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Spectrum Research for Aviation Final Report

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Robert J. Kerczewski
Communication Systems and Technology
Human Exploration and Space Flight Division On Site

Prepared for:

NASA Glenn Research Center
21000 Brookpark Road
Cleveland, OH 44135

Authorized by: Civil Systems Group

Abstract

Task TO-G-026 was established to identify possible spectrum allocations to support the Scalable Traffic Management for Emergency Response Operations (STEReO) Project's approach of applying Unmanned Aircraft Systems (UAS) Traffic Management (UTM) concepts to the management of disaster response. Both large and small unmanned aircraft have been found to provide significant benefits in disaster response. However, application of unmanned aircraft is limited by the difficulty in managing disaster area airspace. UTM concepts can greatly increase the ability to safely apply UAS to many disaster response requirements. The use of UAS requires communication links to provide command and control, telemetry, delivery of mission payload data, and situational awareness/navigation functionality to enable safe operations. The outcome of Task TO-G-026 research provides guidance in identifying appropriate potential spectrum bands required to support STEReO disaster response operations. This report presents these research results.

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1. Introduction

The purpose of Task TO-G-026 is to identify possible spectrum allocations to support the Scalable Traffic Management for Emergency Response Operations (STEReO) Project's approach of applying Unmanned Aircraft Systems (UAS) Traffic Management (UTM) concepts to the management of disaster response [1,2,3,4]. Both large UA and small UA (a.k.a. drones) have been found to provide significant benefits in disaster response [53,56]. However, application of UA is limited by the difficulty in managing disaster area airspace, which can also include manned aircraft at low altitudes. UTM concepts can greatly increase the ability to safely apply UA to many disaster response requirements.

The use of UAS requires communication links to provide command and control, telemetry, delivery of mission payload data, and situational awareness/navigation functionality to enable safe operations. Task TO-G-026 specifies several areas of focus:

- Drone and aircraft Detect and Avoid spectrum so that they may operate in close proximity during operations.
- Aviation and Ground Mesh networks. Dedicated spectrum is needed for emergency operations, with a common modulation, control, and networking for interoperability.
- Autonomous Drone operations beyond line-of-sight operations with half duplex receive commanding with opportunistic telemetry via available onboard communications systems.

The outcome of the resulting research provides guidance in identifying appropriate potential spectrum bands required to support STEReO disaster response operations.

The following section summarizes these results. Appendices provide background information developed during the research.

2. Spectrum Study Results

2.1 Requirements

Requirements for radiofrequency spectrum for STEReO-based disaster management have been identified through an operational concept development described in Appendix A – Concepts of Operations for Disaster Response.

In Appendix A, operational concepts for the STEReO disaster response are described, and corresponding communications concepts supporting the operational concepts are proposed. Minimum and maximum data rate requirements are applied to individual elements of the communications concepts, allowing aggregation of data rate requirements. This process was carried out for several examples in order to determine broad bounds for communications requirements, bearing in mind the large number of variables involved in covering a wide range of possible disaster scenarios. These results are sufficient to determine suitability of radiofrequency spectrum bands to provide sufficient communications volume.

Based on the operational concepts and communications concepts, and considering appropriate spectrum allocations for different requirements, the data requirements are grouped into five categories.

The Wireless Command/Control (C2) Link provides critical communications to and from the UA to enable safe control of the UA, including commands from the UAS operator to the UA and telemetry from the UA, which can include such things as position, environmental conditions, and situational awareness data. Because of the operations in airspace potentially containing other aircraft, both unmanned and manned, the C2 link is of critical importance and requires protected aviation spectrum.

The Wireless Payload Data Link transfers payload data from the UA to the UAS Operator for use by those managing the disaster response. This non-safety-of-flight data does not require protected aviation spectrum but benefits from dedicated aeronautical use spectrum that is managed to avoid degrading interference from other users.

The Wireless Vehicle-to-Vehicle Management Link supports communications between and among multiple UA intended for coordinated operations. It supports separation of aircraft, both from each other and from other aircraft in the airspace. It may also support an ad hoc mesh network among a fleet of semi-autonomous or autonomous UA providing these functions. Depending on the airspace configuration it may be considered safety-of-flight and therefore a critical communication requiring dedicated spectrum.

The Wireless Vehicle-to-Vehicle Payload Relay Link supports the relay of payload data between UA required to deliver data to the UAS operator on the ground from beyond line-of-sight locations. This includes possible support of an ad hoc mesh network among a fleet of semi-autonomous or autonomous UA. Payload data is not safety-of-flight, but the importance of delivery of such data in support of the disaster response mission requires sufficient protection from interference provided by dedicated aeronautical spectrum.

The Wireless Detect and Avoid (DAA) Link supports low-rate vehicle-to-vehicle communications for self-management and separation of aircraft. DAA data may also be relayed to the UAS Operator to support airspace situational awareness via the C2 link. For this study, airborne detect and avoid radar is not considered.

The broad communications ranges as developed in Appendix A are:

- Wireless Command/Control (C2) link: 1 kbps to 10 Mbps
- Wireless Payload Data Link: 1.5 kbps to 111.1 Mbps
- Wireless Vehicle-to-Vehicle Management Link: 10 kbps to 1 Mbps
- Wireless Vehicle-to-Vehicle Payload Relay Link: 10 kbps to 111.1 Mbps
- Wireless Detect-and Avoid (DAA) (non-radar): 1 kbps to 1 Mbps

The radiofrequency spectrum to be used for these STEReO applications can be grouped as follows. The Wireless Command/Control (C2) Link requires protected aviation spectrum due to potential proximity to other aircraft, at least in many cases, involving safety-of-flight. Therefore, Aeronautical Mobile (Route) Service (AM(R)S) spectrum should be applied.

The Wireless Vehicle-to-Vehicle Management Link allows coordination of multiple UA in mission performance and is especially important for semi-autonomous and autonomous fleets of UA. Safety-of-flight may be involved in airspace containing other aircraft. This link may also be involved in detect and avoid data transmission. Depending on these variables, the Wireless Vehicle-to-Vehicle Management Link can be grouped with the C2 link, or with the Wireless Vehicle-to-Vehicle Payload Relay Link.

The Wireless Payload Data Link and Wireless Vehicle-to-Vehicle Payload Relay Link do not require protected aviation spectrum, as safety-of-flight cannot be invoked. However, mission data requirements would dictate that dedicated aeronautical spectrum be applied in order to avoid data loss due to interference. Aeronautical Mobile Service (AMS) spectrum would best meet this requirement.

There are a number of spectrum bands dedicated to airborne detect and avoid (DAA) in the Aeronautical Radionavigation Service (ARNS). These bands support airborne radar applications, including weather radar. Detect and avoid based on broadcast and reception of short data bursts containing GPS location, altitude, ground speed and other information, such as ADS-B and UAT, are considered communications links and operate within aeronautical mobile service bands. Such DAA for the purpose of STEReO application may be able to make use of the spectrum for Wireless Vehicle-to-Vehicle Management Link.

2.2 Spectrum Survey Results

In Table 1, various possible spectrum bands are presented and evaluated with the potential for supporting the STEReO applications: Wireless Command/Control (C2) link (C2); Wireless Payload Data Link and Wireless Vehicle-to-Vehicle (V-to-V) Payload Relay Link (Payload); Wireless Vehicle-to-Vehicle Management Link; and Wireless Detect-and Avoid (DAA). This information summarizes the information presented in Appendix B: Aviation Spectrum Survey.

2.3 Discussion

It is observed that a large number of different entities are involved in UAS regulatory and standardization activities relevant to application of radiofrequency spectrum. In the U.S., the Federal Aviation Administration (FAA), Federal Communications Commission (FCC), and National Telecommunications and Information Agency (NTIA) have various and overlapping jurisdictions, while in Europe the European Aviation Safety Agency (EASA) and European Conference of Postal and Telecommunications Administrations (CEPT) are involved. Internationally, the International Telecommunications Union (ITU) and International Civil Aviation Organization (ICAO) have significant activities relevant to global frequency allocation and usage. ICAO, the Radio Technical Commission for Aeronautics (RTCA), EASA and others address the development of standards, while industry groups such as 3rd Generation Partnership Project (3GPP) advance industry and user agendas.

Table 1. Summary of Aviation Spectrum Survey Results, Part 1

Allocation	Designation	Band		Current Application	STEReO Application	Rating	Comment
AM(R)S	HF	2 850 – 22 000	kHz	Air-ground communication (HF voice and data)	C2	1	Highly congested, subject to rigid planning
AM(R)S, ARNS	VHF	108 – 117.975	MHz	VOR/ILS localizer GBAS/VDL Mode 4 (voice and data)	C2	1	Highly congested, navigation aids predominate
AM(R)S	VHF	117.975 – 137	MHz	Air-ground/air-air communications (VHF voice and data)	C2	1	Highly congested, subject to rigid planning
AM(R)S, ARNS	UHF/L-Band	960 – 1 164	MHz	LDACS (for datalink), LDACS (for Alternative-PNT) UHF	C2	5	Highly congested, navigation aids predominate; LDACS under standardization; has been proposed for small UA
	UHF/L-Band	978	MHz	Universal Access Transceiver (UAT)	DAA	4	Navigation application; congested
	UHF/L-Band	1030	MHz	Traffic Awareness Beacon Sysem (TABS)	DAA	7	Low cost beacon compatible with ADS-B, TCAS, etc
	UHF/L-Band	1090	MHz	Automatic Dependent Surveillance (ADS)	DAA	4	Navigation application; congested
AM(R)S, AMS(R)S	C-Band	5 030 – 5 150	MHz	UAS CNPC/Airport Surface Communication (AeroMACS)	C2	10	Allocated for UAS application; sharing between AM(R)S and AMS(R)S is under study; AM(R)S application to small UA probable; FCC studying channel allocation/licensing
AMS(R)S	L-Band	1 610 – 1 626.5	MHz	SatCom (e.g., IRIDIUM, Inmarsat)	C2	3	Current systems costly, high SWAP
AMS(R)S	C-Band	5 000 – 5 150	MHz	GNSS,navigation aids, UAS CNPC	C2	7	Potential for low cost low SWAP; no systems currently on orbit or planned.
AMS	C-Band	4400-4990	MHz	Remote sensing, telemetry, maritime	Payload	1	Characteristics for UAS for oceanic imaging applications under development; other uses constrained by other in-band systems
	Ku-Band	14.5-15.35	GHz	Remote sensing	C2, Payload, V-to-V, DAA	9	Characteristics defined for UAS remote sensing data, may also be used for airborne UAS C2 data links. Further system definition may be required; sufficient spectrum.
	Ku-Band	15.4-15.7	GHz	*non-safety aeronautical mobile applications*	Payload, V-to-V	7	WRC-23 Agenda Item 1.10 new allocation to AMS; Characteristics for UAS appplications including wildfire response under development; not appropriate for C2; V-to-V uncertain; sufficient spectrum
	K-Band	21.2-22	GHz	Remote sensing	Payload	4	Characteristics not defined for UAS applications
	K-Band	22-22.21 GHz		*non-safety aeronautical mobile applications*	Payload, V-to-V	7	WRC-23 Agenda Item 1.10 new allocation to AMS; Characteristics for UAS appplications including wildfire response under development; not appropriate for C2; V-to-V uncertain; sufficient spectrum
	K-Band	22.5-23.6	GHz	Research, remote sensing, fire-fighting, emergency management	Payload	4	Characteristics not defined for UAS applications
	K-Band	25.25-27.5	GHz	Research, remote sensing, fire-fighting, emergency management	Payload	4	Characteristics not defined for UAS applications
	V-Band	45.5-47	GHz	Research, remote sensing, fire-fighting, emergency management	Payload	5	Option for unmanned applications;ufficient spectrum
FSS/UAS	X-Band	10.95-11.2	GHz	Fiixed Satellite Service, space-to-Earth	C2	8	WRC-23 Agenda Item 1.08; use of Fixed Satellite Servicefor UAS C2 links; on-orbit asstets in place; low SWAP narrowband avionics would be needed; Also, LEO constellations such as Starlink and OneWeb operate in these bands; Starlink has recently received approval from the FCC to serve aricraft
	X-Band	11.45-11.7	GHz				
	Ku-Band	11.7-12.2 (Region 2)	GHz				
	Ku-Band	12.2-12.5 (Region 3)	GHz				
	Ku-Band	12.5-12.75 (Regions 1, 3)	GHz				
	K-Band	19.7-20.2	GHz				
	Ku-Band	14-14.47	GHz	Fiixed Satellite Service, Earth-to-space	C2	8	WRC-23 Agenda Item 1.08; use of Fixed Satellite Servicefor UAS C2 links; on-orbit asstets in place; low SWAP narrowband avionics would be needed; Also, LEO constellations such as Starlink and OneWeb operate in these bands; Starlink has recently received approval from the FCC to serve aricraft
	Ka-Band	29.5-30.0	GHz				

Table 1. Summary of Aviation Spectrum Survey Results, Part 2

ITS (MS)	C-Band	5 850-5 925	MHz	Itelligent Transport System (ITS) in the 5.9 GHz Mobile Service Band	DAA, V-to-V	7	Good potential use for short rangte V-to-V under emerging ITS standardization, especially suited to DAA. However, spectrum for this application is not internationally harmonized, further, in the US the ITS band has been reduced to 5895-5925 MHz.
MS	UHF	703-733	MHz	(LTE, 5G NR)	C2, Payload, V-to-V	3	Aeronautical exception in one or more regions would need to be changed; insufficient specturm for some payload data; spectrum under license; infrastrucutre may not be available or expensive to own.
	UHF	758-788	MHz	(LTE, 5G NR)			
	UHF	791-821	MHz	(LTE)			
	UHF	832-862	MHz	(LTE)			
	UHF	880-915	MHz	(GSM, UMTS, LTE)			
	UHF	925-960	MHz	(GSM, UMTS, LTE)			
	L-Band	1710-1785	MHz	(GSM, LTE)		5	Insufficient specturm for some payload data; spectrum under license; infrastrucutre may not be available or expensive to own.
	L-Band	1805-1880	MHz	(GSM, LTE)			
	S-Band	1920-1980	MHz	(LTE, 5G NR)			
	S-Band	2110-2170	MHz	(LTE, 5G NR)			
	S-Band	2500-2570	MHz	(LTE)		3	Aeronautical exception in one or more regions would need to be changed; insufficient specturm for some payload data; spectrum under license; infrastrucutre may not be available or expensive to own.
	S-Band	2570 -2620	MHz	(LTE)			
	S-Band	2620-2690	MHz	(LTE)			
	S-Band	3.4-3.8	GHz	(5G NR)			
MS, Land Moible	VHF	25-50	MHz	Public Safety)in US, elsewhere)	C2, Payload, V-to-V	2	Mix of many service allocations; primarily land mobile in US; intererence difficulties in emergency scenarios; needed allocation changes would be extremely difficult internationally
	VHF	150-174	MHz				
	VHF	220-222	MHz				
	UHF	450-470	MHz				
	UHF	758-769/788-79	MHz				
	UHF	768-775/798-80	MHz				
	UHF	806-809/851-85	MHz				
	UHF	809-815/854-86	MHz				
	C-Band	4940-4990	MHz				
	C-Band	5850-5925	MHz				
Unlicensed (by footnote)	HF	13 553-13 567	kHz	Unlicensed applications	C2, Payload, V-to-V	3	Bands not allocated uniformaly internationally; equipment readily available; uncontrolled interference environment likely to get worse over time; power limitations; insufficient spectrum for some payload data
	HF	26 957-27 283	kHz				
	VHF	40.66-40.70	MHz				
	UHF	902-928	MHz				
	S-Band	2 400-2 500	MHz				
	C-Band	5 725-5 875	MHz				
	Ka-Band	24-24.25	GHz				

Overall, these efforts are advancing at different paces and are only coordinated to a certain degree. As a result, clear and final decisions on the appropriate spectrum for UAS applications are yet to be achieved, in particular for small UAS which are the subject of the STEReO Project's efforts.

It can also be noted that application of small UAS to disaster response has been applied for many years in many locations and situations around the world, with a reasonably strong consensus on the very high value drone operations can bring. An organized, coordinated activity in the advancement of drone-based methods to disaster response would enable a much faster, more capable, and lower cost development and deployment. The STEReO Project should be the focal point for this organizing activity. As part of this, the development of appropriate communications capabilities in support of STEReO-based disaster management is needed.

In this study, the identification of the most appropriate spectrum bands for the STEReO application would benefit from clarification of link performance requirements. In particular, which communication links, under what conditions, will require safety-of-flight designated spectrum: some C2 links, all C2 links, V-to-V coordination links? Do V-to-V management links constitute C links? Understanding these relationships will enable the decision on spectrum usage to be clarified, with the goals of reducing the number of spectrum bands to be applied with a consequent reduction in equipment.

2.4 Recommendation

Foremost is the need to develop communications standards for disaster response based on the use of small UAS (drones). Standardized, cross-platform communication will provide increased interoperability, ease of cooperation and collaboration, reduced training, and overall reduced costs. Focusing on internationally harmonized frequency bands and communications standards will enable development of low-cost systems and equipment that can be deployed in addressing disaster response both nationally and internationally. All of the required communications links—C2, payload, and vehicle-to-vehicle including ad hoc mesh network standards—should be considered. Therefore, it is recommended that the STEReO Project or subsequent research and development projects focused on disaster response include this standardization element and foster a collaborative national and international effort to achieve standardized communications systems.

The spectrum study results indicate the most likely spectrum band or bands for application to the STEReO communications requirements, based on existing information and current progress in national and international spectrum regulation as follows.

For the C2 link, the 5030–5091 MHz band has been allocated to AM(R)S and the 5030-5150 MHz band has been allocated to AMS(R)S, both of which can support control and non-payload communications (CNPC). This provides protected aviation spectrum to enable the critical command and control function, therefore this band represents the best opportunity for capturing spectrum for this application. Both line-of-sight (LOS) and beyond line-of-sight (BLOS) links can be established using the same spectrum bands. Regulatory and standardization processes are mainly focused on large UAS applications; however, application to small UAS is also under consideration, including allocation and licensing of frequency channels. The disaster response application requires development and regulatory approval of system characteristics, analysis of system compatibility, system testing, and standards development.

BLOS C2 links can also potentially be supported through other satellite communications links. The use of Fixed Satellite Service (FSS) links is under consideration by upcoming 2023 World Radiocommunications Conference (WRC-23) for both Ku-Band and Ka-Band spectrum to support UAS command and control. As these make use of already existing on-orbit satellites, the key infrastructure is in place. Current system characteristics in development focus on large UAS, so analysis of operations for small UAS using equipment of compatible size, weight, and power (SWAP) is required, as well as development and regulatory approval of system characteristics, followed by prototype development and testing. However, the FSS links could also support payload data, potentially using the same equipment, which creates a very good capture opportunity.

Applying FSS assets in geostationary orbit requires overcoming significant link loss such that data rates would be power limited. However, low Earth orbit (LEO) constellations such as Starlink and OneWeb operate much closer to the Earth and therefore have much lower link loss. As they are addressing the mass consumer market, very low cost and low SWAP electronics are expected to become available. In July of 2022, the FCC gave authorization to SpaceX to provide Starlink satellite internet services to vehicles in motion, including aircraft. The quality of performance of these LEO systems needs to be assessed, and the opportunity for testing now exists, even as the LEO constellations are still being populated. Even if performance proves to be insufficient for critical links, the LEO systems may still be valuable for providing link redundancy, and so provide a reasonably high capture opportunity.

For the payload links, both air-to-ground and air-to-air relay, AMS spectrum is the best opportunity for capturing spectrum in sufficient quantity to cover all disaster scenarios. Although there are many mobile service (MS) spectrum bands available and already in use by the mobile telecommunications industry, many of these bands are not designated for aeronautical use, have insufficient spectrum availability both in terms of bandwidth and availability, and rely on infrastructure that may be unavailable in disaster situations. The most promising AMS bands are 14.5-15.35 GHz, 15.4-15.7, and 22-22.21 GHz. The latter two bands are currently under consideration for allocation to AMS at WRC-23 and proposed system characteristics under development specifically include support of UAS wildfire response. The 14.5-15.35 GHz band also allows narrowband C2 links for UAS. These AMS bands would also be able to support communications between aircraft; therefore, they could provide vehicle-to-vehicle management and payload relay communications, which could also include detect-and avoid communications.

For detect-and-avoid links, other than radar, communications links for vehicle-to-vehicle management links can be applied. Use of ADS-B has been discouraged for small UAS due to congestion of the ADS-B and UAT bands, but ADS-B In receive capability is useful for detection of equipped aircraft. Traffic Awareness Beacon System (TABS) operates at 1030 MHz and is intended as a low-cost ADS-like beacon system that is compatible with ADS-B and TCAS receivers, thus a combination of TABS and ADS-B In can provide a situational awareness for all equipped aircraft. Non-equipped or non-cooperative aircraft can only be detected through radar. Use of the 5.9 GHz Intelligent Transport Systems (ITS) band utilizing short range communications being standardized for various ITS applications may be a good approach for DAA messaging among small UAS. However, the reduction of available spectrum from 75 MHz to 30 MHz in the U.S. will compress ITS applications into a smaller spectral band, and as this includes automotive applications, the interference implications require further study. In addition, the ITS band is not internationally harmonized, although there are efforts underway within ITU-R towards international harmonization.

Appendix A. Concepts of Operation for Disaster Response

A.1 The Unmanned Aircraft System (UAS) Traffic Management (UTM) Concept

The overall concept of UTM is well described by the Federal Aviation Administration's (FAA) Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Concept of Operations v 2.0, published on March 2, 2020 [14]. The document describes the architecture developed collaboratively by NASA and the FAA that supports a federated set of services to enable cooperative management of low-altitude UTM operations between UAS Operators, facilitated by third-party support providers through networked information exchanges. The UTM architecture is intended to support common situational awareness among all UTM stakeholders (e.g., Operators, FAA, and other government agencies). At this point, the development of standards to permit, authorize, or allow the use of UTM services is being undertaken by a number of organizations. The UTM concept is also accepted internationally and organizations such as the International Civil Aviation Organization (ICAO) and the European Aviation Safety Agency (EASA) are actively engaged in defining and standardizing UTM [29,33,45].

As the FAA's ConOps describes, UTM is predicated on layers of information sharing and data exchange —from Operator to Operator, vehicle to vehicle, and Operator to the FAA—to achieve safe operations. Operators share their flight intent with each other and coordinate to deconflict and safely separate trajectories. As opposed to standard air traffic management, the primary means of communication and coordination between Operators, the FAA, and other stakeholders is through a distributed information network, and not between pilots and air traffic controllers via voice or data link. The UTM architecture is described in Figure A1.

UAS operators are responsible for managing the operations of UA under their control safely within the constraints of weather, airspace constraints, and the planned and actual flight paths of other UA and manned aircraft. This is accomplished through coordination via the functionality of UAS Service Suppliers (USS), which can be provisioned by UA operators themselves or through third party entities. The USS accesses the necessary information—airspace constraints and notices, weather, terrain, obstructions, surveillance information, other relevant operations—and coordinates with other USSs, exchanging flight plans and operational intent to assure, and negotiate where necessary, safe operations. UTM provides sufficient separation between UAs, between UAs and manned aircraft, and between UAs and terrain and other obstructions while enabling operators to achieve their UA mission goals.

In order to enable assessment of wireless communications requirements for UTM-based operations to support a spectrum study, the notional concept shown in Figure A2 has been developed. The intention of this figure is to describe the information flows potentially requiring wireless communications links, as there is a tendency to underestimate the volume and complexity involved, and to support the development of radiofrequency (RF) communications operational concepts.

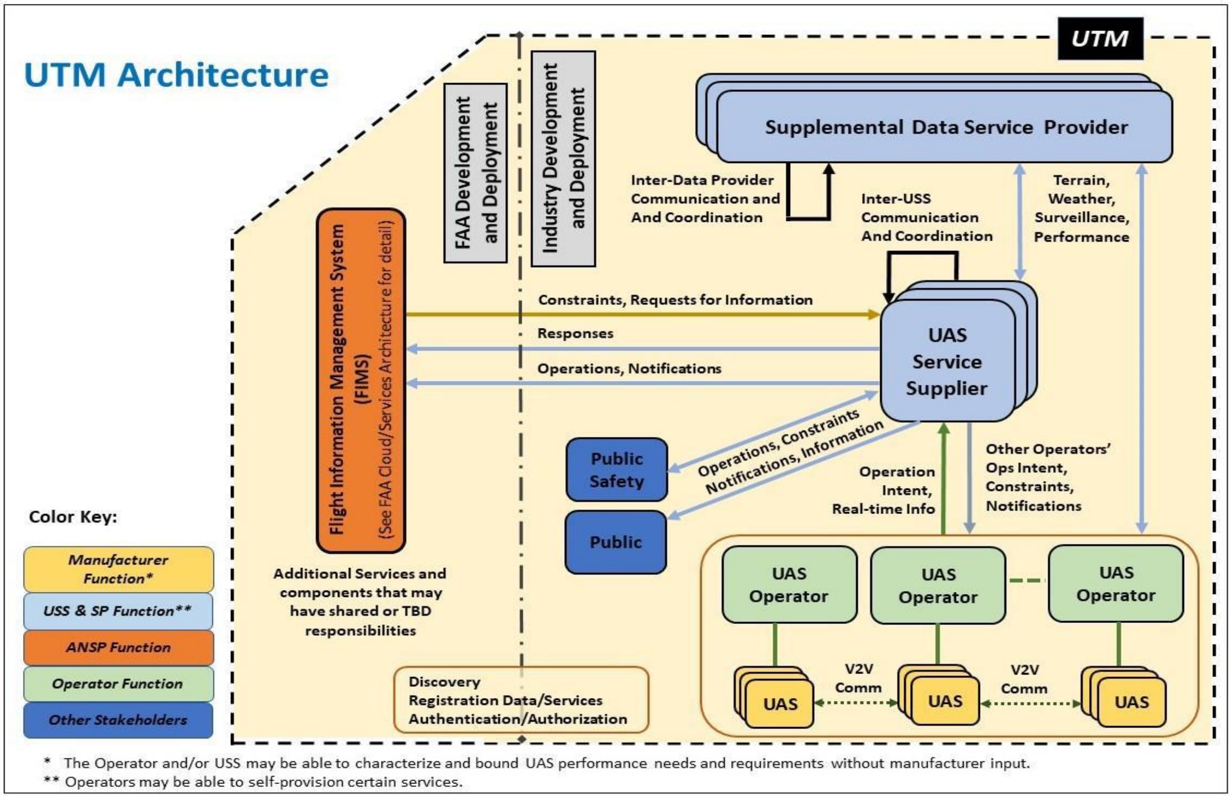

Figure A1. Notional UTM architecture [14].

The key communications links include:

- Controller/operator to UA command and control
  - Within Visual Line-of-Sight (VLOS), Beyond Visual Line-of-Sight (BVLOS), and Beyond Radio Line-of-Sight (BRLOS)
- UA telemetry to controller/operator
  - VLOS, BVLOS, BRLOS
- UA payload/mission data to controller/operator
  - VLOS, BVLOS, BRLOS
- UA to UA for drone fleet coordination and machine-to-machine communication especially for autonomous flight
- Detect and Avoid (DAA) technologies, including:
  - Remote ID (RID)
  - Automatic Dependent Surveillance (ADS-B)-out and ADS-B in (978 MHz and 1090 MHz)
  - Traffic Collision Avoidance System (TCAS)
  - Radionavigation (i.e., radar, etc.)
- Various Mission Operations employing RF transmission and reception (e.g., ground surveillance, asset tracking, atmospheric detection, etc.)

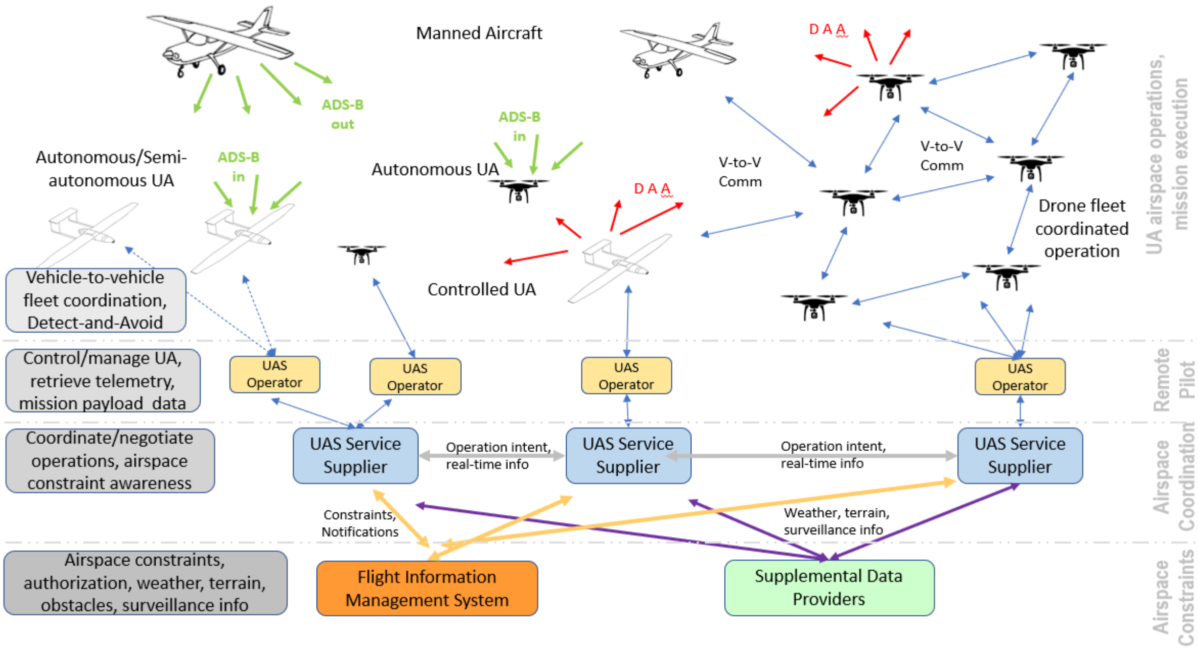

Figure A2. UTM notional concept.

A.2 NASA's Scalable Traffic Management for Emergency Response Operations (STEReO)

NASA's STEReO Project leverages NASA experience in developing UTM in collaboration with the FAA to address the tremendous potential for application of UA to emergency response operations [1,2,3,4]. STEReO has three broad goals: reduce emergency response times, scale up the role of aircraft, and provide operations that can adapt to rapidly changing conditions during a disaster. STEReO also develops and tests collaborative tools to take remote sensing information, for example, from sensors on aircraft able to find gas leaks after an earthquake and distribute a common picture of mission operations. STEReO's partners range from federal agencies to city and state fire departments, utilities, and private companies. A key focus of STEReO is wildfire response and includes live flight demonstrations of a wildfire event and a virtual simulation of a hurricane response.

Key STEReO concepts:

- Collaborative tools to ingest remote sensing information and distribute a common mission operating picture.
- Communication networks to make the system more resilient to challenging operational environments.
- Vehicle-to-vehicle and onboard autonomy technologies ensure the safety and resiliency of operations.
- Technologies for more autonomous UAS flight to ensure those operations are both safe and responsive to dynamic situations.
- Application of NASA's UAS traffic management system as a public safety UAS Service Supplier to access and coordinate use of the airspace by both manned and unmanned operations.

Benefits of STEReO:

- Standardized, cross-platform communication means increased interoperability and ease of cooperation/collaboration.
- Increased situation awareness and common operating picture allow for earlier detection and decision making.
- Scalable to size and complexity of environment, operations, and mission objective.

A.2.1 Disaster Response

NASA's STEReO Project is intended to enable UA to provide significant improvement in disaster response through the application of UTM concepts. Various natural and man-made disasters, such as floods; landslides; volcanic eruptions; hurricanes, tornadoes, and other types of severe storms; wildfires; earthquakes; nuclear accidents; major urban fires; and many others result in severe infrastructural damage and loss of essential services rendering disaster response slow and difficult. UA have been found to be extremely useful in aiding disaster response management, providing mapping, and damage assessment and enabling operations in extreme weather conditions [55].

Among many applications, UAs can provide [58]:

- Reconnaissance and Mapping
- Structural Assessment
- Emergency and Medical Supply Delivery
- Wildfire—Detection and Extinguishing
- High-Rise Building Fire Response
- Chemical, Biological, Radiological, Nuclear, or Explosive (CBRNE) Event
- Search and Rescue Operations
- Insurance Claims Response and Risk Assessment
- Logistics Support
- Emergency Communications/Communications Relay

The UTM concept comes into play in particular for large-scale disasters, as human dispatchers and controllers at operation command centers managing aircraft and vehicle allocation, mission planning, and execution need decision-support tools to manage limited resources safely and efficiently [10]. Multiple entities at the national, regional, and local levels may be managing separate operations. UTM can be used to manage and coordinate multiple UAS operations between multiple operators to provide a common situational awareness of UAS assets and their status, aiding response managers in developing and maintaining an accurate assessment of the current deployment of assets and status of operations.

Figure A3 presents the essential elements of the UTM-supported disaster response concept. This concept is derived from the UTM operational concept and from the disaster response architecture described in [10], "Supporting Disaster Relief Operations through UTM: Operational Concept and Flight Tests of Unmanned and Manned Vehicles at a Disaster Drill." In this concept, the UTM function coordinates UAS traffic management among the command centers of multiple agencies responding to the disaster. UTM receives operation intent and requested flight paths and provides deconflicted flight path approvals. It also receives real-time state data of both unmanned and manned aircraft and monitors for flight path non-conformance and provides alerts of possible separational loss or violation of operational restrictions. The UAS service supplier function is developed to respond specifically to disaster response requirements.

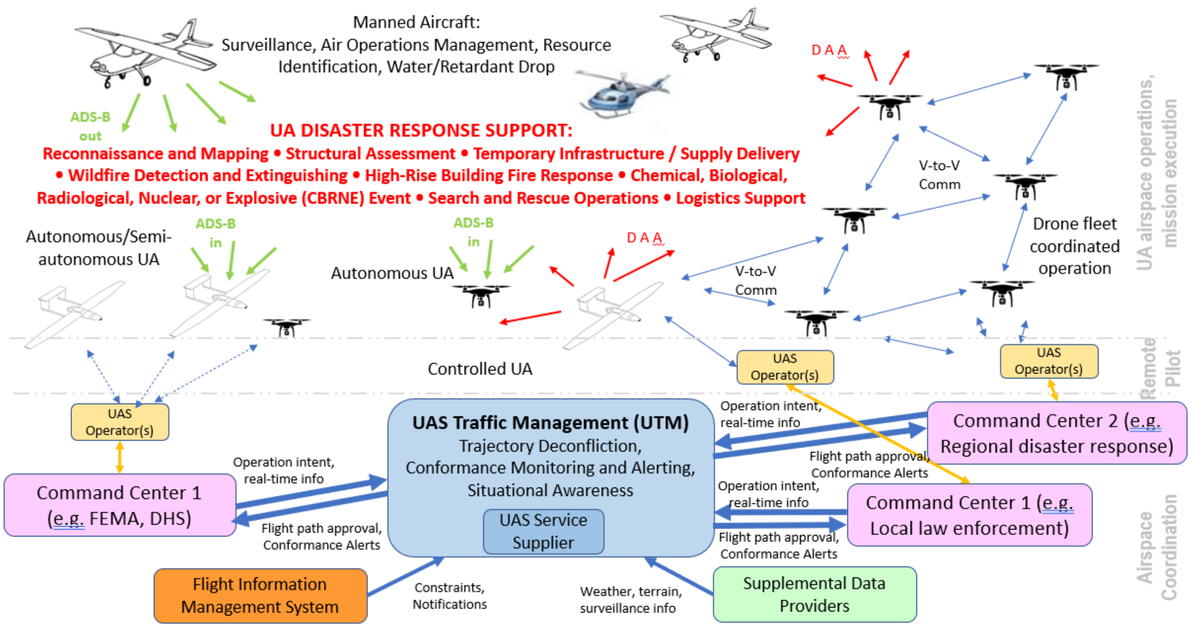

Figure A3. UTM-supported disaster response concept.

A.2.2 Wildfire Response

Wildfire response is a focus of the STEReO Project and testing and demonstration has already occurred, including a field demonstration at a U.S. Forest Service training exercise in Phoenix, Arizona in 2021 [5]. In applying UTM concepts to wildfire response, the primary application is for air traffic management, including geofencing, weather and wind advisories, route planning, sequencing, spacing, contingency management, and separation management [7]. In the wildfire scenario, piloted and unpiloted aircraft are both present in the (usually) restricted airspace in the wildfire vicinity and send data to each other to ensure separation. In addition, small general aviation aircraft have also been observed operating in violation of the airspace restriction and must also be avoided [NASA].

UTM provides weather and wind advisories to pilots, as well as other constraint information used to ensure safe operations, which additionally reduces some strain from aerial supervisors. UTM enables operations management to be coordinated among operators, boosting flexibility and scalability of operations in an airspace that is not organized according to conventional practices. Additional UA activities in wildfire response include aerial surveillance, hot spot detection, delivery of equipment and supplies, tracking of ground assets and personnel, and delivery of water and fire-retardant drops.

UA may be operated as coordinated drone fleets, partially or fully autonomous, requiring mesh interconnectivity to enable separation to be maintained and data to be relayed to the operations command center. Detect-and-avoid capability is required to maintain separation between drones and between drones and manned aircraft.

The essential operational concept for wildfire response is described in Figure A4. In contrast to the disaster response concept above, a single point of operational command is assumed for a wildfire response. The command center includes the UTM functionality, as well as UAS operations and the firefighting operation management. In terms of employing a single command center, the wildfire response concept will also apply to other types of small-scale disaster response where multiple command operations are not required.

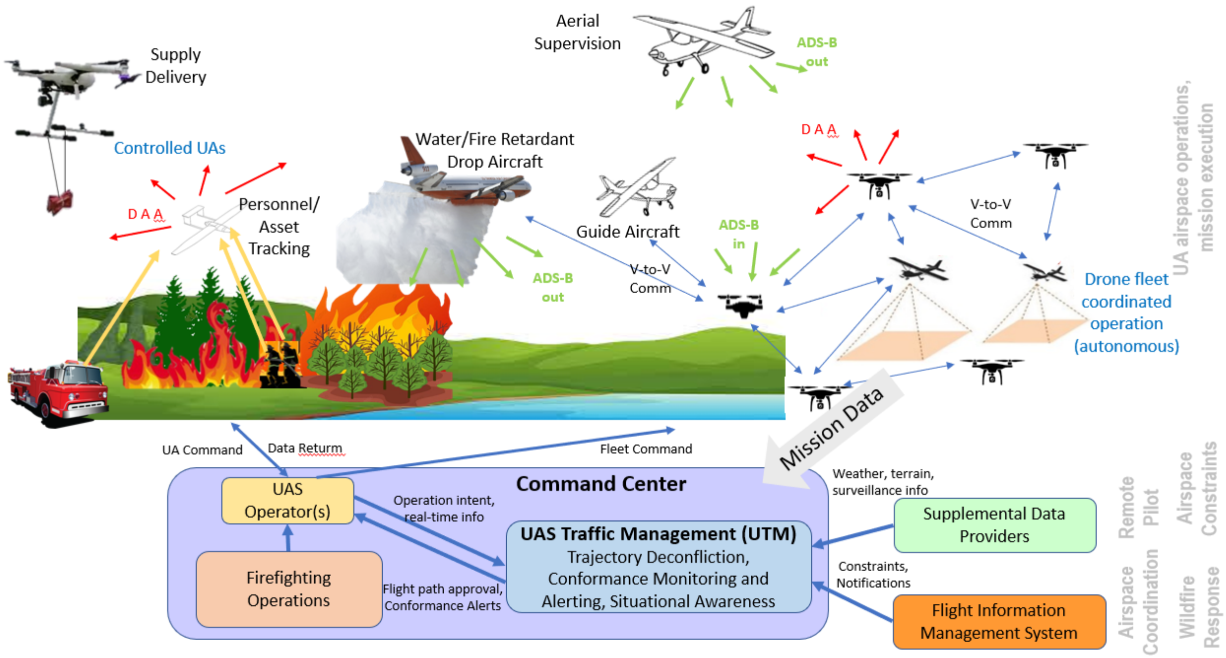

Figure A4. UTM-supported wildfire response concept.

A.3 Communications Concepts

Communications concepts corresponding to the operational concepts described above are developed to enable an understanding of communications requirements, in particular for assessing appropriate radiofrequency spectrum for application to the STEReO-based disaster management concept.

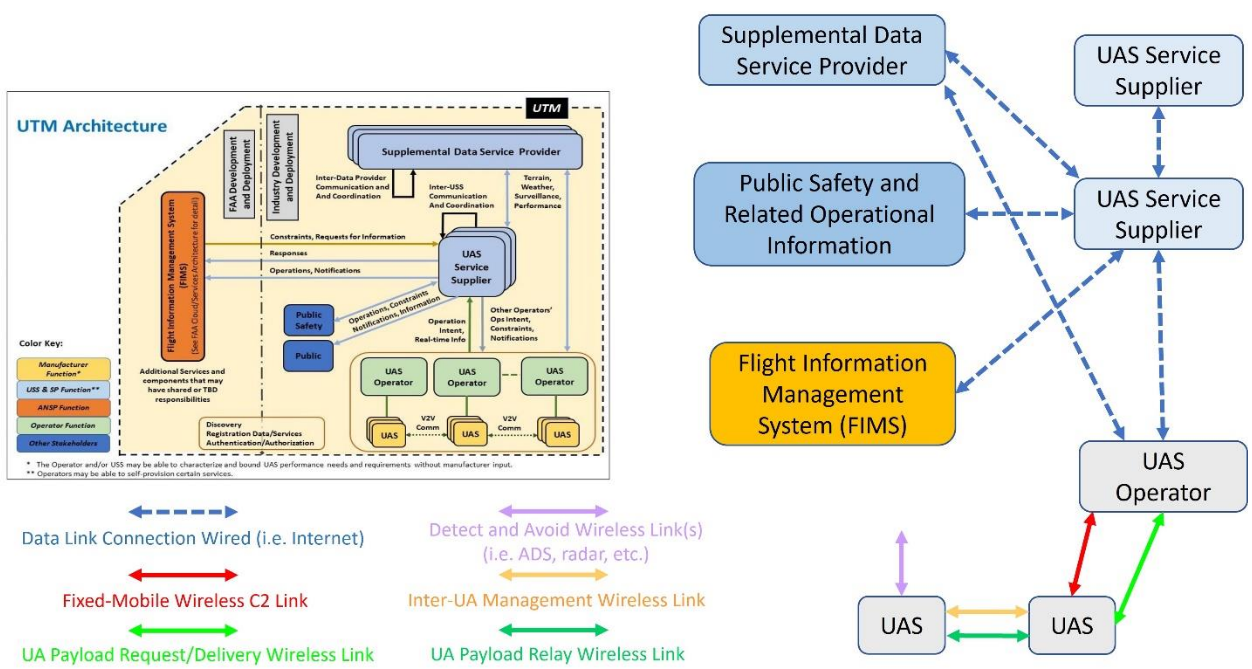

Figure A5. UTM Communications Concept with a single UAS operator.

In Figure A5, the communications concept applicable to a basic UTM operation with a single UAS operator illustrates the primary communications links. A UAS operator interacts with a UAS service supplier (USS) to obtain the required UTM functionality to manage one or more UA in the designated operational airspace. The UAS operator will be able to maintain separation from other aircraft through pre-operational planning and through situational awareness of other aircraft and airspace conditions. The data connections between the UAS operator and USS or Supplemental Data Service Provider are terrestrial internet networks.

Wireless C2 links provide command and control of the UA and receipt of any necessary telemetry information. Wireless payload request/delivery links provide requests to the UA to perform specific operational functions and the resulting payload data is returned to the UAS operator. Multiple UA performing coordinated operations, possibly as semi-autonomous or fully autonomous aircraft, may require wireless interconnections for intra-fleet management and separation and for relaying payload data to the UAS operator, possibly through an ad-hoc mesh network functionality.

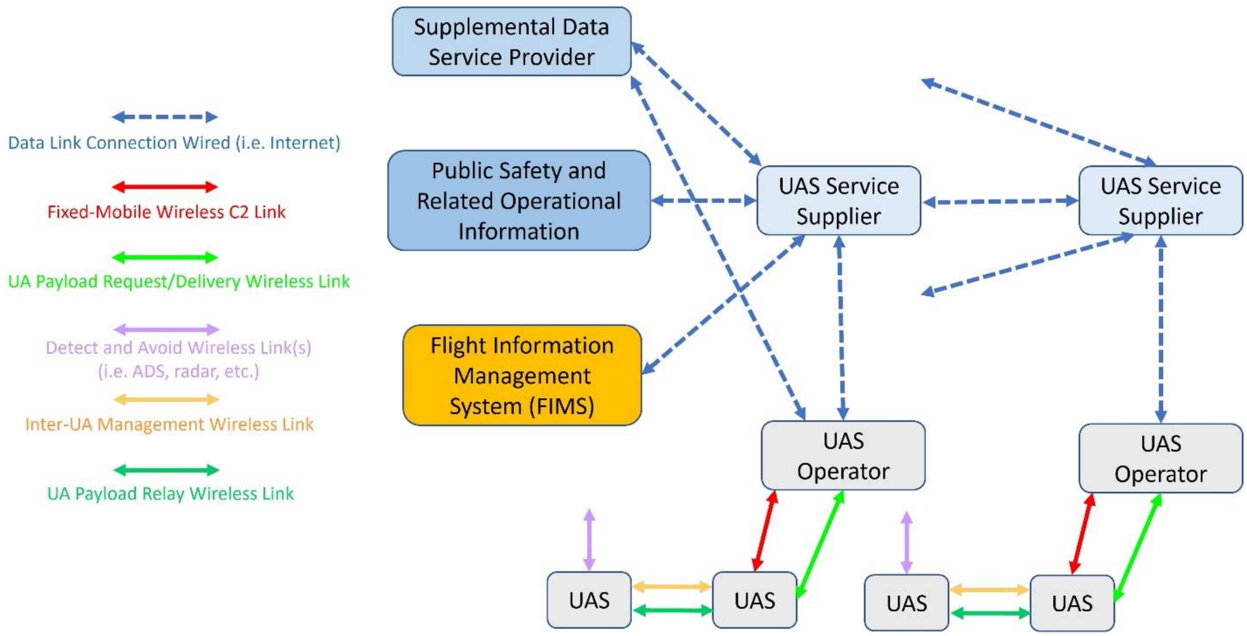

Figure A6. UTM Communications Concept with multiple UAS operators.

In Figure A6, the communications concept is extended to the case of multiple UAS operators. This is the expected typical case, as UTM is really intended to support airspace with multiple independent UA operations. The types of terrestrial and wireless links required are the same as the single UAS operator case. UAS operators may be connected to different USS, in which case airspace management and coordination of operations require communication between the several USS.

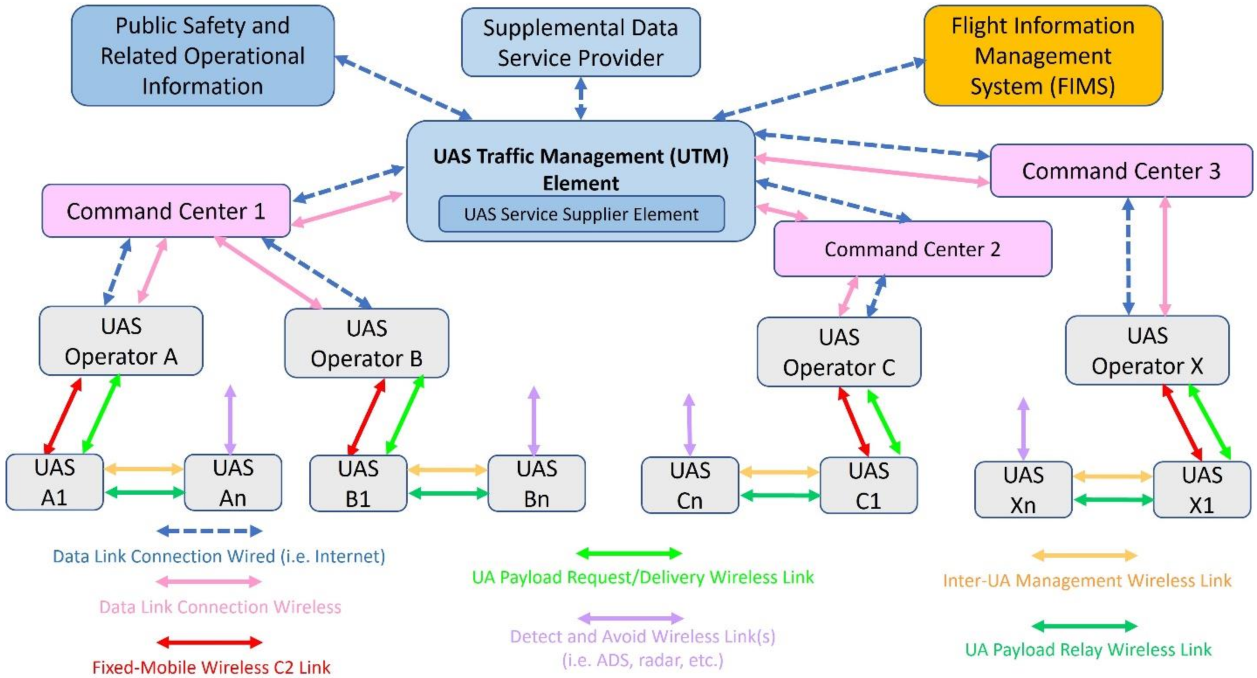

Figure A7. UTM-supported disaster response communications concept.

The communication concept for UTM-supported disaster response is illustrated in Figure A7. This concept differs from the normal UTM concept because the USS function is integrated into a UTM element which is providing both airspace management and the disaster response functionality—analyzing incoming data being received from various sources, including to a large extent data from UA performing sensing and imaging functions throughout the disaster area to provide usable information to the disaster response managers. In addition, multiple command centers supporting various disaster response entities (e.g., national, regional, and local) are operating independently managed UA or UA fleets but must coordinate their activities for both UA/aircraft separation and disaster response management.

Command centers may be employing one or more UA operators, each operating one or more UA or UA fleets. These command centers may have wired connection to the UTM Element or make use of terrestrial internet connections. However, they may also be in remote locations without such internet access, or previously existing infrastructure may be unavailable due to the disaster itself. In such cases, wireless connectivity would need to be established to support the UTM-supported disaster communication concept.

The wildfire response communications concept is depicted in Figure A8. This concept is a simplified version of the disaster response concept. The UTM management element is collocated with the disaster management operation as well as the UAS operator, at least functionally if not physically. Depending on location (remote or near other facilities like airfields and population centers) and the airspace configuration, connectivity with flight information and supplemental data service is optional. If necessary, such connectivity may be available through terrestrial internet service, but would require wireless connection in remote locations. Very large wildfires may require a larger response with multiple groups of responders, in which case the general disaster response concept would apply.

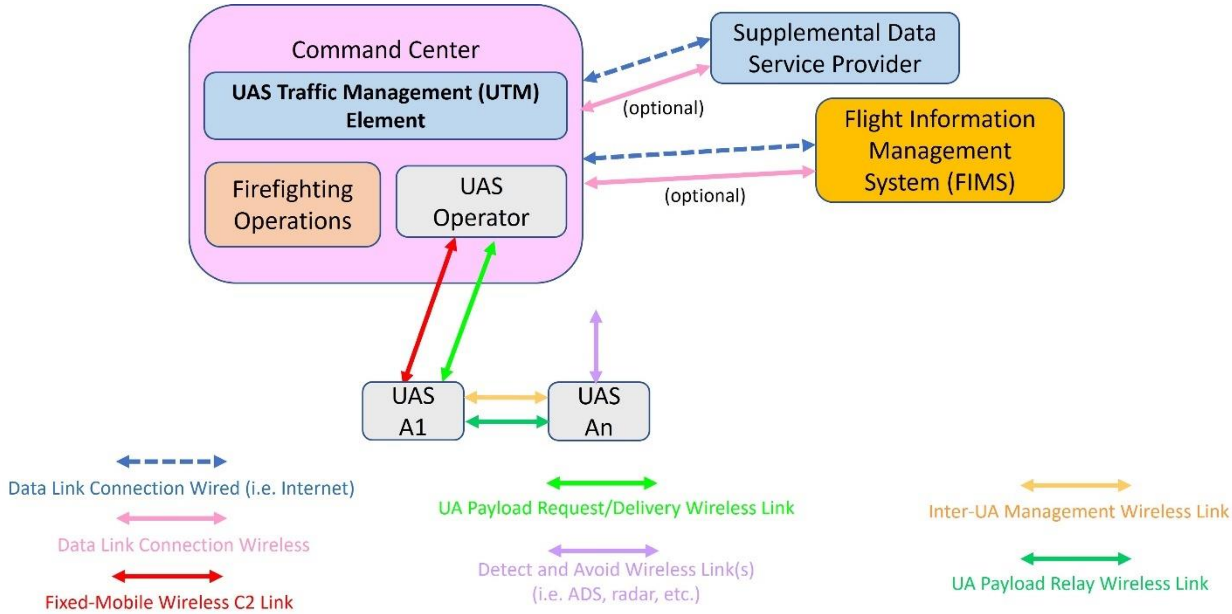

Figure A8. Wildfire response communications concept.

A.4 Communications Estimates

Based on communications concepts described above, broad estimates of wireless data communications estimates can be made. Figure A9 shows an Excel spreadsheet providing wireless link combinations pertaining to various possible communication concepts. Minimum and maximum data rate estimates placed into the spreadsheet cells can be combined to produce aggregate estimates.

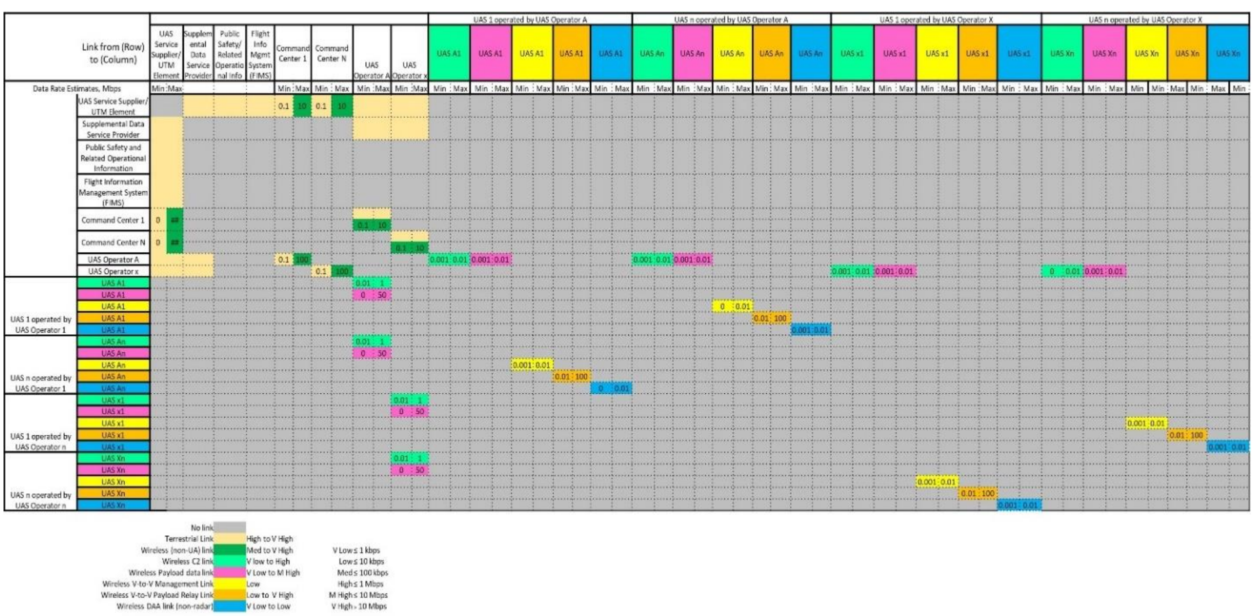

Figure A9. Spreadsheet for developing data rate estimates.

The range of possible configurations for UTM-supported disaster response communications is very large, covering relatively small events through very large events. The amounts and types of payload data collected by UA supporting disaster response can similarly cover a very large range. Several examples of data rate estimates are given below.

Table A1. Data Estimates for UTM Communications Concept with a Single UAS Operator (Mbps)

	UAS Operator A									
# of UA per Operator	N=1		N=3		N=10		N=30		N=100	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Wireless C2 link	0.011	1.01	0.033	3.03	0.11	10.1	0.33	30.3	1.1	101
Wireless Payload data link	0.002	50.01	0.006	150	0.02	500.1	0.06	1500.3	0.2	5001
Wireless V-to-V Management Link	0	0	0.006	0.06	0.3	3	2.94	29.4	35.4	354
Wireless V-to-V Payload Relay Link	0	0	0.06	600	0.2	2000	0.6	6000	2	20000
Wireless DAA link (non-radar)	0.002	0.02	0.006	0.06	0.02	0.2	0.06	0.6	0.2	2

Table A1 provides an example for the UTM Communications Concept for a single UAS operator (see Figure A5). The UAS operator may be directly operating one or more UA, but larger fleets of UA will be semi-autonomous or autonomous. Small numbers of UA may cover large geographic areas and produce significant amounts of payload data, while larger numbers of UA would likely produce less payload per UA by covering smaller areas. Hence the very large payload data requirements in Table A1 for larger numbers of UA are not realistic. As shown below, recent estimates proposed for ITU-R documents currently under development suggest a more modest maximum requirement of 111.1 Mbps. In addition, large values for the C2 link data rate requirements for large numbers of UA reflect an aggregation of video telemetry normally required for only a very limited number of UA; a fleet of autonomous UA would not require video telemetry returned to the UA operator.

Table A2. Data Estimates for UTM Communications Concept with Multiple UAS Operators (Mbps)

	UAS Operator A		UAS Operator B		UAS Operator C		UAS Operator D		UAS Operator E		TOTAL	
# of UA per Operator	N=3		N=10		N=5		N=30		N=7			
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Wireless C2 link	0.033	3.03	0.11	10.1	0.055	5.05	0.33	30.3	0.077	7.07	0.605	55.55
Wireless Payload data link	0.006	150	0.02	500.1	0.01	250.1	0.06	1500.3	0.014	350.1	0.11	2751
Wireless V-to-V Management Link	0	0	0.3	3	0	0	2.94	29.4	0	0	3.24	32.4
Wireless V-to-V Payload Relay Link	0	0	0.2	2000	0	0	0.6	6000	0	0	0.8	8000
Wireless DAA link (non-radar)	0.006	0.06	0.02	0.2	0.01	0.1	0.06	0.6	0.014	0.14	0.11	1.1

Table A2 provides an example for the UTM communications concept for multiple UAS operators (see Figure A6). In this example, five different UA operators are operating from 3 to 30 UA. As with the single UA operator case, UA fleets of 10 or more would be operating autonomously. The comments above for the single UAS operator example regarding very large data rate requirements for payload and C2 data apply similarly to the multiple UAS operator example.

Table A3. UTM-supported Disaster Response Communications Concept (Mbps)

			Command Center 1				Command Center 2		Command Center 3					
	UTM Element		UAS Operator A		UAS Operator B		UAS Operator C		UAS Operator D		UAS Operator E		TOTAL	
# of UA per Operator			N=3		N=10		N=5		N=30		N=7			
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Wireless (non-UA) data link	0.6	330	0.2	110	0.2	110	0.2	110	0.2	110	0.2	110	1.6	880
Wireless C2 link	---	---	0.033	3.03	0.11	10.1	0.055	5.05	0.33	30.3	0.077	7.07	0.605	55.55
Wireless Payload data link	---	---	0.006	150.03	0.02	500.1	0.01	250.1	0.06	1500.3	0.014	350.1	0.11	2751
Wireless V-to-V Management Link	---	---	0	0	0.3	3	0	0	2.94	29.4	0	0	3.24	32.4
Wireless V-to-V Payload Relay Link	---	---	0	0	0.2	2000	0	0	0.6	6000	0	0	0.8	8000
Wireless DAA link (non-radar)	---	---	0.006	0.06	0.02	0.2	0.01	0.1	0.06	0.6	0.014	0.14	0.11	1.1

Table A3 provides an example for the UTM-supported disaster response communications concept (see Figure A7). This is similar to the multiple UAS operators example of Table A2, but it also includes wireless data rate requirements for connections between UAS operators, command centers and the UTM management element. Comments for the previous examples regarding very large data rate requirements for payload and C2 data also apply for this example.

Table A4. Wildfire Response Communications Concept (Mbps)

			UAS Operator									
# of UA	Supplemental Data/FIMS		N=1		N=3		N=10		N=30		N=100	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Wireless (non-UA) data link (Optional)	0.01	1	---	---	---	---	---	---	---	---	---	---
Wireless C2 link	---	---	0.011	1.01	0.033	3.03	0.11	10.1	0.33	30.3	1.1	101
Wireless Payload data link	---	---	0.002	50.01	0.006	150	0.02	500.1	0.06	1500.3	0.2	5001
Wireless V-to-V Management Link	---	---	---	---	0.006	0.06	0.3	3	2.94	29.4	35.4	354
Wireless V-to-V Payload Relay Link	---	---	---	---	0.06	600	0.2	2000	0.6	6000	2	20000
Wireless DAA link (non-radar)	---	---	0.002	0.02	0.006	0.06	0.02	0.2	0.06	0.6	0.2	2

Table A4 provides an example for the wildfire response communications concept (see Figure A8). The primary difference in this example is the addition of a possible link from the command center to supplemental data sources which could be necessary in some wildfire response scenarios. Other comments in the previous examples regarding very large data rate requirements for payload and C2 data also apply for this example.

Table A5. Wildfire Response 30 UA Autonomous Fleet Example (Mbps)

	# of links/UA	# of links/fleet	Mbps Data Rate/link	Mbps Total/cell	Frequency Reuse	Total
Wireless C2 link	---	3	0.001	0.003	9	0.027
Wireless Payload data link	1	30	0.0015	0.045	9	0.405
Wireless V-to-V Management Link	4	120	0.001	0.12	9	1.08
Wireless V-to-V Payload Relay Link	12	360	0.0015	0.54	9	4.86
Wireless DAA link (non-radar)	4	120	0.001	0.12	9	1.08

A final example, shown in Table A5, considers the wildfire response scenario suggested by NASA for an autonomous fleet of 30 UA managed through an ad hoc wireless network. The fleet is self-managed except for a possible low-rate command link. UA in this fleet connect to up to four adjacent UA for fleet management. Payload data is relayed among UA to several possible downlink paths to the mission operation (UAS operator) with at least one redundant path. For this scenario, payload data consists of imaging data requiring a 1.5 kbps data rate. This example shows a total data rate requirement of several Mbps.

Current work in ITU-R Working Party 5B includes the development of technical characteristics, operational scenarios, spectrum needs, coexistence, and sharing studies of non-safety aeronautical mobile systems for bands being considered for new allocations in the Aeronautical Mobile Service (AMS) [72].

Table A6 is extracted from [72]. The table provides estimated spectrum resources for several potential airborne wideband line of sight data link deployment scenarios involving the use of UA. Scenario 6.2 is a wildfire detection scenario in which two UA with multiple sensors provide real time data directly to wildfire response vehicles on the ground. The analysis in [72] results in an aggregate data rate requirement of 111.1 Mbps.

Table A6. Estimation of the Spectrum Resource Per Cluster (TABLE 8-1 from [72])

			Scenario			
		Units	**6.2**	6.3	**6.4**	**6.5**
Data links	No. per cluster	Ø	2 [1]	6 [2]	3 [3]	8 [4]
Data links	Payload throughput per link	Mbps	50 [5]	30 [6]	10, 20 [7]	Fwd.: 20, 40, 60, 80; Rtn.: 80, 160, 240, 320 [8]
Data links	Overhead factor [9]	%	10	10	10	10
Data links	Raw throughput per link	Mbps	55	33	11, 22	Fwd.: 22, 44, 66, 88; Rtn.: 88, 176, 264, 352
Control links	No. per cluster [10]	Ø	2	6	3	8
Control links	Payload throughput per link [11]	Mbps	0.5	0.5	0.5	0.5
Control links	Overhead factor	%	10	10	10	10
Control links	Raw throughput per link	Mbps	0.55	0.55	0.55	0.55
Multiplexing scheme [12]		Ø	Frequency Division Multiple Access (FDMA)			
Frequency Reuse (FR) inside a cluster		Ø	0 [13]			1 [14]
Aggregate raw throughput per cluster [15] [16]		Mbps	111.1	201.3	46.65	352.55
Spectrum efficiency		bps/Hz	1			3
Spectrum resource per cluster [17]		MHz	111.1	201.3	46.65	117.52

The communications estimate examples in this section illustrate the general requirements for wireless data rates needed to support disaster response deployment of UA managed under UTM. However, the range of data rate requirements is very broad, reflecting many variables in implementing a large variety of different disaster response scenarios. These variables include the size and geographic extent of the disaster, the level of damage and destruction and loss of communications infrastructure, the types and volumes of sensing data required to support the response, the number of UA required to acquire data, the number and types of independent responding organizations, the location of the event relative to population centers, transportation infrastructure, airfields, etc., and many others.

Applying the communications concepts described in this appendix and considering several representative examples, data rate range requirements can be broadly estimated as follows:

- Wireless Command/Control (C2) link: 1 kbps to 10 Mbps
- Wireless Payload Data Link: 1.5 kbps to 111.1 Mbps
- Wireless Vehicle-to-Vehicle Management Link: 10 kbps to 1 Mbps
- Wireless Vehicle-to-Vehicle Payload Relay Link: 10 kbps to 111.1 Mbps
- Wireless Detect-and Avoid (non-radar): 1 kbps to 1 Mbps

These data rates provide guidance in determining appropriate radiofrequency spectrum bands that can support the STEReO Project disaster response operations.

Appendix B. Aviation Spectrum Survey

A survey of radiofrequency spectrum status and usage as it pertains to aviation in general and UAS has been undertaken in support of task TO-G-026. This survey takes into account U.S., international, and industry information sources, and it provides the background information necessary to assess possible approaches to fulfilling communications requirements for the STEReO project UTM-based approach to disaster response, including wildfire response requirements. The following subsections provide an overview of the results.

International frequency spectrum allocations are decided by World Radio Communication Conferences (WRC) convened under the auspices of the International Telecommunications Union (ITU). These international allocation decisions are incorporated into the ITU-Radiocommunications Sector (ITU-R) International Radio Regulations, which is essentially an international treaty. The next WRC is scheduled to be held in 2023 (WRC-23). Within the US, management of the radio frequency spectrum is divided between government and non-government users. The National Telecommunications and Information Administration (NTIA) administers government allocations (including, for example, NASA and military usage), and the Federal Communication Commission (FCC) manages non-governmental allocations (for example, commercial and amateur usage).

B.1 International Spectrum Regulation—International Telecommunications Union Radiocommunications Sector (ITU-R)

B.1.1 ITU-R Services

The ITU-R Radio Regulations allocate portions of the radiofrequency spectrum to specifically defined services [39]. The following services are relevant to aeronautical applications, including unmanned aircraft (UA) wireless communications:

Mobile service (MS): A radiocommunication service between mobile and land stations, or between mobile stations.

- The mobile service is most often used for networked wireless services – i.e., 3G, 4G/LTE, 5G, etc.
- Note that many MS bands specifically prohibit aeronautical mobile service and hence cannot be applied to UA, however separate aeronautical mobile service allocations exist, and new allocations are being considered at WRC-23.

Mobile-satellite service (MSS): A radiocommunication service:

- Between mobile earth stations and one or more space stations, or between space stations used by this service; or
- Between mobile earth stations by means of one or more space stations.
  - The mobile-satellite service is being increasingly applied to networked wireless services –i.e., 3G, 4G/LTE, 5G, etc., through Low Earth Orbit (LEO) satellite constellations.
  - MSS bands do not have specific prohibitions against aeronautical mobile-satellite service, however separate aeronautical mobile-satellite service allocations also exist.

Aeronautical mobile service (AMS): A mobile service between aeronautical stations and aircraft stations, or between aircraft stations.

- "Aircraft stations" refers to (fixed or mobile) stations on the ground or at sea.

Aeronautical mobile (Route) service (AM(R)S): An aeronautical mobile service reserved for communications relating to safety and regularity of flight, primarily along national or international civil air routes.

- Not applicable to any other applications except safety and regularity of flight.
- This band requires special measures to ensure freedom from harmful interference, and therefore is not available for non-safety-related activities, with few exceptions.

Aeronautical mobile (Off-Route) service (AM(OR)S): An aeronautical mobile service intended for communications, including those relating to flight coordination, primarily outside national or international civil air routes.

Aeronautical mobile-satellite service (AMSS): A mobile-satellite service in which mobile Earth stations are located on board aircraft.

Aeronautical mobile-satellite (Route) service (AMS(R)S): An aeronautical mobile-satellite service reserved for communications relating to safety and regularity of flights, primarily along national or international civil air routes.

- Not applicable to any other applications except safety and regularity of flight.
- This band requires special measures to ensure freedom from harmful interference, and therefore is not available for non-safety-related activities, with few exceptions.

Aeronautical mobile-satellite (Off-Route) service (AMS(OR)S): An aeronautical mobile-satellite service intended for communications, including those relating to flight coordination, primarily outside national and international civil air routes.

Aeronautical radionavigation service (ARNS): A radionavigation service intended for the benefit and for the safe operation of aircraft.

- This band requires special measures to ensure freedom from harmful interference, and therefore is not available for non-safety-related activities, with few exceptions.

Aeronautical radionavigation-satellite service (ARNSS): A radionavigation-satellite service in which Earth stations are located onboard aircraft.

- This band requires special measures to ensure freedom from harmful interference, and therefore is not available for non-safety-related activities, with few exceptions.

The Radio Regulations also designate, by footnote 5.150, several bands for unlicensed applications:

5.150 The following bands:

- 13 553-13 567 kHz (center frequency 13 560 kHz),
- 26 957-27 283 kHz (center frequency 27 120 kHz),
- 40.66-40.70 MHz (center frequency 40.68 MHz),
- 902-928 MHz in Region 2 (center frequency 915 MHz),
- 2 400-2 500 MHz (center frequency 2 450 MHz),
- 5 725-5 875 MHz (center frequency 5 800 MHz), and
- 24-24.25 GHz (center frequency 24.125 GHz)

are also designated for industrial, scientific, and medical (ISM) applications. Radiocommunication services operating within these bands must accept harmful interference which may be caused by these applications. ISM equipment operating in these bands is subject to the provisions of No. 15.13.

- Very important to note that these unlicensed applications are not protected from interference and thus performance of communications links cannot be guaranteed.

B.1.2 World Radiocommunication Conference 2023 (WRC-23)

Changes to the Radio Regulations will next be considered at WRC-23. The agenda for WRC-23 is given in Annex A to this Appendix. ITU-R working parties develop the technical studies to support agenda item decisions and Working Party 5B (WP5B) has the responsibility for, inter alia, agenda items relevant to aviation. A brief description is given here on agenda items (AI) of potential relevance to Task TO-G-026 for STEReO application to disaster response communications.

AI 1.4 High altitude IMT base stations (HIBS).
This agenda item considers allowing high-altitude platforms to serve as International Mobile Telecommunications (IMT); i.e., 5G wireless networked base stations. As 5G can provide a highly reliable and prioritized level of communications service, such HIBS base stations have the potential to provide service to disaster areas where terrestrial infrastructure is unavailable but will not provide aviation safety communications and are likely not applicable to smaller scale disaster events.

AI 1.8 Accommodation of the use of FSS networks for control and non-payload communications of unmanned aircraft systems.
This agenda item considers regulatory changes required to accommodate the use of fixed satellite service networks by control and non-payload communications of unmanned aircraft systems. This would provide for safety service (i.e., command and control) communications for UAS traversing significant distances or in areas without terrestrial infrastructure, so potentially for UAS in the disaster response application. This activity has been on-going since at least 2007, highlighting the difficulty that can be encountered in achieving changes to the radio regulations in general, the long lead times required to complete the process for regulatory change, and the sensitivity internationally to the use of unmanned aircraft.

AI 1.9 Aeronautical HF modernization.
This agenda item considers regulatory changes to accommodate digital technologies for commercial aviation safety-of-life applications in existing HF bands allocated to the aeronautical mobile (R) service. Although HF frequencies provide for beyond radio line-of-sight propagation potentially applicable to certain disaster response scenarios, the congestion in the HF bands and difficult channel planning process make such an application extremely difficult.

AI 1.10 Non-safety applications of the aeronautical mobile service.
This agenda item studies possible new allocations for the aeronautical mobile service for the use of non-safety aeronautical mobile applications. AMS can provide spectrum to support non-safety UA communications, such as vehicle-to-vehicle communications and delivery of payload data. Studies being conducted by WP 5B have used wildfire response as a case study, including the use of UAS. Use of small UAS (for example, drone fleets) would require additional study to determine compatibility with other services and adjacent bands.

AI 1.15 Harmonize use of 12.75-13.25 GHz geo-stationary FSS for Earth stations on aircraft/vessels with the use of the frequency band 12.75-13.25 GHz by earth stations on aircraft and vessels communicating with geostationary space stations in the fixed-satellite service globally.
This agenda item could potentially provide additional spectrum capacity for aircraft payload communications, including for UAS. There is some concern of possible impact to Agenda Item 1.8, however.

AI 1.16 Facilitate the use of various frequency bands in the range 17.7-30 GHz for non-geostationary FSS Earth stations in motion.
This agenda item is relevant to Agenda Item 1.8, as it has been argued that Earth stations in motion (ESIMs) should be treated similarly to Earth stations on UAS and could have a potentially degrading effect on the UAS command and control links in the same bands.

AI 1.18 Narrowband MSS in the frequency bands 1 695-1 710 MHz, 2 010-2 025 MHz, 3 300-3 315 MHz and 3 385-3 400.
This agenda item considers potential new allocations to the mobile satellite service to support narrow-band mobile satellite systems. Such systems could potentially provide support to disaster response UAs in terms of command and control, although possibly not sufficient bandwidth for mission payload data.

AI 9.1a Recognition and protection of space weather sensors.
The significance of this agenda item is the potential for space weather sensors to create interference to other co-channel and adjacent channel services, including for aviation.

B.2 International Spectrum Standardization for Civil Aviation—International Civil Aviation Organization (ICAO)

ICAO is a United Nations Organization that supports the global air transportation system. ICAO’s Air Navigation Bureau develops and maintains the Global Aviation Safety Plan and the Global Air Navigation Plan. The Air Navigation Commission (ANC) considers and recommends Standards and Recommended Practices (SARPs) and Procedures for Air Navigation Services (PANS) for adoption or approval by the ICAO Council. The ANC maintains technical panels in a number of areas to support the development of standards and procedures. The panels of greatest relevance to UA are the Frequency Spectrum Management Panel and the Remotely Piloted Aircraft Systems Panel. In addition, the Unmanned Aircraft Systems Advisory Group (UAS-AG) organizes several relevant task groups and organizes symposia and other meetings to advance the safe use of UAS. Recent and current work being performed by these panels was reviewed in support of Task TO-G-026.

B.2.1 ICAO Frequency Spectrum Management Panel (FSMP)

The FSMP has several significant roles relevant to UAS [27]. The panel develops the ICAO Position for the WRC regarding issues relevant to aviation spectrum and other material as necessary to support the update of the ITU Radio Regulations. The ICAO position is very influential at the WRC as many administrations do not have aviation spectrum technical organizations and defer to advice provided by ICAO through its official position. The panel develops and maintains the ICAO Spectrum Strategy and the ICAO Policy on Radio Frequency Spectrum, necessary to enable the advancement of technological developments and innovation, for aviation to efficiently manage its limited frequency spectrum.

FSMP lists among its objectives the development and maintenance of standards and recommended practices (SARPs) and guidance material to facilitate frequency management of communication, navigation and surveillance systems; proposals to the ICAO spectrum strategy; mapping out the future requirements for spectrum to support communication, navigation and surveillance systems; proposals to the detailed ICAO Policy on all relevant aeronautical frequency spectrum allocations; developing input material for studies within the ITU Radiocommunication Sector (ITU-R) relevant to aeronautical interests in the development of ITU-R Recommendations and Reports; and addressing issues of interference from aeronautical and non-aeronautical sources.

The FSMP held its 14th working group meeting 25-29 April 2022 [36]. Relevant issues on the meeting agenda:

Agenda Item 3 ICAO WRC-23 Position

- Identified conflicts between administration preliminary proposals and ICAO Position
- Discussion of possible future agenda item proposals from administrations
- Modifications/Updates to the ICAO WRC-23 Position

Agenda Item 5 Development of (planned) Material for ITU-R Studies on:

- WRC-23 AI1.8 FSS for UAS
- WRC-23 AI1.9 Wideband HF
- WRC-23 AI1.10 Non-safety AMS

With regards to the ICAO WRC-23 Position, the FSMP continues to refine the position document that will ultimately be approved by the ICAO council. The position addresses WRC-23 Agenda Items as follows [35]:

- WRC-23 Agenda Items 1.6, 1.7, 1.8, 1.9, 1.10 and 9.2 address issues where aviation is seeking action by the WRC.
- WRC-23 Agenda Items 1.1, 1.2, 1.3, 1.4, 1.11, 1.13, 1.15, 1.16, 1.17, 4, 8, and 9.1 topic b could potentially affect aviation use of spectrum and hence aviation should participate in studies to ensure there is no undue impact. As a result, they are included in this position.
- No impact on aeronautical services has been identified from WRC-23 Agenda Items 1.5, 1.12, 1.14, 1.18, 1.19, 2, 3, 5, 6, 7, 9.1 topic a, 9.1 topic c, 9.1 topic d and 9.3 which are therefore not addressed in this position.

For Agenda Item 1.8, regarding the use of the fixed satellite service to support UAS control and non-payload communications links (CNPC), significant revision of the ICAO position has been proposed, but no changes were agreed upon at the meeting. The current unrevised position is summarized below.

WRC-23 Agenda Item 1.8

ICAO Position:

To support ITU-R studies, as called for by Resolutions **155 (Rev.WRC-19) and 171 (WRC-19)**. To support the modification of No. 5.484B and Resolution **155 (Rev.WRC-19)**. ICAO is expecting that the decision of WRC-23 will result in a Resolution that: • clearly provides primary status; • removes any apparent inconsistencies; • acknowledges that in accordance with the Annexes of the Convention of the International Civil Aviation Organization (ICAO), ensuring the safety-of-life aspects of the use of UAS CNPC is the role of the responsible States; 1. • provides sufficient information to support and/or validate safety cases; and • ensures that safety cases do not need to be revisited as a result of future satellite co-ordination agreements.

For Agenda Item 1.10, regarding new allocations for the aeronautical mobile service (AMS) for the use of non-safety aeronautical mobile applications in the bands 15.4-15.7 GHz and 22-22.21 GHz, no revision of the ICAO position was proposed. The current position is summarized below.

WRC-23 Agenda Item 1.10

ICAO Position:

To support ITU-R studies as called for by Resolution **430 (WRC-19)**. To support, based on the agreed results of studies, new allocations to the aeronautical mobile service only for use by non-safety aeronautical mobile applications. To ensure that any such modification does not adversely affect the status or provision of aeronautical safety services.

The FSMP held its 15th working group meeting FSMP WG/15 (August 22–September 1, 2022).

The meeting held discussions on the current version of the ICAO position for WRC-23. No significant changes are noted; however, a number of outstanding issues remain that will be addressed in the 16th working group meeting in February 2023.

At the 15th FSMP working group meeting, Information Paper 2 addressed the compatibility of AM(R)S and AMS(R)S operations in the 5 030-5 091 MHz frequency spectrum [64]. The paper proposes some options in managing the spectrum between terrestrial and satellite users. An approach adopted by ICAO for this frequency band will be helpful for enabling implementation of systems, including potentially for small UAS supporting disaster response operations. Figure B1 presents options for compatible use of the spectrum under consideration [64].

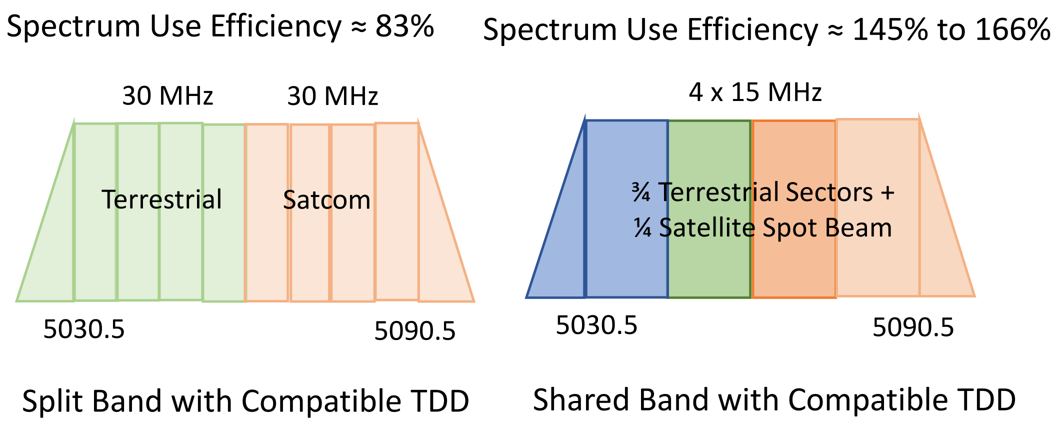

Figure B1. Options for compatible use of the 5030-5091 MHz spectrum band [64].

B.2.2 ICAO Unmanned Aircraft Systems Advisory Group (UAS-AG)

The Unmanned Aircraft Systems Advisory Group (UAS-AG) was established in 2015 to support the Secretariat in developing guidance material and expedite the development of provisions to be used by states to regulate unmanned aircraft systems (UAS), with its industry and international partners, as well as the Member States [37]. The advisory group has sponsored 22 UAS & RPAS Webinars and Symposia to date.

However, a presentation at one of these symposia, the DRONE ENABLE—ICAO's Unmanned Aircraft Systems Industry Symposium, September 22–23, 2017, should be noted in this report. "Potential spectrum and telecom technologies for small UAS" was presented by Nikolai Vassiliev of the ITU and provided several significant conclusions [34]:

Potential spectrum for UAS can be found in three categories: aeronautical safety bands, licensed bands, and unlicensed bands. Aeronautical safety bands are protected from interference, managed by aviation regulatory bodies, and already intensively used. Licensed bands (such as cellular networks, 5G, etc.), while shared with other users, have available capacity and control of interference and Quality of service (QoS) through system design. Unlicensed bands (such as Wi-Fi, ISM), while generally available and free to use for short-range communications, are subject to power limits and protection from interference is not ensured. Figure B2 provides an example analysis of possible application of aeronautical safety bands [34].

Range	Frequency band	Current aviation usage	Feasibility for UAs
HF	2.85 – 22.0 MHz	Voice and data	No Congested, subject to careful, formal planning
VHF	117 – 137 MHz	Voice and data	In principle No congested, subject to careful, formal planning
L-band	960 – 1164 MHz	Air-ground coms, DME, UAT, ADS-B…	In principle No Congested
C-band	5030- 5091 MHz	MLS, RPAS C2	Could be studied Mainly for RPAS, but 5030 – 5091 MHz under study for small UAS in some countries

Figure B2. Feasibility of aviation safety bands for UAS (example of some bands) [34].

Vassiliev suggested that choices of spectrum and communications technologies be applied to different UAS categories based on requirements for operational range and channel QoS. For example, licensed spectrum or dedicated bands for professional UAS and BLOS operations vs. unlicensed bands for recreational UAS operated at LOS, 5G and satellite networks for BLOS operations, Wi-Fi and short range for LOS operations, and some limited application of aeronautical systems for LOS/BLOS.

B.2.3 ICAO Remotely Piloted Aircraft Systems (RPAS) Panel

The Remotely Piloted Aircraft Systems Panel (RPASP) coordinates and develops ICAO SARPs, Procedures and Guidance material for remotely piloted aircraft systems (RPAS), to facilitate a safe, secure, and efficient integration of remotely piloted aircraft (RPA) into non-segregated airspace and aerodromes [38]. Among several focus areas for the RPASP are detect and avoid (DAA) or surveillance systems including airborne collision avoidance systems (ACAS) ground proximity warning systems or other safety nets, and telecommunications for the command and control (C2) link and air traffic control.

The RPAS Manual on Remotely Piloted Aircraft Systems includes coverage of C2 Link and Communications and detect and avoid systems. The manual is not focused on low-altitude small UAS, but rather on large UAS operating in air traffic managed airspace. However, definitions of required link performance for UA command and control may provide some guidance for spectrum and bandwidth requirements.

Several important points have been identified during the development of the C2 link portion of the RPAS Manual [28]. The C2 Link must have adequate performance to support the services it carries, which can include air traffic management or voice/data (if relayed through the UA), navigation, surveillance, and detect and avoid (DAA) and collision avoidance. Link performance requirements for the C2 link for safely controlling the UA will depend on the level of autonomy of the UA—remote pilot-in-the-loop, remote flight management, or fully autonomous.

A wide range of possible UAS configurations are possible. Data rates for C2 are not expected to be high, less than 50 kbps. Low data rates make higher performance C2 Links easier to achieve. The delivery of high data rate video for enhanced situational awareness will likely exceed the available spectrum.

RLOS links suffer from large signal fades especially when the RPA is close to the ground, while BRLOS (such as satellite links) can suffer from weather-related signal fading. Signal path obstruction by the UA airframe can also cause signal fading. Multiple antennas on the UA and on the ground and the use of frequency diversity can mitigate these effects.

B.3 Federal Communications Commission (FCC)

FCC has responsibility regarding regulation of spectrum and UAS [20]. In the United States, Congress has assigned responsibility for managing the nation's radio spectrum resources to the FCC and the National Telecommunications and Information Administration (NTIA). The FCC is responsible for the administration of nonfederal RF spectrum, while NTIA administers spectrum for federal use (e.g., use by the Department of Defense, NASA, etc.). As the majority of the spectrum is allocated to both federal and nonfederal use, spectrum management increasingly addresses the use of bands where the FCC and NTIA have joint jurisdiction.

B.3.1 Consideration of L-Band and C-Band AM(R)S Spectrum for UAS

In the FAA Reauthorization Act of 2018, Congress instructed the FCC, NTIA, and FAA to report on the possible use by UAS of spectrum that was recommended for allocation for AM(R)S and control links for UAS by WRC-07 (L-band, 960-1164 MHz) and WRC-12 (C-band, 5030-5091 MHz), on an unlicensed, shared, or exclusive basis, for operations within or outside of the UTM system.

The 960–1164 MHz band is heavily used by incumbent systems, including critical navigation systems. ITU studies examining spectrum for UAS use suggested that it was feasible for UAS to be used in certain portions of the 960-1164 MHz band in some countries. Subsequently, the FCC in 2015 amended the United States Table of Frequency Allocations to add an AM(R)S allocation at 960-1164 MHz. The 5030-5091 MHz band is much less encumbered and considered to be more feasible as a platform for UAS operations.

The FCC concluded in its report to Congress [18]:

> *The 5030-5091 MHz band as well as certain flexible-use bands are potential options for supporting such UAS communications. The 5030-5091 MHz band appears to offer promise for intensive UAS use because it is unencumbered, but that band poses some technical and regulatory issues that require further review before UAS operations may be permitted. In addition to the 5030-5091 MHz band, many stakeholders have expressed interest in a wide range of other spectrum bands, including existing flexible-use spectrum bands used by commercial broadband mobile providers, with varying characteristics that may present different challenges and benefits for UAS operation.*
>
> *Although these networks offer the potential to support wide-area UAS operations across the nation in the near term, they also present interference concerns and other operational questions*

that must be addressed. While we are encouraged by studies and work to date concerning the potential of flexible-use spectrum and LTE technology to support UAS, we find that further review of these issues will be required to ensure that integration of UAS occurs in a manner that serves the public interest. Finally, the 960-1164 MHz band is encumbered with numerous critical aeronautical navigation uses, making the deployment of UAS in the band challenging. While some comments suggest that UAS operations should be permitted in this spectrum, the record largely reflects concern regarding the possible impacts of such use to incumbents in the 960-1164 MHz band.

B.3.2 Public Safety Spectrum

The FCC also manages public safety spectrum for the mission-critical communications needs of First Responders charged with the protection of life and property, such as police, fire fighters and Emergency Medical Service (EMS) providers. Public safety spectrum also serves the public safety-related telecommunications needs of state and local governments generally [22].

The public safety bands are currently designated as Public Safety Land Mobile under FCC rules. Use for aeronautical mobile to support UAS links would require changes to existing rules. The following are public safety bands designated by the FCC:

- 25-50 MHz (VHF Low Band)
- 150-174 MHz (VHF High Band)
- 220-222 MHz (220 MHz band)
- 450-470 MHz (UHF Band)
- 758-769/788-799 MHz (700 Broadband)
- 768-775/798-805 (700 Narrowband)
- 806-809/851-854 MHz (NPSPAC Band)
- 809-815/854-860 MHz (800 MHz Band)
- 4940-4990 MHz (4.9 GHz Band)
- 5850-5925 MHz band (5.9 GHz Band)

The 758-769/788-799 MHz broadband allotment is licensed to the First Responder Network Authority (FirstNet), which is responsible for building and operating the nationwide broadband public safety network. All other public safety channels are licensed by the FCC under varying rules and administrative procedures. All channels, except those in the 4.9 GHz and 5.9 GHz bands, are subject to frequency coordination to ensure against mutual interference. The 5.9 GHz band, known as the Dedicated Short-Range Communications Service (DSRCS), is intended to promote automobile safety.

B.3.3 FCC Technical Advisory Committee (TAC)

The FCC's Technical Advisory Committee (TAC) established a working group to study aspects of communications for UAS, including appropriate radiofrequency spectrum. An extensive report was issued containing a number of results, conclusions, and recommendations. The report did not focus on small UAS but was inclusive of possible small UAS requirements.

The TAC issued its report "Communication Strategies for Unmanned Aircraft Systems (UAS)" on December 4, 2019 [21]. The following information is extracted and/or summarized from [21].

Spectrum issues studied included C2, payload, identification, monitoring, and collision avoidance. Specific questions studied included:

- What frequency bands are available today, and are they sufficient?
    - Consider payload needs as part of this.
- Which UAS activities can be carried out using existing systems or services (CMRS, Land-mobile, Satellite, Aviation, GNSS, etc.)?
- What are the trade-offs for the various alternative frequency bands?
- To what extent has loss of communications been a major contributor to loss of UAV?
- What are the issues of harmful interference to systems on the ground?
- What new requirements and roles for radar arise from UAS?

The following are key conclusions of the study.

The application of WiFi (2.4Ghz, 5.8 GHz) and Bluetooth (2.4 GHz) for UAS operations was evaluated for various characteristics: availability/reliability; capacity; coverage; security; integration (systems that fulfil multiple roles are preferable); latency; deployment issues; and cost. The evaluation applied to command and control; backup command and control; payload; separation assurance; broadcast ID; and networked tracking. The study noted that BVLOS range is limited to 7 km. Bluetooth Mesh Network can provide wider coverage than standalone BT as well as network connectivity but require dense concentrations of participating devices. Dense urban environments could lead to loss of command and control. A 2008 study found likely interference when using 2006 figures for devices per capita in computing interference; the number of devices per capita is now about 10x the 2006 value.

Technology Comparisons with 3GPP

- 3GPP systems, Wi-Fi and BT can provide the necessary communications to support UAS.
- 3GPP Systems may be more robust in some situations since:
    - They operate in protected spectrum.
    - Central control allows additional flexibility to overcome interference issues by providing capabilities such as allocating additional radio resources to overcome interference or lowering power levels to reduce interference.
- Although 3GPP V2X can potentially provide more robust capabilities for Remote ID broadcast or collision avoidance, it is not currently adapted for UAVs.
    - V2X support in LTE is currently being deployed (mainly outside the US), but this is tailored for automotive applications and assumes 5.9 GHz.
    - Adaptions to V2X to support UAVs is planned for 3GPP R17, but it is unclear what frequency band this will use for broadcast.

Recommendations:

- Analysis should be partitioned into different environments based on the level of radio frequency interference in each environment.
- Anticipate significant reliability challenges when using unlicensed bands for UAS communications for operations in urban environments.
- Future Work
    - Investigate the applicability of satellite communications for UAS.

RF Analysis Tools and Methods: The TAC working group recommends appropriate analytic tools be identified or created for effective policy making regarding UAS spectrum capacity and requirements.

- Consider both aviation and non-aviation bands (including terrestrial mobile and unlicensed).
- Consider both air-to-ground and ground-to-air links.
- Include link, coverage, capacity, in-band, and out-of-band interference analysis.

Some bands have Aeronautical Operation restrictions.

> *Note 1: This is not a complete list of all bands of interest.*
> *Note 2: An absence of expressed restrictions on Aeronautical Service in the Table of Allocations (ToA) or in the FCC's service rules for a band does not mean that the FCC has contemplated or analyzed aeronautical or UAS operations for that band.*

Aeronautical restrictions are due to a variety of reasons.

Common reasons include:

- Co-primary Aeronautical or Space Services in the band, or in adjacent bands.
- Sensitive federal systems (e.g., radars).
- Same-area use by FS, especially if used by public safety and/or utilities.

Figure B3 provides further information on bands with aeronautical restrictions.

Potential new interference concerns raised by UAV operations in terrestrial mobile bands were identified in 3 categories: Mobile-Mobile same application; Mobile-Mobile different application; Mobile-Other service. The TAC group recommended a quantitative analysis of UAV radio interactions with other services should be carried out before the FCC makes decisions regarding levels of protection.

The TAC working group analyzed the use of spectrum designated for aviation use

- Consider using spectrum for UAS that supports communications related to the safe operation of telemetry to/from aircraft.
  - AM(R)S – Aeronautical mobile (route) service intended for communications, including those related to flight coordination, primarily outside national or international civil air routes
  - ARNS – Aeronautical radionavigation service - particularly radio altimeters, traffic alert and collision avoidance
  - AMS(R)S – Aeronautical mobile satellite (route) service intended for communications where terrestrial communications are not available or reliable link via the ground cannot be achieved
  - AMS – Aeronautical mobile service intended to provide telemetry data for flight testing purposes
- Consider certain frequencies available/allocated to aviation services in the range 108 MHz–5650 MHz
  - Small UAS (sUAS) value the low cost and high integration of commercial RF components, available in this range.
  - Antenna requirements become challenging for sUAS below this frequency range.

Band	Lower (MHz)	Upper (MHz)	Lower (MHz)	Upper (MHz)	Incumbent Services	Regulations	Aeronautical operation
Licensed Spectrum							
Cellular / ESMR	817	849	862	894	FS, MS (land mobile)	allocation, rules, assigned, operational	restricted
AWS	1670	1675	n/a	n/a	FS, MS	allocation, rules, assigned	restricted
AWS	1695	1710	1995	2020	Federal Met-Sat in lower. FS, MSS in upper.	allocation, rules, assigned, operational	restricted
WCS	2305	2320	2345	2360	FS, MS, BSS, RLS	allocation, rules, assigned, operational	Partially restricted
MSS/ATC	2484	2495	n/a	n/a	RDSS, FS	allocation, rules, assigned(?)	restricted
BRS	2496	2690	n/a	n/a	FS	allocation, rules, assigned, operational	restricted
CBRS	3550	3700	n/a	n/a	FS, MS, FSS	allocation, rules	restricted
Frontiers	37000	40000	n/a	n/a	FS, FSS, MS	allocation, rules, partially assigned	Partially restricted (37-38 GHz)
Unlicensed Spectrum							
U-NII-3	5470	5850	n/a	n/a	RLS, MRNS, Met	allocation, rules, operational	unspecified (US), restricted (ITU)
WiGig	57000	71000	n/a	n/a	FS, FSS, MS, SRS, ISS, EESS, RLS, RNSS	allocation, rules, operational	unspecified (restricted in 64-66 GHz)
Under consideration							
UNII-5 to 8	5925	7125	n/a	n/a	FS, FSS, MS	TBD	restricted

Figure B3. Bands with aeronautical restrictions.

General potential barriers to use of aviation bands by sUAS were identified:

- Operational Issues: Using the same spectrum as civil aviation will likely require sUAS platforms to comply with aviation safety standards and FAA technical standard orders related to each band.
- Cost: Aviation-grade avionics costs could overwhelm the total cost of the sUAS.
- Weight and Size: Avionics available for operation in aviation spectrum could make sUAS too heavy and impact sUAS form factor.
- Congestion: Potential large volume of sUAS could place overwhelming demands on aviation bands because aeronautical safety spectrum is already saturated.

General potential benefits from use of aviation bands by sUAS were identified:

- Equipment utilizing aviation frequency bands and certified under Part 87 could benefit from ICAO Convention potentially eliminating need to obtain equipment certification in every country in which the device operates.
- Interference protection offered by aviation bands make these bands attractive (and mandatory) for "safety related communications" at all altitudes.

Spectrum appropriate for UAS of different sizes and uses

- Aviation frequency bands are likely the most appropriate bands for larger UAVs, UAVs that will transport heavier cargo or people, and UAVs that are most likely to integrate into the national airspace.
  - UAVs operating where there is reliable commercial wireless service may want to leverage licensed commercial wireless bands for some communications functions, and aviation bands for other communications functions

- Other spectrum options include
  - Fixed and Mobile Satellite Service
  - Mobile Service not including Unlicensed
  - Unlicensed spectrum
- Notes
  - Licensed commercial wireless spectrum is entitled to interference protection, and can offer a high quality of service, similar to aviation bands that are entitled to interference protection.
  - Unlicensed spectrum—WiFi, ISM and Bluetooth—is not entitled to interference protection, and offers no guarantees of reliability or availability, which may pose a number of issues for leveraging these bands for aeronautical systems.

Frequency Band: 108-117.975 MHz

- Allocated to Aeronautical Radionavigation Service and Aeronautical Mobile (Route) Service (via footnote 5.197A).
- On a global basis, the band 108–117.975 is used for instrument landing systems (ILS localizer) and VHF omnidirectional range (VOR) and is transitioning the ground-based augmentation system (GBAS) for the foreseeable future. Only GBAS may operate in the band 108-112 MHz to transmit navigational information in support of air navigation and surveillance functions. Any AM(R)S system operating in the band 108-117.975 MHz shall meet ICAO SARPs which are designed to protect FM broadcast stations.

Frequency Band: 117.975-121.9375 MHz

- Allocated to Aeronautical Mobile (Route) Service.
- The band 117.975-137 MHz is the main communications band for line-of-sight air-ground voice and data communications and is used at all airports, for en-route, approach and landing phases of flight and for a variety of short-range tasks for general aviation and recreational flying activities (e.g., gliders and balloons). The use of this band is exclusively for air-ground communications relating to the safety and regularity of flight (ATC and AOC).
- Due to above uses this band is unlikely to be available for UAS use.

Frequency Band: 121.9375-123.0875 MHz

- Allocated to Aeronautical Mobile Service. Allocated to nonfederal use.
- The band 117.975-137 MHz is the main communications band for line-of-sight air-ground voice and data communications and is used at all airports, for en-route, approach and landing phases of flight and for a variety of short-range tasks for general aviation and recreational flying activities (e.g., gliders and balloons). The use of this band is exclusively for air-ground communications relating to the safety and regularity of flight (ATC and AOC).
- Due to above uses this band is unlikely to be available for UAS use.

Frequency Band: 123.0875-137 MHz

- Allocated to Aeronautical Mobile Service.
- The band 117.975-137 MHz is the main communications band for line-of-sight air-ground voice and data communications and is used at all airports, for en-route, approach and landing phases of flight and for a variety of short-range tasks for general aviation and recreational flying activities (e.g., gliders and balloons). The use of this band is exclusively for air-ground communications relating to the safety and regularity of flight (ATC and AOC).
- The 136-137 MHz portion is available for air traffic control purposes, such as automatic weather observation stations (AWOS), automatic terminal information services (ATIS), flight information services-broadcast (FIS-B), and airport control tower communications.

- Due to above uses this band is unlikely to be available for UAS use.

Frequency Band: 328.6-335.4 MHz

- Allocated to Aeronautical Radionavigation Service.
- On a global basis, the frequency band 332.8-335.4 MHz is used for the ILS glide path.
- Further review as to whether this band could be considered is necessary.

Frequency Band: 960-1164 MHz

- Allocated to Aeronautical Radionavigation and Aeronautical Mobile (Route) Services.
- Planned to be used for future air-ground (and air-air) data communications (e.g., LDACS) although achieving compatibility with Distance Measuring Equipment (DME) and secondary surveillance radar (SSR) could be problematic. DME channelization is complicated.
- Automatic Dependent Surveillance—Broadcast (ADS-B) operates in this band (1030/1090 MHz) and is a critical component of aviation detect and avoid requirements.
- The frequency 978 MHz is used for the Universal Access Transceiver (UAT), which provides for ADS-B and up-linking of data messages.
- Due to above uses this band is unlikely to be available for UAS use

Frequency Band: 1164-1215 MHz

- Allocated to Aeronautical Radionavigation Service and Radionavigation Satellite Service (space-to-Earth) (space-to-space). Footnote information of interest -
  - Use of the band 960-1215 MHz by the aeronautical radionavigation service is reserved on a worldwide basis for the operation and development of airborne electronic aids to air navigation and any directly associated ground-based facilities.
- While having no regulatory status, significant DOD communications system operates in this band.
- Used for GPS/Galileo/Beidu/Glonass signals.
- Due to above uses this band is unlikely to be available for UAS use.

Frequency Band: 5030-5091 MHz

- Allocated to Aeronautical Radionavigation Service, Aeronautical Mobile (Route), Aeronautical Mobile-Satellite (Route). Footnote information of interest -
  - The use of the frequency band 5 030-5 091 MHz by the aeronautical mobile (R) service is limited to internationally standardized aeronautical systems.
  - In the frequency band 5 030-5 091 MHz, the aeronautical mobile-satellite (R) service is subject to coordination under No. 9.11A. The use of this frequency band by the aeronautical mobile-satellite (R) service is limited to internationally standardized aeronautical systems. (WRC-12)
- This band is a potential candidate for UAS C2, especially larger UAS platforms that may require an aviation safety spectrum allocation.

Key recommendation:

- As UAS operations become more complex, including larger aircraft operating at higher altitudes, flying over people, and carrying passengers, the need to use aeronautical mobile (route) service and aeronautical mobile satellite (route) service spectrum increases for communications impacting the safety of the flight.
- Mobile service spectrum (i.e., Cellular (CMRS)) could be an option for safety-related communications where the necessary reliability requirements as set by the appropriate government agency(ies) can be met.

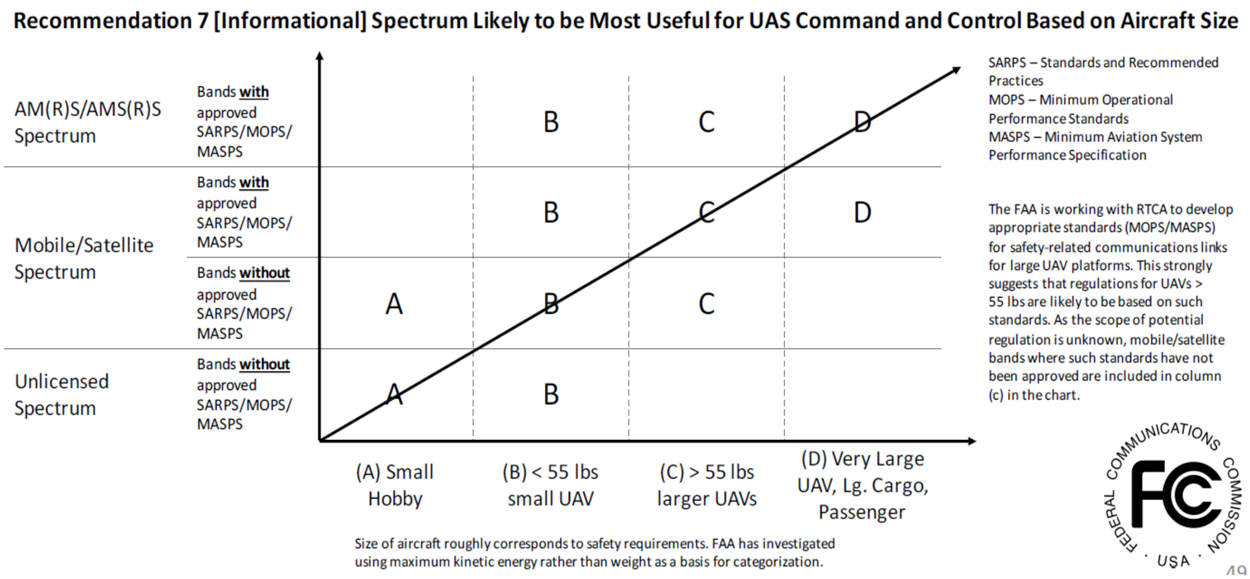

Figure B4. Spectrum for UAS Command and Control as a function of UAS size.

Recommendations regarding the type of spectrum for use in UAS command and control as a function of aircraft size are depicted in Figure B4.

Some small UAVs (< 55 lbs.) can use unlicensed spectrum (under certain “non-impactful” conditions).

- Small UAVs could be permitted to utilize Mobile Spectrum without developing minimum aviation operational, performance, or international aviation recommended practices (MOPS/MASPS/SARPS).
- In certain circumstances, even small UAVs might need to utilize very reliable aviation safety spectrum. The option should not be precluded.
  - Use of Mobile/Fixed Communication Networks (MFCN) for the command and control and payload links of UAs within the current MFCN harmonized regulatory framework.

B.4 National Telecommunications and Information Administration (NTIA)

The National Telecommunications and Information Administration (NTIA) manages the federal government’s use of spectrum, with assistance and advice from the Interdepartmental Radio Advisory Committee [23]. NTIA’s activities include establishing and issuing policy regarding allocations and regulations governing the federal spectrum use; preparing for, participating in, and implementing the results of international radio conferences; assigning frequencies and maintaining spectrum use databases.

B.4.1 The Commerce Spectrum Management Advisory Committee (CSMAC)

The Commerce Spectrum Management Advisory Committee (CSMAC) advises the NTIA on spectrum policy issues. The CSMAC established a subcommittee for unmanned aircraft spectrum. The subcommittee issued its final report in April 2021 [26]. The subcommittee addressed the following topics:

- Spectrum to support command and control operations will be critical for these emerging industry applications, to include urban air mobility and transcontinental cargo delivery.
- What are appropriate models for ensuring timely and secure access to frequencies necessary to support UAS command and control requirements? What governance characteristics are important? Are there liability issues to consider for this function? Is it a third-party frequency coordinator model?
- What is the potential need to create an entity that supports and facilitates collaboration across the disparate federal advisory committees for UAS?

The subcommittee did not focus on small UAS but considered small UAS applications along with other UAS classes. The following information is extracted and/or summarized from [26].

UAS spectrum access models considered:

- Third-party coordinator
- Terrestrial commercial wireless networks
- Commercial satellite communications (SATCOM) networks
- Unlicensed access
- Dynamic spectrum access
- Band partitioning

Third-Party Coordinator

- An aviation spectrum expert third-party coordinator acts on behalf of the FCC and NTIA to issue the necessary license authorization to transmit to UAS providers on a demand basis to terrestrial ground stations dedicated to UAS CNPC links.
- Each UAS would be assigned one or more frequencies (including alternate channels) along the planned route they intend to fly.
- Both single and multiple third-party coordinators would be applicable for this model.
- Technology options include certified aviation UAS CNPC systems.
- Possible UAS types – Large UAS platforms required to fly at high altitudes and/or integrate with existing FAA-controlled airspace.
- Potential evolutions – Automated system with pre-coordination of assignment criteria.

Terrestrial Commercial Wireless Networks

- Commercial licensed wireless network providers use existing cellular networks to provide individual UAS connectivity within most wideband channels.
- Mobile services spectrum is traditionally licensed exclusively in some bands and shared in others, using deployed network infrastructure.
- Use of existing access control structure accommodates the coordination of spectrum, with each base station dynamically assigning the available frequency bands and resource blocks while each network’s time/frequency access is automatically controlled by single system.
- Technology options – 4G/5G.
- Existing examples of Model -Nationwide terrestrial carrier networks.
- Possible UAS Types – Small UAS.
- Potential evolution:
  - Physical network modifications could be implemented to provide additional coverage for UAS at altitude, including future high altitude base stations.
  - Development of specific UAS standards, protocols, and certification as part of the 3rd Generation Partnership Project (3GPP) open standards process for networks to meet FAA certification, security, and assurance requirements.

    - Network slicing could provide end-to-end virtualization of the physical network and enable quality of service (QoS) requirements.
- Notable Disadvantages:
    - Operational range and altitude for existing networks not primarily designed for users at different altitudes or operating at significant speed.
    - How UAS traffic on shared commercial networks is protected and prioritized.
    - Possible security incidents.

Also, not noted in the report but the lack of coverage in remote, low/unpopulated, oceanic areas pertains to the disaster response scenario.

Commercial SATCOM Networks

- One or more commercial SATCOM providers use current and future satellite commercial networks to provide UAS connectivity within either dedicated or shared wideband channels.
- Use of existing commercial SATCOM access control structure accommodates the coordination of spectrum use, with necessary traffic management in place.
- Services can provide overlapping coverage in large areas, including areas not possible with terrestrial services such as remote or oceanic regions.
- Technology options – Multiple nationwide and global coverage Geostationary Orbit (GSO) and Non-Geostationary Orbit (NGSO) constellations ranging from L to Ka bands.
- Existing examples of model – L-band services for Air Traffic Control, AMS(R)S and UAS C2, Ku/Ka SATCOM services for commercial aircraft passenger services.
- Possible UAS types – Larger platforms flying at altitudes above the tree line in oceanic and remote areas, including within FAA-controlled airspace.
- Potential evolution:
    - Development of smaller antennas that could support small UAS
- Notable Disadvantages:
    - Less robust coverage in urban canyons, etc.
    - As with other access technologies, operation at frequency bands such as Ku/Ka SATCOM are susceptible to rain fade.

Unlicensed Access

- All devices operate equally and are required to accept and mitigate interference on an equal basis.
- Technology options – Wi-Fi, 5G NR-U, other ISM technologies.
- Existing examples of model – UAS and model aircraft used for recreational use.
- Possible UAS types – Small UAS flying locally, such as in low population density areas and for non-safety critical data.
- Possible evolution:
    - The policy/logic is controlled by a centralized database system to adjust system behaviors, performance, and enforcement measures as needed.
- Notable Disadvantages:
    - Interference protection must not rely on regulatory guarantees.
        - RF environments of unlicensed bands are variable and cannot guarantee reliability or availability.
        - Not appropriate for safety-critical data.
        - Limited range based on power and usage restrictions for unlicensed bands.

Dynamic Spectrum Access

- Radios look for available spectrum based on the detected local RF usage.

- Can utilize licensed and/or unlicensed spectrum and dictate Primary and Secondary UAS spectrum users.
- Primary users are assigned a frequency by a Third-Party Coordinator or other method, while secondary use is on a non-interference basis to primary users.
- Technology options – Acts as on overlay to existing communication technology.
- Existing examples of model – CBRS SAS, 5 GHz band Dynamic Frequency Selection.
- Possible UAS types – Emergency operations, operations in undeveloped regions, and scenarios with more UAS than available channels.
- Possible evolutions:
  - The core policy/logic is controlled by a centralized database system to adjust behaviors for sensing cueing, and enforcement as needed.
  - Coordination can be augmented through sensing, either terrestrial network and/or device-based sensing.
- Notable Disadvantages:
  - Increased UAS radio complexity to support necessary sensing.
  - Need for technology updates to support detection of new signals as system develops.

Band Partitioning

- Partition of bands between different models is dependent on operational requirements.
- Sharing can be achieved by either frequency/band partitioning (with potential guard bands) or geographic separation (with potential separation distances).
- Existing examples of model – European proposal for joint SATCOM/terrestrial UAS CNPC system in 5030–5091 MHz.
- Possible UAS types – Multi-role mission UAS flying between vastly different airspace types.
- Possible evolution:
  - Dynamic partitioning may change based on usage requirements for each service (e.g., urban vs. rural).
  - Additional studies would be warranted.
- Notable Disadvantages:
  - Would require additional filters, transceiver complexity and/or a guard band between the different technologies, which in turn may reduce the peak frequency band capacity.
  - Limited examples of UAS frequency band partition.
  - Already predicted that existing spectrum capacity not sufficient, let alone partitioning of the band, which may add further spectrum restrictions.

Findings: Spectrum Access Models

- Multiple UAS spectrum access models are appropriate.
  - Multiple overlapping approaches expected for a mature UAS ecosystem.
  - Safety spectrum a consideration dependent on the regulatory mandates by the FAA.
- Important governance characteristics of UAS spectrum access models.
  - Safety assurance, spectrum access prioritization, enforcement, coordination, planning to ensure link availability, continuity during handoffs, and contingency planning.
  - Third-party coordinator could be a broader, less specific role across other access models.
- All models have potential liability issues.
  - Compliance with FAA/FCC regulations a large component.
  - Applicable to UAS operators, CNPC link service providers, and third-party coordinators.
- Necessary parameters that FCC and NTIA will need to incorporate into possible service rules for UAS spectrum is potentially extensive.
  - Combined with an urgent need for action given the rate of UAS development.

Federal Advisory and other Committees for UAS (see Figure B5).

- FCC TAC
- FAA DAC
- UAS ExCom
- NASA UPP
- PNT Advisory Board

Findings: Federal Advisory and Other Federal Committees for UAS

- There are disparate federal advisory and other committees with ongoing UAS activities.
- No national committee is assuming leadership, specifically as a national focal point and centralizing function, on UAS spectrum.
- Instead of making spectrum decisions in isolation, the NTIA and FCC need to be informed of UAS spectrum requirements and coordinate federal, nonfederal, and shared spectrum use.
- U.S. leadership is needed to provide direction, coordination, and integration for UAS spectrum activities across organizations, and to advance the way ahead.
- There is a need to create an entity that supports and facilitates spectrum-related collaboration across the disparate federal advisory and other committees for UAS.

UAS Activities

	FCC Technological Advisory Council (TAC)	FAA Reauthorization Bill, Section 374	FAA Drone Advisory Committee (DAC)	International Civil Aviation Organization (ICAO)	NASA UAS Traffic Mgt (UTM) Pilot Program (UPP)	RTCA	3GPP
Purpose	Provides technical advice to the FCC, under FACA	Responds to Congress under Section 374 of FAA Reauthorization Act of 2018 (Public Law 115-254)	Provides FAA with advice on key UAS integration issues by helping to identify challenges and prioritize improvements	Builds consensus on international civil aviation standards and recommended practices and policies, under the UN	Develops, demonstrates, and provides enterprise services to support implementation of initial UTM operations	A standards development organization, including SC-228 which develops minimum operational performance standards (MOPS) for UAS	A standards organization which develops protocols for mobile telecommunications, including UAS 5G connectivity
Scope	Study the spectrum issues for UAS and identify spectrum useful for UAS C2	FAA, NTIA, and FCC to submit a report to Congress on use of 960-1164 MHz (L-band) and 5030-5091 MHz (C-band) for UAS operations	Create broad support for an overall UAS integration strategy and vision	Addressing spectrum planning for 5 GHz band, including UAS in 5030-5091 MHz; coordinating with ICAO RPAS Panel	Define initial set of industry and FAA capabilities to support UAS traffic mgt (UTM) at flight levels below 400 feet; transfers NASA research to FAA to support automated UTM operations	Development of aviation standards and supporting guidance material for FAA certified C2 links to be used by UAS operating in non-segregated, controlled airspace	3GPP TR 36.777 in Release 15 provides the results of a study on potential LTE enhancements for UAS; 3GPP RAN provided technical specs for LTE support of UAS
Spectrum	Aviation and non-aviation bands (incl. terrestrial mobile and unlicensed)	960-1164 MHz (L-band) and 5030-5091 MHz (C-band); other spectrum might be acceptable depending on safety case		Focus on licensed spectrum for operation	No discussion of spectrum bands in summaries or reports	960-1164 MHz (L-band), 5030-5091 MHz (C-band) and commercial SATCOM links	Commercial cellular bands
Access Models	Consider extension of Service Area Boundaries metric to higher altitudes	White space approach for L-band; need to identify access mechanism for C-band		Dedicated aviation spectrum for terrestrial links or detailed aviation performance models defined for commercial SATCOM links			

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Figure B5. UAS spectrum-related activities.

Recommendations

- CSMAC recommends that NTIA play a leadership role in coordinating across the federal government and providing direction and resources to facilitate UAS spectrum access.
- NTIA should convene a group of federal stakeholders to gain consensus on spectrum requirements and to ensure that multiple spectrum access models and multiple bands can be leveraged to meet those needs. NTIA must coordinate federal agency uses of spectrum for UAS.
- CSMAC recommends that NTIA initiate and champion designation of a central POC within the executive branch for UAS coordination.
- Facilitate information sharing and collaboration across federal agencies, industry, and academia and other non-profit organizations.

B.5 Intelligent Transport Systems

In recent years, spectrum authorities have been considering allocations of spectrum for Intelligent Transport Systems (ITS). ITS is a system to support transportation of goods and humans with information and communication technologies in order to use the transport infrastructure and transport means efficiently and safely (cars, motorcycles, bicycles, trains, planes, ships, and other). [82] Table B1 from [82] below shows several legacy and advanced ITS applications. A number of standards organizations are developing ITS standards, and ITU-R reports and recommendations are also under development.

The 5.9 GHz band is being applied to ITS applications, falling within the international Mobile Service spectrum. Some administrations in each of the three ITU Regions have deployed radio local area networks in the frequency band 5 725-5 850 MHz and some administrations are considering allowing radio local area networks in the frequency band 5 850-5 925 MHz [81]. Table B2 demonstrates the emerging potential to move toward spectrum harmonization in some countries, but with different bands already being developed, the outcome is uncertain.

Within the United States, the FCC allocation table footnote NG160 states: In the band 5850-5925 MHz, the use of the nonfederal mobile service is limited to operations in the Intelligent Transportation System radio service. This aligns with some ITS spectrum allocations in other countries. However, in 2021 the FCC adopted revised rules to repurpose the lower 45 megahertz of the 5.850-5.925 GHz band for the expansion of unlicensed mid-band spectrum operations, while retaining the upper 30 megahertz of spectrum for intelligent transportation system (ITS) operations [83]. The potential impact is to compress ITS applications into a substantially reduced spectrum band. Given the short-range nature of ITS V-to-V communications in this band, application to DAA for STEReO-based disaster response drone applications may still be possible without degradation from interference, but further study is needed.

B.6 Federal Aviation Administration (FAA)

The FAA strategic Plan for FY 2019–2022 [17] includes the UAS and Integrated Pilot Program Initiative to enable the safe and secure integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS). A key activity in this initiative is UAS Traffic Management (UTM), in which the FAA partners with NASA and industry to develop a framework for the automation of traffic management for unmanned aircraft.

Among FAA UAS activities is the Drone Advisory Committee (DAC). The FAA tasked the DAC "to engage operators in low altitude airspace to obtain feedback on how remote identification might be used to increase situational awareness and use this feedback to develop recommendations on how the FAA can address responses to the RFI." The FAA had been seeking information on how the Remote ID rule may provide an opportunity to increase the situational awareness of UAS for piloted aircraft [18].

Table B1. Classification of Legacy ITS and Advanced ITS [82]

Dedicated Short Range Communication (DSRC)	**Europe**: road tolling and similar applications
	North America: vehicle-to-vehicle and vehicle-to-infrastructure communication based on IEEE 802.11p / WAVE technology in 5.9 GHz, comparable to C-ITS based on IEEE 802.11p / ETSI ITS-G5 in Europe.
	Japan: technology for ETC, road tolling and vehicle to infrastructure traffic information systems
Legacy ITS	– TTT: Transport and Traffic Telematic, mainly in Region 1, also called DSRC in Europe • CEN DSRC tolling • HDR DSRC tolling, – ETC: In Japan, Korea and China • V2I (ETC 2.0, ARIB STD-T75) in Japan – VICS: Vehicle Information Communication Systems in Japan
Advanced ITS	Cooperative ITS (C-ITS) building on ad hoc networks with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure communication (V2I), together called vehicle-to-X (V2X), e.g. – V2X (ETSI ITS-G5, IEEE 802.11p) – V2X (LTE based V2X) – V2X (WAVE, IEEE 802.11p), also called DSRC in US – V2X (ITS Connect, ARIB STD-T109)

Table B2. Examples of Frequency Usage for Evolving ITS Within Regions [81]

Region 1	
Country or Group	**Frequency bands**
CEPT	5 855-5 925 MHz
United Arab Emirates	5 8555 925 MHz
Region 2	
Country or Group	**Frequency bands**
Canada	5 8505 925 MHz
United States	5 8505 925 MHz
Region 3	
Country or Group	**Frequency bands**
Australia	5 8555 925 MHz
China	5 9055 925 MHz
Japan	755.5764.5 MHz 5 7705 850 MHz
Korea	5 8555 925 MHz
Singapore	5 8555 925 MHz

B.7 European UAS Activities

The European Aviation Safety Agency (EASA) and European Conference of Postal and Telecommunications Administrations (CEPT) Electronic Communications Committee (ECC) are among European organizations studying spectrum aspects for UAS.

Among areas under study are the application of mobile services bands supporting LTE and 5G-based services for UAS communications.

Harmonized mobile bands under study [46]:

- 700 MHz (703-733 MHz UL/758-788 MHz DL) (2x30 MHz) (LTE, 5G NR)
- 800 MHz (791821 MHz DL/832862 MHz UL) (2x 30 MHz) (LTE)
- 900 MHz (880915 MHz UL/925960 MHz DL) (2x 35 MHz) (GSM, UMTS, LTE)
- 1800 MHz (17101785 MHz UL/18051880 MHz DL) (2 x 75 MHz (GSM, LTE)
- 2.1 GHz (19201980 MHz UL/21102170 MHz DL) (2 x 60 MHz) (LTE, 5G NR)
- 2.5 GHz (2570 MHz2620 MHz TDD) 50 MHz (LTE)
- 2.5 GHz (25002570 MHz UL/26202690 MHz DL) (2 x70 MHz) (LTE)
- 3.5 GHz (3.4-3.8 GHz TDD) 400 MHz (5G NR)

B.8 Summary of Potential Bands for UAS

The following are some of the bands that may potentially be applied to UA.

AM(R)S

• HF	2 850 – 22 000 kHz	Air-ground communication (HF voice and data)
• VHF	108 – 117.975 MHz	VOR/ILS localizer GBAS/VDL Mode 4 (voice and data)
• VHF	117.975 – 137 MHz	Air-ground and air-air communications (VHF Voice and data)
• UHF/L-Band	960 – 1 164 MHz	LDACS (for datalink), LDACS (for Alternative-PNT)
• UHF	978 MHz	Universal Access Transceiver (UAT)
• C-Band	5 030 – 5 150 MHz	UAS CNPC/Airport Surface Communication (AeroMACS)

AMS(R)S

• L-Band	1 610 – 1 626.5 MHz	Satellite Communications (IRIDIUM)
• C-Band	5 000 – 5 150 MHz	

AMS

- C-Band 4400-4990 MHz
- Ku-Band 14.5-15.35 GHz
- K-Band 21.2-22 GHz
- K-Band 22.5-23.6 GHz
- K-Band 25.25-27.5 GHz
- V-Band 45.5-47 GHz

- Under consideration (WRC-23 Agenda Item 1.10):
  - Ku-Band 15.4-15.7 GHz
  - K-Band 22-22.21 GHz

UAS Control and Non-Payload Communications in the Fixed Satellite Service Bands (WRC-23 AI 1.8)

For downlink (space-to-Earth):

- X-Band 10.95-11.2 GHz
- X-Band 11.45-11.7 GHz
- Ku-Band 11.7-12.2 GHz (Region 2)
- Ku-Band 12.2-12.5 GHz (Region 3)
- Ku-Band 12.5-12.75 GHz (Regions 1 and 3
- K-Band 19.7-20.2 GHz

For uplink (Earth-to-space):

- Ku-Band 14-14.47 GHz
- Ka-Band 29.5-30.0 GHz

Mobile Service (MS)

• UHF	703-733 MHz (UL)	(LTE, 5G NR)
• UHF	758-788 MHz (DL)	(LTE, 5G NR)

- UHF   791-821 MHz (DL)   (LTE)
- UHF   832-862 MHz (UL)   (LTE)
- UHF   880-915 MHz (UL)   (GSM, UMTS, LTE)
- UHF   925-960 MHz (DL)   (GSM, UMTS, LTE)
- L-Band   1710-1785 MHz (UL)   (GSM, LTE)
- L-Band   1805-1880 MHz (DL)   (GSM, LTE)
- S-Band   1920-1980 MHz (UL)   (LTE, 5G NR)
- S-Band   2110-2170 MHz (DL)   (LTE, 5G NR)
- S-Band   2570 MHz -2620 MHz (TDD)   (LTE)
- S-Band   2500-2570 MHz (UL)   (LTE)
- S-Band   2620-2690 MHz (DL)   (LTE)
- S-Band   3.4-3.8 GHz (TDD)   (5G NR)

Public Safety

- 25-50 MHz   (VHF Low Band)
- 150-174 MHz   (VHF High Band)
- 220-222 MHz   (220 MHz band)
- 450-470 MHz   (UHF Band)
- 758-769/788-799 MHz   (700 Broadband)
- 768-775/798-805   (700 Narrowband)
- 806-809/851-854 MHz   (NPSPAC Band)
- 809-815/854-860 MHz   (800 MHz Band)
- 4940-4990 MHz   (4.9 GHz Band)
- 5850-5925 MHz band   (5.9 GHz Band)

ITS

- 5 850-5 925 MHz   (International allocation)
- 5 895-5 925 MHz   (U.S. allocation)

B.9 Annex to Appendix B – Activities of the ITU-R with respect to WRC-23

The agenda of WRC-23 was adopted at the 2019 World Radiocommunication Conference (WRC-19) and is listed in the following section.

During the interconference period (2019-2023), the ITU-R establishes study groups to develop possible methods to address the agenda items for the upcoming conference. The study groups subdivide work into working parties organized to undertake studies to develop the technical basis for decisions on the WRC-23 agenda items.

Study Group 5 covers agenda items associated with terrestrial services. Within Study Group 5, four working parties focus on specific areas. Working Party 5B (WP 5B) is responsible for the Maritime Mobile Service including the Global Maritime Distress and Safety System (GMDSS), the Aeronautical Mobile Service and the Radiodetermination Service.

Therefore, items of importance to aeronautical communications fall under the purview of WP 5B.
With respect to the WRC-23 agenda items, the WP is either the lead group (LG), joint lead group (JLG) or contributing group (CG) to which have been attributed to the following AI:

WP 5B-1 Radio Determination

- AI 1.2 IMT in various frequency bands in the frequency range 3.3-10.5 GHz (CG)
- AI 1.3 Mobile in the frequency band 3.6-3.8 GHz (CG)
- AI 1.4 High altitude IMT base stations (CG)
- AI 1.12 Space radar sounders at 45 MHz (CG)
- AI 1.14 Earth exploration satellite service at 231.5-252 GHz (CG)
- AI 1.18 Narrowband MSS in the frequency range 1.695-3.4 GHz (CG)
- AI 1.19 FSS in the frequency band 17.3-17.7 GHz (CG)

WP 5B-2 Aeronautical

- AI 1.1 Protection of aeronautical and maritime mobile systems in international waters from IMT in the frequency band 4 800-4 990 MHz (JLG)
- AI 1.6 Sub-Orbital Vehicles (LG)
- AI 1.7 Aeronautical Mobile Satellite (R) Service in the aeronautical mobile VHF band (LG)
- AI 1.9 Aeronautical HF modernization (LG)
- AI 1.10 Non-safety applications of the Aeronautical Mobile Service (LG)
- AI 1.13 Space research in the frequency range 14.8-15.35 GHz (LG)

WP 5B-3 Maritime

- AI 1.11 Global Maritime Distress and Safety System modernization (LG)

WP-5B-4 Miscellaneous

- AI 1.5 Review of spectrum use of the frequency band 470-960 MHz in Region 1 (CG)
- AI 9.1a Recognition and protection of space weather sensors (CG)

WP 5B-5 Satellite Related Issues

- AI 1.8 Accommodation of the use of FSS networks for control and non-payload communications of unmanned aircraft systems (LG)
- AI 1.15 Harmonize use of 12.75-13.25 GHz geo-stationary FSS for Earth stations on aircraft/vessels (CG)
- AI 1.16 Facilitate the use of various frequency bands in the range 17.7-30 GHz for non-geo-stationary FSS Earth stations in motion (CG)
- AI 1.17 Inter-Satellite Links in the frequency range 11.7-30 GHz (CG)

B.9.1 The WRC 23 Agenda

1.1 to consider, based on the results of ITU R studies, possible measures to address, in the frequency band 4 800-4 990 MHz, protection of stations of the aeronautical and maritime mobile services located in international airspace and waters from other stations located within national territories, and to review the power flux-density criteria in No. 5.441B in accordance with Resolution 223 (Rev. WRC 19)

1.2 to consider identification of the frequency bands 3 300-3 400 MHz, 3 600 3 800 MHz, 6 425 7 025 MHz, 7 025-7 125 MHz and 10.0-10.5 GHz for International Mobile Telecommunications (IMT), including possible additional allocations to the mobile service on a primary basis, in accordance with Resolution 245 (WRC 19)

1.3 to consider primary allocation of the frequency band 3 600 3 800 MHz to the mobile service in Region 1 and take appropriate regulatory actions, in accordance with Resolution 246 (WRC 19)

1.4 to consider, in accordance with Resolution 247 (WRC 19), the use of high-altitude platform stations as IMT base stations (HIBS) in the mobile service in certain frequency bands below 2.7 GHz already identified for IMT, on a global or regional level

1.5 to review the spectrum use and spectrum needs of existing services in the frequency band 470-960 MHz in Region 1 and consider possible regulatory actions in the frequency band 470 694 MHz in Region 1 on the basis of the review, in accordance with Resolution 235 (WRC 15)

1.6 to consider, in accordance with Resolution 772 (WRC 19), regulatory provisions to facilitate radiocommunications for sub-orbital vehicles

1.7 to consider a new aeronautical mobile-satellite (R) service allocation in accordance with Resolution 428 (WRC 19) for both the Earth-to-space and space-to-Earth directions of aeronautical VHF communications in all or part of the frequency band 117.975-137 MHz, while preventing any undue constraints on existing VHF systems operating in the aeronautical mobile (R) service, in the aeronautical radionavigation service, and in adjacent frequency bands

1.8 to consider, on the basis of ITU R studies in accordance with Resolution 171 (WRC 19), appropriate regulatory actions, with a view to reviewing and, if necessary, revising Resolution 155 (Rev. WRC 19) and No. 5.484B to accommodate the use of fixed-satellite service networks by control and non-payload communications of unmanned aircraft systems

1.9 to review Appendix 27 of the Radio Regulations and consider appropriate regulatory actions and updates based on ITU R studies, in order to accommodate digital technologies for commercial aviation safety-of-life applications in existing HF bands allocated to the aeronautical mobile (R) service and ensure coexistence of current HF systems alongside modernized HF systems, in accordance with Resolution 429 (WRC 19)

1.10 to conduct studies on spectrum needs, coexistence with radiocommunication services and regulatory measures for possible new allocations for the aeronautical mobile service for the use of non-safety aeronautical mobile applications, in accordance with Resolution 430 (WRC 19)

1.11 to consider possible regulatory actions to support the modernization of the Global Maritime Distress and Safety System (GMDSS) and the implementation of e-navigation, in accordance with Resolution 361 (Rev. WRC 19)

1.12 to conduct, and complete in time for WRC 23, studies for a possible new secondary allocation to the Earth exploration-satellite service (active) for spaceborne radar sounders within the range of frequencies around 45 MHz, taking into account the protection of incumbent services, including in adjacent bands, in accordance with Resolution 656 (Rev. WRC 19)

1.13 to consider a possible upgrade of the allocation of the frequency band 14.8-15.35 GHz to the space research service, in accordance with Resolution 661 (WRC 19)

1.14 to review and consider possible adjustments of the existing frequency allocations or possible new primary frequency allocations to the Earth exploration-satellite service (passive) in the frequency range 231.5-252 GHz, to ensure alignment with more up-to-date remote-sensing observation requirements, in accordance with Resolution 662 (WRC 19)

1.15 to harmonize the use of the frequency band 12.75-13.25 GHz (Earth-to-space) by Earth stations on aircraft and vessels communicating with geostationary space stations in the fixed-satellite service globally, in accordance with Resolution 172 (WRC 19)

1.16 to study and develop technical, operational, and regulatory measures, as appropriate, to facilitate the use of the frequency bands 17.7-18.6 GHz, 18.8-19.3 GHz, and 19.7-20.2 GHz (space-to-Earth) and 27.5-29.1 GHz and 29.5-30 GHz (Earth-to-space) by non-geostationary fixed-satellite service earth stations in motion, while ensuring due protection of existing services in those frequency bands, in accordance with Resolution 173 (WRC 19)

1.17 to determine and carry out, on the basis of ITU R studies in accordance with Resolution 773 (WRC 19), the appropriate regulatory actions for the provision of inter-satellite links in specific frequency bands, or portions thereof, by adding an inter-satellite service allocation where appropriate

1.18 to consider studies relating to spectrum needs and potential new allocations to the mobile-satellite service for future development of narrowband mobile-satellite systems, in accordance with Resolution 248 (WRC 19)

1.19 to consider a new primary allocation to the fixed-satellite service in the space-to-Earth direction in the frequency band 17.3-17.7 GHz in Region 2, while protecting existing primary services in the band, in accordance with Resolution 174 (WRC 19)

2 to examine the revised ITU R Recommendations incorporated by reference in the Radio Regulations communicated by the Radiocommunication Assembly, in accordance with further resolves of Resolution 27 (Rev. WRC 19), and to decide whether or not to update the corresponding references in the Radio Regulations, in accordance with the principles contained in resolves of that Resolution

3 to consider such consequential changes and amendments to the Radio Regulations as may be necessitated by the decisions of the conference

4 in accordance with Resolution 95 (Rev. WRC 19), to review the Resolutions and Recommendations of previous conferences with a view to their possible revision, replacement, or abrogation

5 to review, and take appropriate action on, the Report from the Radiocommunication Assembly submitted in accordance with Nos. 135 and 136 of the ITU Convention

6 to identify those items requiring urgent action by the radiocommunication study groups in preparation for the next world radiocommunication conference

7 to consider possible changes, in response to Resolution 86 (Rev. Marrakesh, 2002) of the Plenipotentiary Conference, on advance publication, coordination, notification and recording procedures for frequency assignments pertaining to satellite networks, in accordance with Resolution 86 (Rev. WRC 07), in order to facilitate the rational, efficient, and economical use of radio frequencies and any associated orbits, including the geostationary-satellite orbit

8 to consider and take appropriate action on requests from administrations to delete their country footnotes or to have their country name deleted from footnotes, if no longer required, taking into account Resolution 26 (Rev. WRC 19)

9 to consider and approve the Report of the Director of the Radiocommunication Bureau, in accordance with Article 7 of the ITU Convention

9.1 on the activities of the ITU Radiocommunication Sector since WRC 19:

- In accordance with Resolution 657 (Rev. WRC 19), review the results of studies relating to the technical and operational characteristics, spectrum requirements and appropriate radio service designations for space weather sensors with a view to describing appropriate recognition and protection in the Radio Regulations without placing additional constraints on incumbent services;
- Review the amateur service and the amateur-satellite service allocations in the frequency band 1 240 1 300 MHz to determine if additional measures are required to ensure protection of the radionavigation-satellite service (space-to-Earth) operating in the same band in accordance with Resolution 774 (WRC 19);
- Study the use of International Mobile Telecommunication systems for fixed wireless broadband in the frequency bands allocated to the fixed service on a primary basis, in accordance with Resolution 175 (WRC 19);

9.2 on any difficulties or inconsistencies encountered in the application of the Radio Regulations; and

9.3 on action in response to Resolution 80 (Rev. WRC 07)

Appendix C. Sources

Documentary sources consulted in support of Task TO-G-026 include the following:

1. Scalable Traffic Management for Emergency Response Operations, https://hsi.arc.nasa.gov/groups/AOL/research/stereo.php

2. What is Scalable Traffic Management for Emergency Response Operations? https://www.nasa.gov/ames/stereo

3. Scalable Traffic management for Emergency Response Operations STEReO Workshop – February 11-13, 2020, https://hsi.arc.nasa.gov/groups/aol/research/stereo_workshop.php

4. Mercer, J., McSwain, R., Ippolito, C., Scalable Traffic Management for Emergency Response Operations (STEReO), AIAA Aviation Conference, June 15 – 19, 2020

5. NASA's Scalable Traffic Management for Emergency Response Operations (STEReO) project conducts a field demonstration at a US Forest Service training exercise in Phoenix, Arizona (Mar 15, 2021) https://humansystems.arc.nasa.gov/awards_pubs/news_view.php?news_id=160

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8. Robinson, J. E., Johnson, M. A., Rios, J. L., Prevot, T., Jung, J., Overview of Unmanned Aerial System Traffic Management (UTM), FAA/Eurocontrol APT 115 Meeting, March 26, 2015

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10. Andreeva-Mori, A., Kubo, D., Kobayashi, K., Okuno, Y., Homola, J. R., Johnson, M., and Kopardekar, P., Supporting Disaster Relief Operations through UTM: Operational Concept and Flight Tests of Unmanned and Manned Vehicles at a Disaster Drill, AIAA Scitech 2020 Forum, 6-10 January 2020, Orlando, FL

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13. Unmanned Aircraft Systems Beyond Visual Line of Sight Aviation Rulemaking Committee Final Report – March 10, 2022

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Charles J. Sheehe
NASA Glenn Research Center
charles.j.sheehe@nasa.gov

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Cognizant Program Manager Approval:

Justin L. Bail, SYSTEMS DIRECTOR
HQ STMD/GRC PROGRAMS
HUMAN EXPLORATION & SPACEFLIGHT DIVISION
CIVIL SYSTEMS GROUP

Aerospace Corporate Officer Approval:

James M. Myers, SENIOR VP CIVIL SYSTEMS GROUP
OFFICE OF EVP

Content Concurrence Provided Electronically by:

Robert J. Kerczewski, MTS LEVEL 3 - CASUAL
COMMUNICATION SYSTEMS AND TECHNOLOGY
HQ STMD/GRC PROGRAMS
CIVIL SYSTEMS GROUP

Office of General Counsel Approval Granted Electronically by:

Kien T. Le, ASSISTANT GENERAL COUNSEL
OFFICE OF THE GENERAL COUNSEL
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