACAN equipment classes, $P_{tu} = 40$, $G_{tu} = 3$, $L_{au} = 0$, $G_{ru} = 5.4$, $L_{rc} = 2.5$, $X = 3$, $F_m = 0$, $M_a = 6$, and $T = -99$, and frequency-dependent rejection $F(\Delta f)$ is as shown in Figure B-3. Then, solving (B-2) shows that interference-free operation of the C2 transmitter and the DME/TACAN receiver on the *same* frequency (so that $\Delta f = 0$ MHz and thus FDR = 0 dB) is possible only if the distance between them is at least 305 nmi. However, operation of the two systems at frequencies 1 MHz apart ($\Delta f = 1$ MHz) would increase the FDR to 16 dB and weaken the received interfering signal by the same amount, so that the two systems could operate at a distance as little as 48 nmi.

Expression (B-2) can be used, in conjunction with a terrain database and a current database of existing DME/TACAN beacons, together with their SVs and assigned frequencies, to generate maps showing the parts of U.S. airspace where any UA having specific transmitter characteristics could fly at particular frequencies at or below a given altitude without interfering with any DME or TACAN receivers. Whitespace maps like this could be published in electronic form, made available via the internet, and updated whenever the frequency-assignment database changes. A separate map could be provided for each frequency of interest at whatever frequency increments are desired (e.g., every megahertz or every 50 kilohertz). The map scale should be user-selectable. An interactive map could be provided that would, upon request, list the frequencies currently available for C2 at any selected point in the airspace. Eventually, the frequencies usable in the service volume of any particular UAS could be provided directly to its C2 radios with little or no need for UAS operator intervention.

Expression (B-2) has been employed together with the ITU-R P.2001 propagation model, digitized terrain data, and a database of current DME and TACAN frequency assignments in the 960–1215 MHz band to obtain early estimates of the numbers of 1-MHz wide DME channels that could be found usable by such an electronic map for the C2 radio links of UA flying up to 400 ft AGL over the contiguous U.S. Those estimates appear in Figure B-4. At the assumed altitude, L-band whitespace is much more abundant in some parts of the country than in others, but some whitespace exists almost everywhere. The color of each circular dot represents the number of DME channels found to be usable by a 1-watt (CW) UA C2 transmitter, with a 3-dBi antenna, flying 400 feet above terrain at the site at the *center* of the circle, without interference risk exceeding 1% to any incumbent L-band ground or airborne receiver.

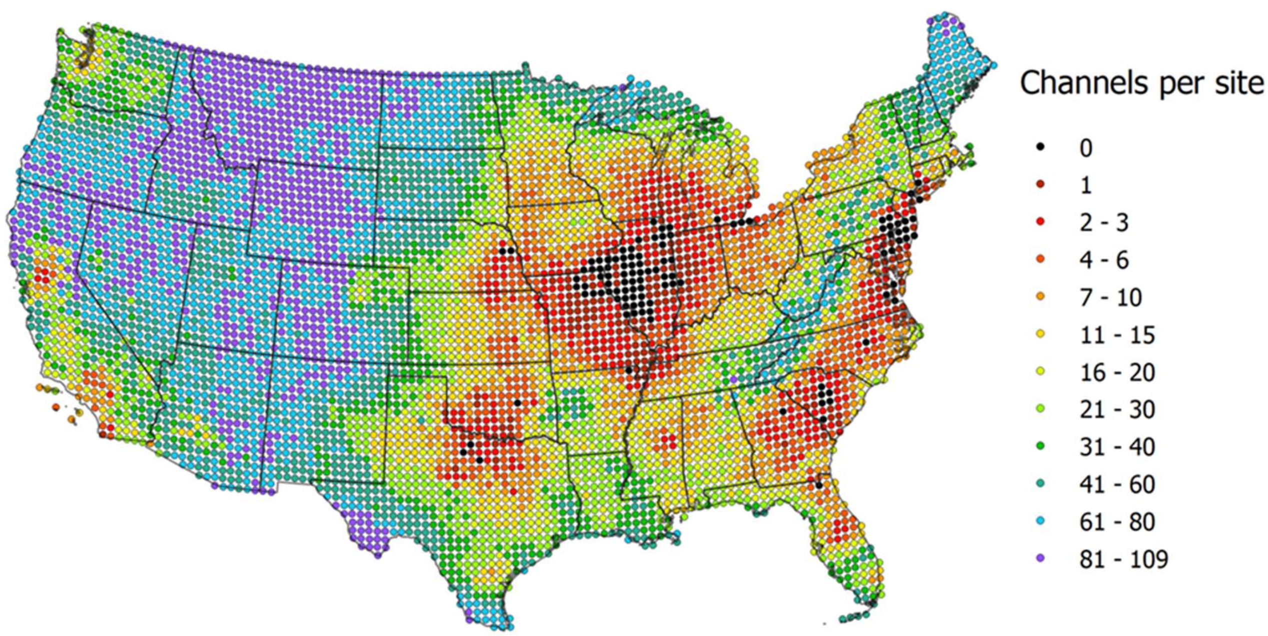

Figure B-4. Early Estimate of Numbers of 1 MHz DME Channels Potentially Usable for C2 by UA Flying 400 Feet Above Ground Level at Each of 5,496 Sites in CONUS

Although CW transmitters and interference thresholds were assumed in generating the whitespace map of Figure B-4, C2 system designs using non-CW (pulsed) transmitters are also possible. Several such systems could time-share a usable DME channel so that their aggregate effect could resemble that of a single CW transmitter. Hence these results are applicable to pulsed as well as CW implementations of a UAS C2 system if the assumed peak pulse power is one watt.

The estimates in Figure B-4 were obtained by:

- Creating a grid of 5,946 points spaced approximately 20 nmi apart within CONUS.
- Identifying, from a U.S. government database, all DME, TACAN, and other incumbent L-band ground stations in the U.S. and Canada, together with their associated SVs.
- Applying expression (B-2), in conjunction with a terrain database and relatively conservative (i.e., pessimistic) assumed values of parameters such as C2 transmitter power and DME/TACAN frequency-dependent rejections of C2 signals, to determine the minimum standoff distances required to protect (with a probability of at least 99%) every incumbent receiver against interference from the hypothetical C2 transmitter at any given point. CW DME and TACAN interference thresholds were used as appropriate in the calculations.
- Ruling out the use by the UA C2 transmitter, at any of the 5,946 points, of any DME channel whose use was found to violate the distance criterion for any of the incumbent receivers.

The predictions embodied in Figure B-4 should be validated by appropriate field tests and bench testing of actual C2 transmitters and DME/TACAN equipment.

The computer program generating the electronic whitespace maps should consider the blocking effects of terrain, buildings, and foliage on radio wave propagation. That will enable C2-equipped UA to fly in some places that would otherwise be ruled out as interference risks. The program should also consider the possibility of ducting (atmospheric effects that sometimes enables undesired signals to propagate farther than under normal conditions). The program used to generate Figure B-4 has those characteristics, except that the terrain database did not include buildings or foliage. The whitespace mapping program should also have a user-selectable scale map scale and provide users with lists of channels that are usable throughout their own SVs. Eventually, the lists might be delivered directly to the radios without the need for UAS operator intervention.

A standard "acceptable" probability (perhaps less than 1%) of interference to DME, TACAN, and other incumbent L-band systems should be defined and incorporated into the program for its use in deciding which areas are whitespace and which are not. To ensure that this standard is met, procedures should be established for identifying any cases of C2 interference to incumbent systems and making appropriate corrective changes to the program. Of course, the smaller the acceptable risk, the smaller the number of usable channels is likely to be.

The numbers of usable channels indicated in the whitespace map would be larger if certain alternative assumptions had been made. For example, if the assumed UA altitude had been lower than 400 feet AGL, there would have been unobstructed interference paths to a smaller number of potential victim DMEs and TACANs, so fewer channels would have been ruled out. On the other hand, increasing the assumed UAS C2 transmitter power to, say, 10 watts would have substantially increased the number of interference cases, thus reducing the number of usable channels.

It is possible for a potential interferer to approach a receiver so closely that no amount of off-tuning can provide enough frequency-dependent rejection to prevent RFI. This may result in the need to identify and maintain "exclusion zones" around ground-based receivers. When identifying whitespace, the program may need to identify such exclusion zones around DME/TACAN beacons and possibly also other ground-based receiving equipment in the band, including those belonging to 1090-MHz receivers.

Eventually, the Federal Aviation Administration (FAA) might consider increasing the total amount of C2 whitespace available in L-band by changing the frequency assignments of incumbent DME, TACAN, and other ground stations in such a way that they will be more spectrally “compact” and occupy less spectrum in the aggregate, thus creating additional spectral room for C2 users. In the near term, however, the FAA is more likely to reduce available whitespace by adding new DME ground stations and expanding the frequency-protected service volumes of those that already exist.

The foregoing analysis has considered only the prevention of RFI from C2 transmitters to the receivers of incumbent L-band systems. It may also be necessary for the program to consider interference in the reverse direction, from incumbent systems to C2. That would add to the complexity of the computer program but might be manageable if all the C2 systems using the band belonged to distinct classes whose receiver characteristics were well defined.

APPENDIX C – UAS C2 COEXISTENCE WITH LINK 16 IN L-BAND

Link 16 enables the exchange of near-real-time tactical data among U.S. and allied military units. It was expected by the DoD that by 2015 over 5000 military units would use Link 16. It uses time-division multiple access (TDMA) with frequency hopping among 51 frequencies to discriminate between different users within a network. It operates on a non-interference basis in the 960-1215 MHz band [9] on a nation-by-nation basis [2]. Part or all of the full set of 51 hopping frequencies may be used in each participating country. Link 16 has been designed and operates in a way not to interfere with (or suffer interference from) DME, but it would not be protected from interference if DME were to be replaced by another type of system since it is not the primary user of the band.

The NTIA Manual [10] details the agreements between DoD and DOT regarding Link 16. The agreements are to assure spectrum access to the 960-1215 MHz band and to maintain mutual compatibility between ATC systems and the Link-16-compliant Joint Tactical Information Distribution System (JTIDS) and Multifunctional Information Distribution System (MIDS) within the U.S. and Possessions (US&P). The following paragraphs are consistent with DoD-DOT agreements:

a. Uncoordinated JTIDS/MIDS TDMA waveform operations are authorized in the 960-1215 MHz band in accordance with the coordination outlined in the authorizing NTIA spectrum certification documents.

b. The DoD shall incorporate engineering features in the JTIDS/MIDS TDMA Waveform equipment in accordance with the NTIA guidance and requirements for JTIDS/MIDS electromagnetic compatibility (EMC) features. The engineering features when implemented shall minimize the possibility for harmful interference between ATC and JTIDS/MIDS TDMA waveform systems operating in the US&P.

c. The DOT will support US&P frequency assignments for JTIDS/MIDS TDMA Waveform operations, with the conditions identified in the authorizing NTIA spectrum certification documents and as set forth in the agreements.

d. The DoD will ensure that by January 1, 2025, all fielded JTIDS/MIDS TDMA waveform terminals will be capable of remapping frequencies. The remapping implementation will be flexible, but there will not be a requirement to remap more than 14 carrier frequencies. The remapping capability will be used as necessary to prevent harmful interference with ATC systems that have been approved by a NTIA Stage 4 spectrum certification.

e. The DOT will ensure that planned and future systems that are to be implemented using spectrum not subject to remapping will be designed to satisfy their minimum performance standards in their intended electromagnetic environments. This will ensure that such new or modified systems shall incorporate features so as to not constrain JTIDS/MIDS TDMA waveform terminal operations in accordance with the approved NTIA Spectrum Certification.

f. Coordination procedures for JTIDS/MIDS TDMA waveform terminal operations involving all 51 frequencies, operations exceeding approved NTIA spectrum certification conditions, and operations involving non-U.S. and new terminals shall be cooperatively developed by the DoD and DOT.

Because it must be non-interfering, Link 16 must accommodate new ARNS systems. This includes changes to waveform (e.g., remapping) and radio terminal and platform design characteristics (e.g., EMC features, signal levels, filters). In addition, restrictions are applied to:

- Functionality (e.g., contention or relay modes)
- Location (e.g., separation distances, special areas)
- Limited operational times
- Coordination requirements
- Authorized level of operations (e.g., an aggregate geographic-area time slot duty factor)

Link 16 does not have a primary allocation in the 960-1215 MHz band. DoD use of the band is governed in conformance with its Link 16 spectrum deconfliction directive [23]. That directive establishes FAA responsibility for authorizing and remapping specific Link 16 channels to ensure that FAA services are uninterrupted.

A range of policy, operational, economic, and technical challenges and implications would arise from altering Link 16 operations:

- Discontinuing DME services undermines the justification for the ITU allocation of ARNS to the 960-1164 MHz band. Negotiations to preserve or amend the allocation to protect Link 16 utilization of the band would include a wide range of stakeholders, including:
    - Ministries of Defense of about 30 countries (e.g., North Atlantic Treaty Organization nations)
    - Civil aviation authorities
    - National spectrum-management authorities (analogous to the FCC and NTIA)
- Various 960-1164 MHz band-clearing scenarios would have negative effects on DoD use of Link 16 since they would result in remapping some number of Link 16 channels.
- The DoD mission may be compromised if the remapping of Link 16 channels approaches the minimum set of channels needed to ensure a viable communications service (i.e., 37 of the 51 allocated channels remaining when 14 are remapped).
- DoD may seek to retain the right to authorize use of remapped Link 16 channels in the event of a national emergency. Such a right may reduce the commercial value of the spectrum.
- If the DoD does not cooperate, as required by the equipment certification, with the remapping of the Link 16 channels in the affected range, then the commercial value of this whole spectrum band will be reduced.
- The FAA would need to collaborate with other affected parties (e.g., DoD) to ensure all their mission objectives are satisfied. Sharing the benefits of vacating the spectrum could help ensure the needed collaboration.

APPENDIX D – FEASIBILITY OF A NATIONWIDE UAS SURVEILLANCE CHANNEL IN L-BAND

UAS are continuing their trend of being the fastest growing new entrant in the NAS. With projections of continued sales and registration growing to 2.69 million small UAS (sUAS) by 2020 per the FAA’s lower-bound estimate [7], many more sUAS will be entering the NAS by 2025. Many of these operations are expected to occur below 400 feet (ft) AGL.

All aircraft are required to stay well clear of other traffic, which is a key requirement for UAS operators. They must have cognizance of nearby aircraft and obstacles for situational awareness. While currently not required to communicate with manned aircraft about their position and identification, the UAS operations allowed near towered airports are required to coordinate with ATC to maintain well clear. Traffic information received from manned aircraft equipped with Automatic Dependent Surveillance-Broadcast (ADS-B) Out will help UAS stay well clear of, and avoid collisions with, those aircraft. However, UAS may have no information about aircraft operating outside ADS-B rule airspace (i.e., airspace in which ADS-B Out is required [24]).

One approach for UAS to communicate their position and identification is to clear one or two L-band DME channels to be used nationwide exclusively for this purpose on a shared basis. These new channels, called cooperative UAS surveillance channels, would allow the exchange of UAS information for the purpose of seeing and being seen for detect and avoid concepts, and to enable the exchange of information needed by UAS Service Suppliers (USS) for managing the UAS traffic. Two identified methods for exchanging UAS traffic information air-to-air (i.e., UA-to-UA) and air-to-ground (i.e., UA-to-USS) are 1) through the new L-band channels, and 2) through an air-to-ground link that uses cellular network services in C-band. This concept could be expanded to all UAS flying in the NAS, but the initial focus would be on serving UAS operated below 400 ft AGL.

Creating new cooperative UAS surveillance channels in L-band would keep most UAS traffic information off current manned aircraft ADS-B links (except when required by the FAA). This action would remove the risk of co-channel interference on the ADS-B channels, which could be high due to the anticipated high UAS traffic densities [25] [26].

Figure D-1 illustrates potential industry-provided methods for communicating UAS traffic information. The architecture in Figure D-1 supports UAS receipt of manned aircraft surveillance information available in the ATC system, but does not include the ATC system obtaining UAS surveillance information for operations outside controlled airspace. UAS not operating under ATC provided by the FAA will operate under UAS traffic management (UTM) provided by USS.

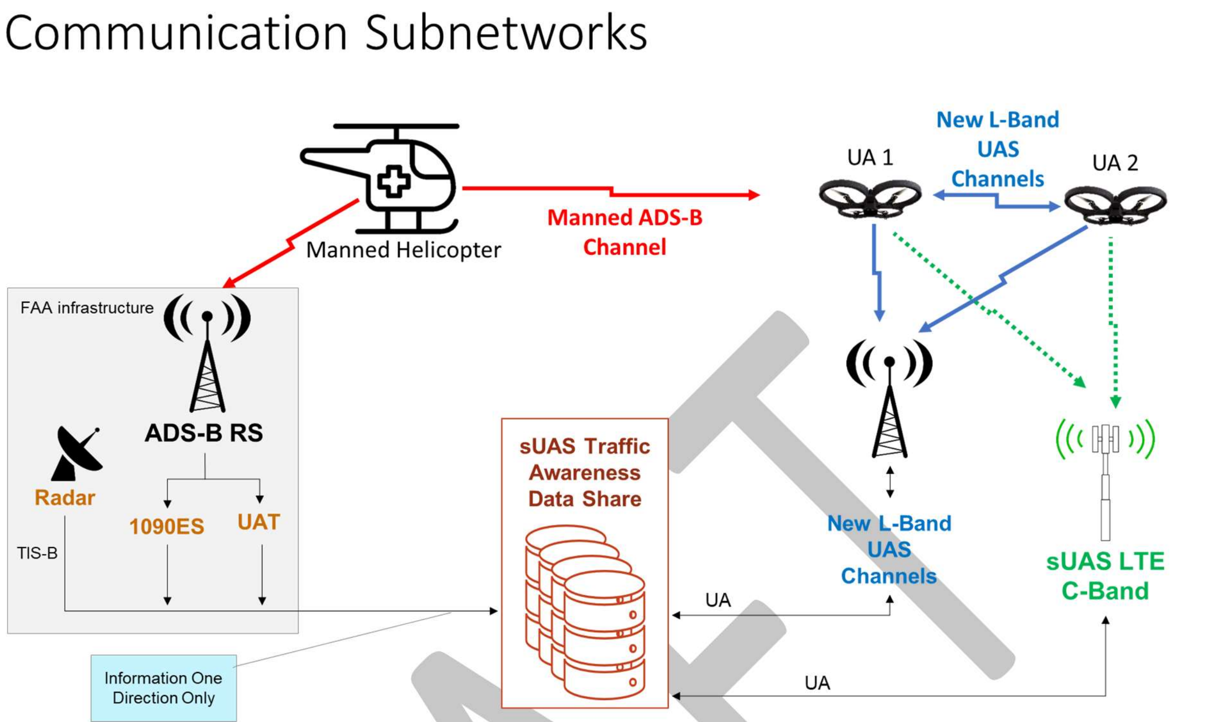

Figure D-1. Communication Paths for UAS Traffic Information Sharing

The proposed UAS traffic information communications architecture allows the integration of any industry-provided method to communicate UAS traffic information using a common message format and protocol. Industry and the FAA would work together to create the message format and protocol. Central to this architecture is common UAS traffic data share. The UAS traffic data share could be a USS-based service under UTM. Multiple UAS traffic information communication solutions may be used in the same operating environments. These solutions must be interoperable with each other. That is, UAS traffic information must be shared in a uniform manner across all the solutions used in a common operating environment.

The proposed concept will require further study and definition. The federal government and industry would need to design this capability jointly. Industry support and commitment to develop, evaluate, test and deploy such a system would be needed as well.

APPENDIX E – FEASIBILITY OF USING LTE FOR UAS C2

The main focus of this report is on concepts to enable the use of the L-band and C-band for UAS C2. At the same time, the topic of the potential use of 4G/5G wireless technologies in current mobile services spectrum was mentioned in multiple stakeholders' written comments to the FAA's concept overview document and in subsequent discussions during the stakeholder roundtable.

In response to stakeholders' feedback, this appendix briefly describes ongoing efforts to evaluate the potential use of 4G LTE and its 5G evolution, in current mobile services bands, to support the connectivity needs of UAS, in particular that of sUAS at low altitudes.

Significant efforts are taking place in parallel across numerous stakeholders including the UAS community, the wireless industry, government and academia to perform research, development, testing and standardization to enable the safe introduction of UAS in the NAS and across the world.

Given that the topic of this appendix is the potential use of wireless technologies in mobile services bands, one of the topics described below is the ongoing sUAS-related standardization activities within 3GPP. Then, the collaboration between industry stakeholders and FAA as enabled within the UAS Integration Pilot Programs is highlighted, with a focus on UAS C2.

It is anticipated that large numbers of new users are expected to request access to the NAS, including UAS and Urban Air Mobility (UAM) vehicles. These new users will need enhanced wireless connectivity to support their envisioned complex and large-scale operations. sUAS flying at low altitudes (i.e., at or below 400 ft AGL) are providing initial use cases for the large-scale introduction of such new users in the NAS. Many sUAS operations beyond the pilot's visual line of sight are being considered by industry. To safely support such operations, reliable and scalable communications solutions are needed for sUAS C2 links and for sUAS connectivity in general.

Activities are ongoing across multiple standards bodies to address various aspects of enabling safe BVLOS UAS operations. Such activities have been highlighted in a recent ATIS report [27] and include those from organizations such as ATSM, IEEE, RTCA and 3GPP. As previously noted, the 3GPP-related activities are described in more detail in this appendix.

4G LTE and 5G wireless technologies are under consideration within the sUAS community and the wireless industry to support the connectivity needs of sUAS in BVLOS operations. 3GPP technical reports and technical specifications are addressing support for sUA as new users (that are airborne) in wireless networks.

Initial efforts in this area have resulted in a 3GPP technical report, TR 36.777 [28], which documented Radio Access Network (RAN) considerations regarding how existing LTE networks, used by terrestrial users, could also support the connectivity needs of low-altitude sUA as a new user type.

TR 36.777 summarized evaluation efforts from multiple industry participants who submitted simulation results and/or field trial results in specific scenarios and geographical areas. All submitted contributions are referenced within the report [28]. It concluded that existing LTE network implementations can serve sUAS. However, challenges can be encountered, and they become more visible as the density of sUA increases. It was noted within the report that potential interference issues[58] could be experienced by sUA and also by the terrestrial network that would support them.

Using parameters identified for system-level simulations in [28], an additional study [29] was performed in a geographical area[59] of approximately 35 by 35 kilometers (km). Envisioned low-altitude sUA operations in the area could include agricultural operations (e.g., crop monitoring) and linear infrastructure inspections. Although performed in a different geographical area, and evaluating different scenarios, that study[60] also indicated performance trends similar to those presented in or referenced within the 3GPP report [28].

TR 36.777 also described potential enhancements to better support sUA. Enhancements[61] include potential ways to better detect interference from sUA, potential methods to reduce interference at the sUA, potential means to reduce interference experienced by the network itself from serving sUA, and techniques[62] to improve sUA mobility performance.

Some of the identified potential enhancements necessitated updates to 3GPP technical specifications as noted in [30]. A set of such updates have been defined as part of the Release 15 work as discussed in [31] and have been incorporated in approved Release 15 specifications.[63,64]

While work in Release 15 specified RAN enhancements to better support the connectivity needs of sUAS, ongoing work in Release 16 is focused on the architecture and services aspects and on application layer improvements. This work includes system requirements to support the connectivity needs of sUAS at low altitudes as specified in [32] and application-layer considerations being analyzed in [33].

Further UAS-related efforts in 3GPP Release 17 continue to be supported by the sUAS community and the wireless industry [34], [35].

Collaboration continues to take place among stakeholders and in partnership with the FAA through the UAS IPP programs [36] and the UTM Pilot Program [37]. As noted in [36], the UAS IPP program

[58] As described in [28], a sUA at altitude, due to its high line-of-sight propagation probability, would likely receive signals from a larger number of cell towers than a typical terrestrial user. Therefore, a sUA would likely experience higher interference than a terrestrial user. In the same way, since a sUA would likely experience line-of-sight propagation conditions to more cell towers than a terrestrial user, a sUA would also cause more interference to more cells than a terrestrial user.

[59] This analysis was performed in a rural environment near Richmond, Virginia, and it incorporated terrain and land-use/clutter data within the analysis area.

[60] Results indicated that, for the described set of parameters and assumptions, in areas characterized by fairly flat terrain and in a rural environment, the received signal levels at the sUA from its serving cell tower decreased as the sUA altitude increased from 100 ft to 400 ft AGL. Results also showed that received signal levels for sUA at 100 ft and 400 ft AGL would be better than those received by terrestrial users within the same area. In areas where terrain impacts were observed, they were observed primarily at the low(er) sUA altitude (e.g., 100 ft AGL). Results also showed that the received signal quality decreased as the sUA altitude increased. This was due primarily because the sUA could “see” and “be seen” by more cell towers, as its altitude increased.

[61] Potential enhancements include use of existing or improved measurement reporting mechanisms at the sUA, identifying the airborne status of the sUA, improved exchanging of information among neighboring cell towers, use of full-dimension multiple-input, multiple-output (MIMO) techniques, use of directional antennas at the sUA, coverage extension techniques, and enhanced power-control based mechanisms.

[62] Potential techniques to improve the sUA mobility performance include enhancements to handover procedures and enhancements to measurement reporting mechanisms by sUA as users in terrestrial networks.

[63] Technical specifications approved in 2018 as part of 3GPP Release 15 that incorporated updates to enhance support for sUAS as users in terrestrial networks include: TS 36.300, TS 36.306, TS 36.213 and TS 36.331.

[64] These updates are also described in detail in technical papers such as [42], [43].

is bringing state, local, and tribal governments together with private sector entities, such as UAS operators and manufacturers, to test and evaluate the integration of civil and public drone operations in the NAS.

In the area of UAS C2, and UAS connectivity more broadly, a set of voluntary common data testing principles and performance metrics have been established through a collaborative process between CTIA and FAA, as mentioned in [38]. These principles and metrics are to be used by wireless companies participating in the UAS IPP program. As further described in [38], this recent collaborative effort could provide an excellent starting point for future reviews of wireless technology metrics.

Research, flight testing and trials, and standards development in 4G LTE and 5G to date have focused primarily on low-altitude sUAS operations. Findings from such activities on the potential use of LTE for sUAS C2 (and for sUAS connectivity more broadly) could highlight communications link performance trends and also areas of further analysis as the focus moves towards higher-altitude users including larger UA and UAM vehicles.

A need is emerging for further technical studies and flight tests to evaluate the feasibility of using terrestrial networks implementing LTE and 5G new radio (NR) radio access technologies to support UAS C2 for UA altitudes higher than 400 ft AGL and potentially using higher frequency bands (e.g., C-band). If deemed feasible, further efforts by industry would likely be needed to develop solutions that could support the communications needs of larger UAS and of UAM vehicles.

An additional important area of further exploration is to identify means of coexistence among non-networked and networked link solutions being envisioned in the 5030-5091 MHz portion of C band.

In summary:

- Standardization activities are ongoing to enable the large-scale use of 4G LTE and 5G wireless technologies for UAS communications.
    - The initial focus is on low-altitude sUAS using mobile services bands.
- Collaboration is taking place among numerous stakeholders and in partnership with the FAA through programs such as the UAS IPP for integrating civil and public sUAS operations in the NAS.
- There is an emerging need to evaluate the feasibility of using terrestrial LTE and 5G networks for communications with larger UAS and UAM vehicles operating at higher altitudes.
- Further exploration is needed to identify means of coexistence among non-networked and networked link solutions being envisioned in the 5030-5091 MHz portion of C-band.

APPENDIX F – KEY TERMS

This appendix presents definitions of key terms used in this report. In doing so, it also defines the report's scope.

F.1 Visual Line of Sight (VLOS)

Section 374 of the 2018 FAA Reauthorization Act indicates that the report to Congress should include recommendations of other spectrum frequencies that may be appropriate, if it is determined that L-band and C-band frequencies are not suitable for UAS operations BVLOS. Accordingly, this report addresses UA operations that occur beyond the pilot's VLOS (BVLOS). A UA can be operated within or beyond the pilot's ability to directly see it with his or her eyes, unaided except by corrective lenses. This delineation has no direct bearing on the UAS C2 link implementation. That is, the acceptable radio technologies, networks, and spectrum bands are not determined solely by the UA's visibility to the pilot. Instead, they are driven by the safety-risk level acceptable to the FAA as well as the C2 link performance needed to keep the UAS operation at or below that risk level.

The following categories with respect to visual line of sight are within this report's scope:

- **VLOS:** Operation of UA within VLOS means the pilot in command can see the UA throughout the entire flight operation, unaided except by corrective lenses to improve one's vision or by sunglasses to reduce the ambient light level. The pilot also must be able to see other aircraft and obstacles in the aircraft's vicinity with sufficient clarity to keep the UA clear of and avoid colliding with them. VLOS operations are within scope.
- **BVLOS:** Operation of UA BVLOS means that the pilot in command cannot see the UA during part or all of the flight. The loss of aircraft visibility to the pilot may be due to obstructions, low ambient light, weather, or other atmospheric conditions, background clutter, or distance.

  Visual observers and surveillance systems may help the pilot ensure safe operation of the UA when it is not visible to the pilot. If the pilot and visual observers collectively are able to see the UA throughout the entire flight, the flight essentially is a VLOS operation. Such "pseudo-BVLOS" operations have been achieved by several UAS operators. However, there is little benefit to such operations other than as an interim research step toward BVLOS operations in which the pilot or visual observers involved in the flight operation collectively do not have visibility of the UA throughout the entire flight. BVLOS operations are within scope.

F.2 Radio Line of Sight (RLOS)

The C2 communications link between a UA and its control station may or may not require a network of one or more intermediate nodes. UA operated within the pilot's VLOS typically use a paired-radio link in which the aircraft radio has a direct, non-networked link to the control station radio. Likewise, UA operated BVLOS typically use a networked connection that involves one or more intermediate network links. However, paired-radio links can be used for BVLOS operations and networked-radio links can be used for VLOS operations. The type of radio link (paired or networked) factors into but does not completely determine the acceptable radio technologies and spectrum bands. Instead, the technology and spectrum choices are driven by the UAS operation's safety-risk level acceptable to the FAA as well as the C2 link performance needed to keep the UAS operation at or below that risk level.

The following categories with respect to RLOS are within scope:

- **RLOS:** Operation of UA within RLOS means that there is a single, direct radio link between the UA and its control station. Radio signals often can travel beyond the pilot's visual range and, depending on the radio frequency (RF) used, sometimes can travel through and around obstacles. Atmospheric conditions may shorten or lengthen a radio link's range. Also, other radio transmissions at or near the frequency used may shorten the effective range. Hence, an unobstructed visual sight line between the control station and UA radios does not guarantee the establishment of a radio link that meets the necessary performance levels.
- **BRLOS:** Operation of UA BRLOS means that a single, direct radio link between the UA and its control station is not possible. In this case, the communications link between the UA and its control station depends on a network. The network could be a terrestrial network such as used for cellular wireless communications services, a satellite-based network, a network of one or more airborne radios (including radios on other UA), or any combination of these network types. If a network is required, the UA operation is BRLOS even if only one radio (i.e., non-networked) link is used.

F.3 Altitude

UA can operate at any altitude accessible to aircraft. What is considered low altitude for some airspace users might be high altitude for others. For the purposes of this report, low, medium, and high altitude are defined below. Although specific altitude thresholds are provided, they are not firmly established and should be considered approximate.

- **Low Altitude:** Operation of UA at low altitude means the aircraft remains below 400 feet (ft) above ground level (AGL). Except when taking off and landing, manned aircraft generally operate above 500 ft AGL to stay at least 500 ft away from people, buildings, and other ground-based obstacles per 14 CFR 91.119 *Minimum Safe Altitudes: General*. However, some restricted-class aircraft, such as crop dusters, routinely operate below 500 ft. In addition, helicopters can operate below 500 ft, such as for medivac operations. Hence, low-altitude UA could encounter manned aircraft.
- **Medium Altitude:** Operations of UA at medium altitude means the aircraft operates above 400 ft AGL and below 18,000 ft above mean sea level (MSL). This altitude band spans all airspace classes except Class A; that is, it includes airspace classes B, C, D, low E, and G.[65] Hence, medium-altitude UA operations occur in airspace often used by manned aircraft.
- **High Altitude:** Operations of UA at high altitude means the aircraft operates more than 18,000 ft MSL. The altitude band includes Class A and high Class E (commonly known as "E above A") airspace. Civilian manned aircraft operations generally do not occur above the

[65] U.S. airspace classes are defined here: https://www.faa.gov/air_traffic/publications/atpubs/aip_html/part2_enr_section_1.4.html

Class A ceiling—Flight Level 600. Some commercial UA operations could occur above Flight Level 600, as could some public aircraft operations.

UAS operations at all altitudes are within scope. Most (though not all) small UA operate at low and medium altitudes, most large UA operate at medium altitude, and some large UA operate at high altitude.

The aircraft's altitude has significant bearing on the radio technology and spectrum selections. Aircraft at higher altitudes typically are farther from the radio at the other end of the communications link, and typically fly faster than aircraft at lower altitudes. Both the aircraft's radio distance and its speed bear on the radio link implementation decisions, as they directly affect radio signal transmission and reception.

Also, UA operated at higher altitudes typically present greater risk to people (both in aircraft and on the ground) and property than UA operated at lower altitudes; hence, their operations typically have higher safety assurance requirements. Those requirements, along with the provided safety-risk mitigations, drive the UAS radio link performance requirements and implementation decisions.

Most commercial UA operations will use highly automated flight control systems at all altitudes. However, some UA operated at low altitudes and within the pilot's VLOS may be hand-flown. Hand-flown aircraft typically require higher C2 link reliability and capacity, and lower data transmission latency than aircraft using automated flight control systems. Hence, the type of flight control has a greater influence than altitude on the C2 link's reliability, capacity, and transmission latency requirements.

F.4 UAS Traffic Management System

Commercial UA operated outside 14 CFR 107 are operated either within the ATC system originally developed for manned aviation or within the UTM system currently being defined, developed, and tested jointly by National Aeronautics and Space Administration (NASA), the FAA, and the commercial UAS industry [39], [40], [7]. In the NAS, the FAA provides ATC services and USS provides UTM services. The performance requirements for safety-related UAS functions likely will depend on whether the operation is within the ATC or UTM system.

- **Within the UTM System:** Operation of UA within the UTM system likely will have less stringent C2 link performance requirements than operations within the ATC system. However, C2 link performance requirements for UAS operations within the UTM system have not been established. (Note: UA operated within the UTM system will not require any communications with the ATC system.) UAS operations within the UTM system are within scope.
- **Within the ATC System:** Operation of UA within the ATC system is expected to have more-stringent radio link performance requirements than those within the UTM system. The FAA has established minimum C2 link performance requirements in Technical Standard Order (TSO) C213, *Unmanned Aircraft Systems Control and Non-Payload Communications Terrestrial Link System Radios* [11], for a specific terrestrial radio link system. Minimum performance requirements for all UAS C2 link systems are under development by RTCA and are expected to be codified by the FAA in TSOs and/or Advisory Circulars. UA operations within the ATC system require pilot voice communications with the air traffic controllers,

unlike operations within the UTM system. UAS operations within the ATC system are within scope.

F.5 Spectrum Types

There are three types of radio spectrum: unlicensed, licensed, and federal government. The FCC manages use of the first two; the NTIA manages use of the third. (In some cases, including the 960-1164 MHz and 5030-5091 MHz bands, spectrum is allocated to be shared by FCC licensees and federal government users.) With one exception, all three types could be suitable for safety-related UAS functions, as long as the UAS operation's safety case established by the UAS operator is accepted by the FAA. The one exception is that unlicensed spectrum must not be used for functions enabling a UAS DAA capability. All radio spectrum types are within scope.

- **Unlicensed:** Unlicensed spectrum refers to radio frequency bands in which technical rules are specified for both the hardware and deployment of radio systems that are open for shared use by an unlimited number of compliant users. Any person or entity may use unlicensed spectrum for either private or public purposes so long as the user's equipment is certified by the FCC and operated in accordance with 47 CFR 15 (and 47 CFR 18 for ISM equipment). In contrast with most licensed spectrum use, unlicensed spectrum users have no regulatory protection against interference from other licensed or unlicensed users operating FCC-compliant devices in the band.
- **Licensed:** Spectrum licensed by the FCC to industry includes, for example, spectrum allocated for terrestrial cellular radio networks providing mobile wireless communication services. Access to licensed spectrum is controlled and managed by the licensee, as are any link performance guarantees. Because access to and use of licensed spectrum typically is well managed, licensed spectrum may be suitable for UAS operations that have safety risks higher than UAS operations allowed to use unlicensed spectrum.
- **Federal Government:** Spectrum assigned to federal government agencies includes, for example, spectrum managed by the FAA for aeronautical services needed to ensure the safety and regularity of flight. Access to such spectrum is managed by the NTIA. The cognizant government entity establishes the spectrum access requirements and processes, in coordination with the FCC and NTIA. Like licensed spectrum, government spectrum may be suitable for UAS operations that have safety risks higher than UAS operations allowed to use unlicensed spectrum. Although radio link performance can be guaranteed in both licensed and government spectrum, radio link performance depends on the spectrum usage regulations and the enforcement of those regulations. Use of federal government spectrum does not necessarily mean higher radio link performance relative to the link performance possible with use of licensed spectrum.