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Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R M.2171

Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace

(2009)

Executive summary

This report is based on two independently developed methodologies in the relevant annexes. These methodologies, even though based on different approaches, provide comparable estimated spectrum requirements.

The methodologies estimating the total spectrum requirements in this report addressed terrestrial and satellite requirements in a separate manner. Deployment of unmanned aircraft systems (UAS) will require access to both terrestrial and satellite spectrum.

The maximum amount of spectrum required for UAS are:

– 34 MHz for terrestrial systems,
– 56 MHz for satellite systems.

1 Introduction and scope

A significant increase in the application of UAS is anticipated over the next decade and beyond. Seamless flight of unmanned aircraft (UA) within conventional air traffic is becoming vital for the further development of UA missions and markets.

The key issue for UAS proponents is to reassure aviation authorities that UA flight within civilian air traffic will:

– integrate seamlessly into current air traffic control (ATC) procedures;
– maintain safety-of-flight levels.

This will influence the corresponding spectrum requirements and the quality of spectrum needed to satisfy these requirements.

Communications are key in UAS systems due to the remote nature of human presence. Safety-of-flight is the driving factor when the seamless flight of UAS within civilian air traffic is at stake. In the end, safe operation of UAS relies on communications which represents a critical step in enabling UAS operations in non-segregated airspaces. The different types of communications addressed in this report are explained below.

All the information given in this paper is only used to determine the spectrum requirements provided in § 5 and is not relevant for operational purposes.

This report is based on two independently developed methodologies in the relevant annexes. These methodologies, even though based on different approaches, provide comparable estimated spectrum requirements.

The report is structured as follows:

Main part

Annex 1 –	Throughput requirements for control and non-payload communications of a single unmanned aircraft.
Annex 2 –	UAS deployment scenario.
Annex 3 –	Aggregate bandwidth requirements for command and control, for support of sense and avoid and ATC relay of unmanned aircraft.
Annex 4 –	Airspace classes, services and flight requirements.
Annex 5 –	Acronyms.

2 General system descriptions and terminology

It is important to use the same terminologies for a better understanding of the topic. This section defines the terminologies used in this document about UAS and sub-systems, categories of airspaces, required radiocommunications for safe operations of UA, and other considerations for the safe operations of UA.

2.1 Terminology

Unmanned Aircraft (UA): Designates all types of aircraft remotely controlled.

Unmanned Aircraft Control Station (UACS): Facilities from which a UA is controlled remotely.

Control Link subsystem: Communication link between the UA and the UACS carrying telecommands (from the pilot to the UA) and telemetry (from the UA to the pilot)[1].

Control and non-payload communications (CNPC): The radio links, used to exchange information between the UA and UACS, that ensure safe, reliable, and effective UA flight operation. The functions of CNPC can be related to different types of information such as: telecommand messages, non-payload telemetry data, support for navigation aids, air traffic control voice relay, air traffic services data relay, target track data, airborne weather radar downlink data, non-payload video downlink data.

Sense and avoid (S&A): S&A corresponds to the piloting principle "see and avoid" used in all air space volumes where the pilot is responsible for ensuring separation from nearby aircraft, terrain and obstacles.

Unmanned Aircraft System (UAS): Consists of the following subsystems:

- Unmanned aircraft (UA) subsystem (i.e. the aircraft itself);
- Unmanned aircraft control station (UACS) subsystem;
- Air traffic control (ATC) communications subsystem (not necessarily relayed through the UA);
- Sense and avoid (S&A) subsystem;
- Payload subsystem (e.g. video camera …).

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[1] It is recognized that other mechanisms, such as using an intermediate aircraft, exist to establish the beyond line of sight communications.

Radio line-of-sight (LoS): is defined as the direct radio line of sight radiocommunication between the UA and UACS.

Beyond radio line-of-sight (BLoS)[1]: is defined as the indirect radio communication between the UA and a UACS using satellite communication services.

Handover operations: is the transfer:

– of a direct (LoS) RF communication from one dedicated UACS to another (LoS) dedicated UACS;

– of a direct (LoS) to an indirect (BLoS) RF communication link or vice versa.

2.2 Classification of air spaces

The aim of the WRC-12 Agenda item 1.3 is to study the spectrum requirements and possible regulatory actions needed to support the safe operation of all kinds of UA in non-segregated airspaces.

Segregated Airspace is restricted airspace of defined dimensions for the exclusive use of specific users.

Non-segregated Airspace is airspace other than those designated as segregated airspace.

A full list of acronyms used in this report is provided in Annex 5.

The category of airspace has a pronounced impact on the data rate required for ATC communications, command and control, and particularly regarding sense and avoid which is addressed in § 5 of this report.

2.3 Required radiocommunications for safe operations of UA

2.3.1 Types of radiocommunications links

For safe operations of UA under LoS and BLoS conditions, three types of radiocommunications between the UA and the UACS are required, which are as follows:

– radiocommunications in conjunction with air traffic control relay;

– radiocommunications for UA command and control;

– radiocommunications in support of the sense and avoid function.

It is left to the UA system designer to combine two or more of these three radiocommunications into a common physical link.

2.3.2 Radiocommunications for air traffic control relay

In non-segregated airspace a link between air traffic control and the UACS via the UA, called ATC relay, will be required to relay ATC and air-to-air communications received and transmitted by the UA.

For communicating with ATC, the UA uses the same equipment as a manned aircraft. This report only considers the downlink bringing the ATC information from the UA to the UACS and the uplink from the UACS to the UA allowing the UACS to communicate with ATC.

As these communications are critical for a safe management of the controlled airspaces, especially in terminal approach areas with high density of aircraft, future ICAO standards are obviously mandatory for these kinds of communications.

2.3.3 Required radiocommunications for command and control

Command and control is the typical link between the UACS and the UA. The following two ways of communications are:

The uplink: To send telecommands to the aircraft for flight and navigation equipment control.

The downlink: To send telemetry (e.g. flight status) from the UA to the UACS. It is anticipated that in some flight conditions or in specific airspaces it could be necessary to downlink video streams. This consideration is of a high importance for the work of the ITU-R related to Resolution 421 (WRC-07) and it must also be considered with the similar requirement that may come from the support of sense and avoid function (see § 2.3.4). Such a requirement could lead to data rates of several hundreds of kbit/s per UA.

In areas under the responsibility of the aeronautical authorities, it is expected that the command and control communications will have to be compliant with ICAO standards to be further specified on this function. Nevertheless, in the periods where the UA will follow a full autonomous flight, the up and down links could have very low data rates.

2.3.4 Required radiocommunications in support of "sense and avoid"

Sense and avoid (S&A) corresponds to the piloting principle "see and avoid" used in all air space volumes where the pilot is responsible for ensuring separation from nearby aircraft, terrain and obstacles (e.g. weather).

To determine appropriate spectrum requirements related to the S&A function, two aspects must be considered:

– Firstly, all the RF equipments designed to collect raw data related to the "sense" function will have specific requirements depending on the ITU-R services involved. For example, the evaluation of the close proximity of the UA using radar equipment will operate in radiodetermination service bands. It should be studied if this functionality can be developed by using existing systems such as radar, ACAS, ADS-B and UAT. The data derived by the sensors could either directly be processed inside the UA or be transmitted to the UACS. The spectrum needed to carry out the "sense" (e.g. radiodetermination spectrum) function is not covered in this report.

– Secondly, the control of the proper operation of this S&A function will be permanently or regularly checked at the UACS. If necessary, S&A parameters may be modified by the UACS, depending upon the area of flight, the weather conditions or the level of autonomy assigned to the UA.

In these bi-directional communications between the UACS and the UA for the S&A function, two different information streams must be considered:

– The S&A data uplink will allow the UACS to control the operation of this function according to the conditions of the flight. Identical to the Control uplink, it is expected that such a communication will not require high bit rates.

– The S&A data downlink from the UA to the UACS which indicates that the S&A function operates as desired. Similar to the Control downlink requirement, the need to send video streams under this S&A function must be considered avoiding duplication between Command and Control and S&A video downlinks.

Similar to the command and control considerations, it is expected that the "S&A data" RF communication requirements will have to be compliant with future ICAO standards for the safe flight of the UA in areas under the responsibility of the aviation authorities.

2.4 Other considerations

Redundancy

Safe operations of future UAS in non-segregated airspace may need independent back-up communications to ensure high reliability of the critical communications links.

Latency elements

A UA designed to fly in controlled airspace must be able to operate in both high and low density airspace. The air traffic control system would not necessarily be able to restrict UA to low density airspace only. Hence:

- it is recommended that larger UA be equipped with a terrestrial link capability wherever possible;
- a UA may use a GEO satellite link in low density sectors and also probably in high density sectors where the total number of UA in that sector is low.

The impact of latency on UAS command and control systems is a prime factor when considering the safety of operations. Latency will be of the utmost importance when establishing a safety case for the operation of UA, particularly in non-segregated airspace. Current air traffic management relies heavily on voice communications although information via data links is being progressively implemented. Hence, new operational requirements for the future data link environment will also need to be developed.

3 Unmanned aircraft categories

Exact definitions can be found in Table 33 of § 2.2.5 of Annex 2 of this report.

In this report, the following three generic categories of UA: small, medium and large has been taken into account.

4 UAS applications

Applications for UAS can be classified into two main groups. Figure 1 gives an overview about the anticipated fields of operation. Table 1 provides examples for each mission type with different scenarios.

Commercial applications provide services which are sold by contractors in the course of carrying out normal business operations.

Governmental applications ensure public safety and security by addressing different emergencies, issues of public interest, and include scientific matters.

FIGURE 1

UAS applications

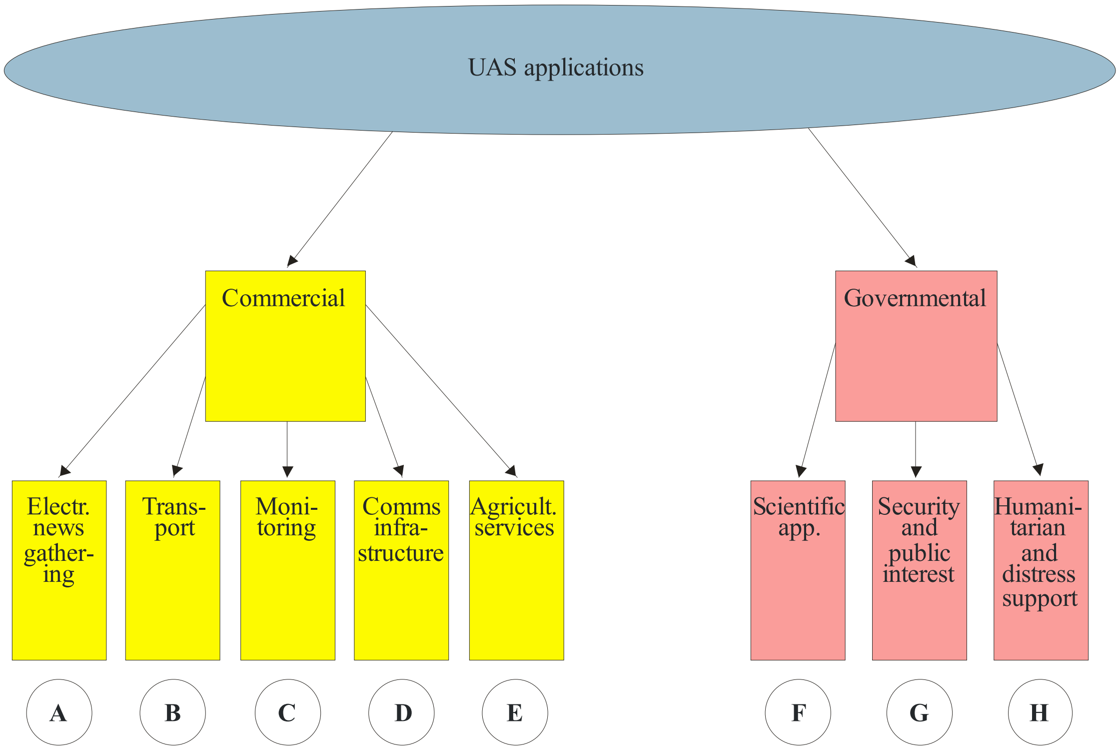

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TABLE 1

Examples

Mission type	**Example description**
Ⓐ	Movie making, sports games, popular events like concerts.
Ⓑ	Cargo planes with reduced man power (one-man-cockpit).
Ⓒ	Inspections for industries, e.g. oil fields, oil platforms, oil pipelines, power line, rail line.
Ⓓ	Provision of airborne relays for cell phones in the future.
Ⓔ	Commercial agricultural services like crop dusting.
Ⓕ	Earth science and geographic missions (e.g. mapping and surveying, aerial photography) biological, environmental missions (e.g. animal monitoring, crop spraying, volcano monitoring, biomass surveys, livestock monitoring, tree fertilization).
Ⓖ	Coast line inspection, preventive border surveillance, drug control, anti-terrorism operations, strike events, search and rescue of people in distress, and national security. Public interest missions like remote weather monitoring, avalanche prediction and control, hurricane monitoring, forest fires prevention surveillance, insurance claims during disasters and traffic surveillance.
Ⓗ	Famine relief, medical support, aid delivery. Search and rescue activities.

5 Spectrum requirements for UAS communications

The overall data rate for a single UAS is expected to be a function of:

– The ATC-UAS communications exchange requirements which in turn are a direct function of the aforementioned categories of airspace.

– The UAS command and control requirements which in turn are a direct function of UAS systems design and engineering considerations pertaining to the UAS degree of systems automation/autonomy.

– The UAS support for sense and avoid requirements which in turn are a function of the category of airspace, the terrain environment (i.e. UAS are at all times responsible for sensing and avoiding terrain when operating at low altitudes) and weather (i.e., unless other suitable mitigation is applied, UAS must be able to sense and avoid areas of adverse weather).

Furthermore, insofar as data rates are concerned, it becomes possible to consider flight under instrument flight rules (IFR), visual flight rules (VFR) and segregated flight.

5.1 Single UA throughput needs

5.1.1 Methodology 1

Tables 2 and 3 are based on the results of the Annex 1.

TABLE 2

Terrestrial estimated non-payload throughput requirements of a single UA in bit/s

	Command and control	ATC relay	Sense and void	Video/weather radar
Proposal: airport surface	12 167	2 × 4 855	9 120	270 000
	30 997			
Proposal: low altitude	12 167	2 × 4 855	9 120	270 000[(1)]
	30 997			
Proposal: medium altitude	5 062	2 × 4 855	9 120	27 000
	23 892			
Proposal: high altitude	5 062	2 × 4 855	9 120	27 000
	23 892			

(1) A factor representing a percentage value of video and weather radar data rate used at the low altitude could apply and is taken into account in Annex 3.

TABLE 3

Satellite estimated non-payload throughput requirements of a single UA in bit/s

	Command and control	ATC relay	Sense and avoid	Video/weather radar
Proposal: medium altitude	5 062	2 × 4 855	9 120	27 000
	23 892			
Proposal: high altitude	5 062	2 × 4 855	9 120	27 000
	23 892			

5.1.2 Methodology 2

Table 4 is based on the results of the Annex 1.

TABLE 4

Maximum non-payload throughput requirements* of a single UA (bit/s)

UA type	Control and NavAids	ATC relay	Non-payload surveillance data(1)
Large	2 437	4 855	287 849
Medium	2 437	4 855	279 120
Small	1 862	0	0

* Averaged over all operational phases.

(1) Includes video, weather radar, sense and avoid, etc.

5.2 UAS deployment scenario

Two methodologies, called Methodology 1 and 2 in this paper, have been used to develop typical UAS deployment scenarios in the 2030 time-frame. The purpose of these scenarios is to estimate the command and control, ATC relay and support of sense and avoid bandwidth requirements. The two methodologies are described below.

5.2.1 Methodology 1

Methodology 1 utilizes studies that estimate the peak instantaneous aircraft count (PIAC) and assumes that 10% of these estimations would be UA. The methodology then determines the bandwidth requirements based on these projected UA usage rates.

The results in Tables 5 and 6 are based on assumptions that can be found in Annex 2 of this report.

TABLE 5

UA density	**UA/10 000 km²**
At surface	(3 UA's at an airport) 2.395
0-FL50 (1 500 m)	4.017
FL50-FL195 (1 500-6 000 m)	1.560
> FL 195 (6 000 m)	0.644
Total density	8.616

TABLE 6

Number of UA's per footprint of the satellite

	UA available for operation	
	GEO	**LEO or GEO multi-spot**
Without small UA	1 711	106

5.2.2 Methodology 2

Methodology 2 begins by describing the UA operations that are anticipated and the characteristics and phases of UA missions. Then the methodology projects the UA population by the 2030 time-frame based on estimated UAS usage rates in both the commercial and government sectors. Finally, the methodology describes scenarios which represent the typical use and mission profiles for UA in order to calculate maximum aircraft densities in given volumes of air space and representative maximum bandwidth requirements. The results in Table 7 are based on assumptions that can be found in Annex 2 of this report.

TABLE 7

Number of UA operating at peak times

UA Categories	Per 10 000 km^2	Per spot-beam	In regional-coverage beam
Large	0.440	21	341
Medium	1.950	93	1 515
Small	8.031	385	0
Total	10.421	501	1 856

5.3 Aggregate assessment of UAS spectrum needs

5.3.1 Methodology 1

Table 8 provides the UAS spectrum needs using the Methodology 1 and calculation presented in Annex 3. It has to be noted that the video requirements is not yet decided as mandatory by the civil aviation authorities.

TABLE 8

Aggregate spectrum requirements

	Except video/weather radar	Video/weather radar only	Total
Terrestrial requirements (MHz)(1)	15.9	18.1	**34**
Satellite requirements (MHz)(2)	29	17	**46**

(1) Wireless connections between the earth station and the UACS may be needed in some cases. In such cases the spectrum requirement may be modified.

(2) The assessment of these spectrum requirements have been based on assumptions described in this report (cells/spots radius, frequency reuse factor …). Regarding sharing studies on WRC-12 Agenda item 1.3 in specific bands, these assumptions and therefore the spectrum requirements could be refined.

The terrestrial spectrum requirements comprise:

– UACS to UA = 4.6 MHz

– UA to UACS = 29.4 MHz.

The satellite spectrum requirements comprise:

- UA to SAT = 18.9 MHz
- UACS to SAT = 4.1 MHz
- SAT to UA = 4.1 MHz
- SAT to UACS = 18.9 MHz.

The details of these requirements are shown in Fig. 2:

FIGURE 2

Links involved for line of sight (LoS)

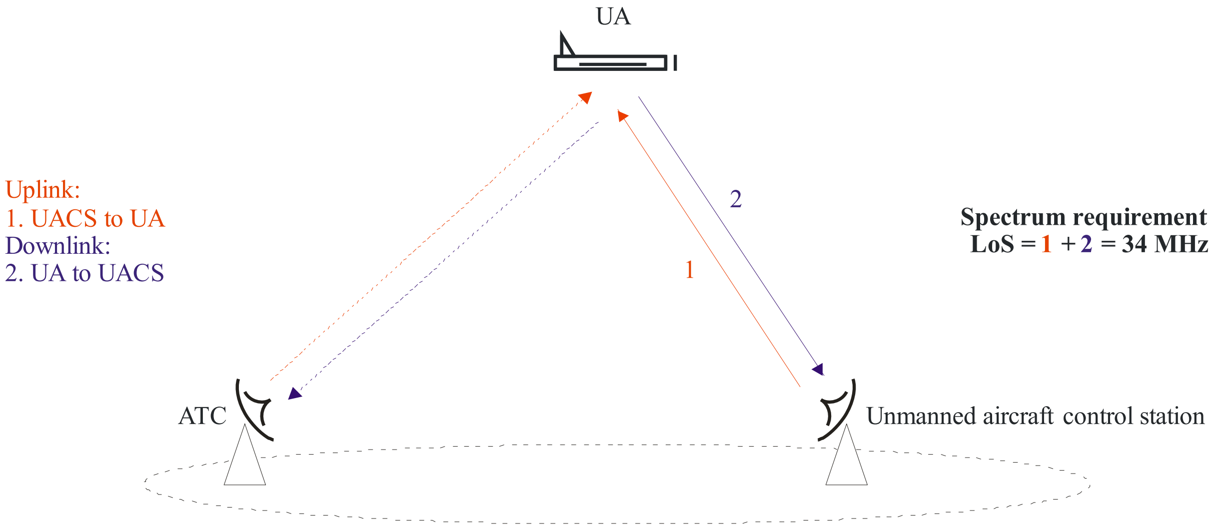

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FIGURE 3

Links involved for beyond line of sight (BLoS) via satellite (with on-board processing)

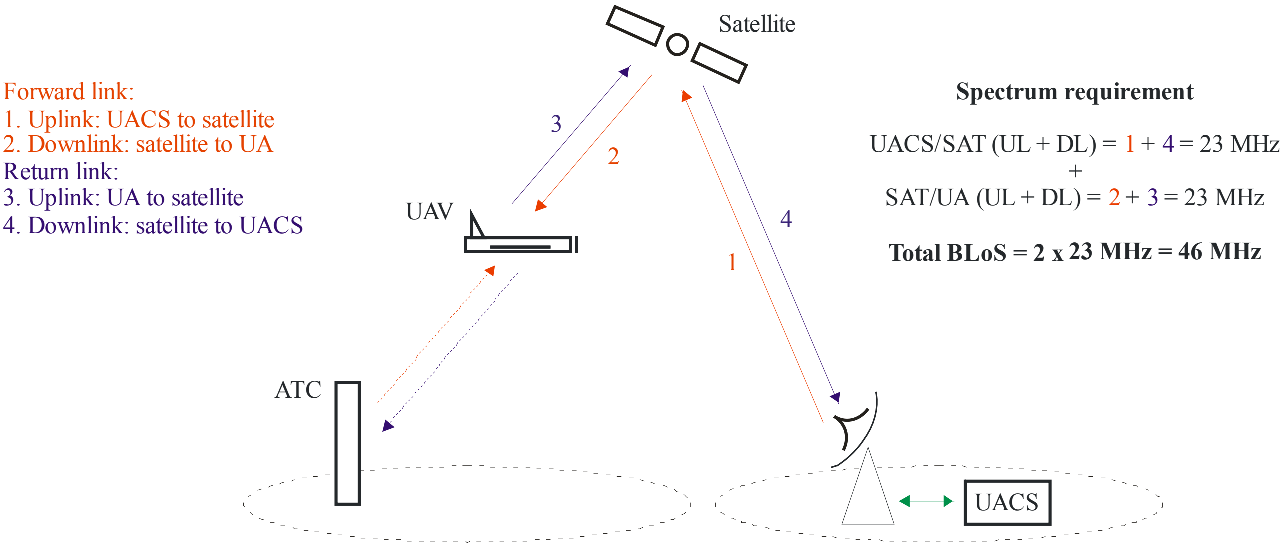

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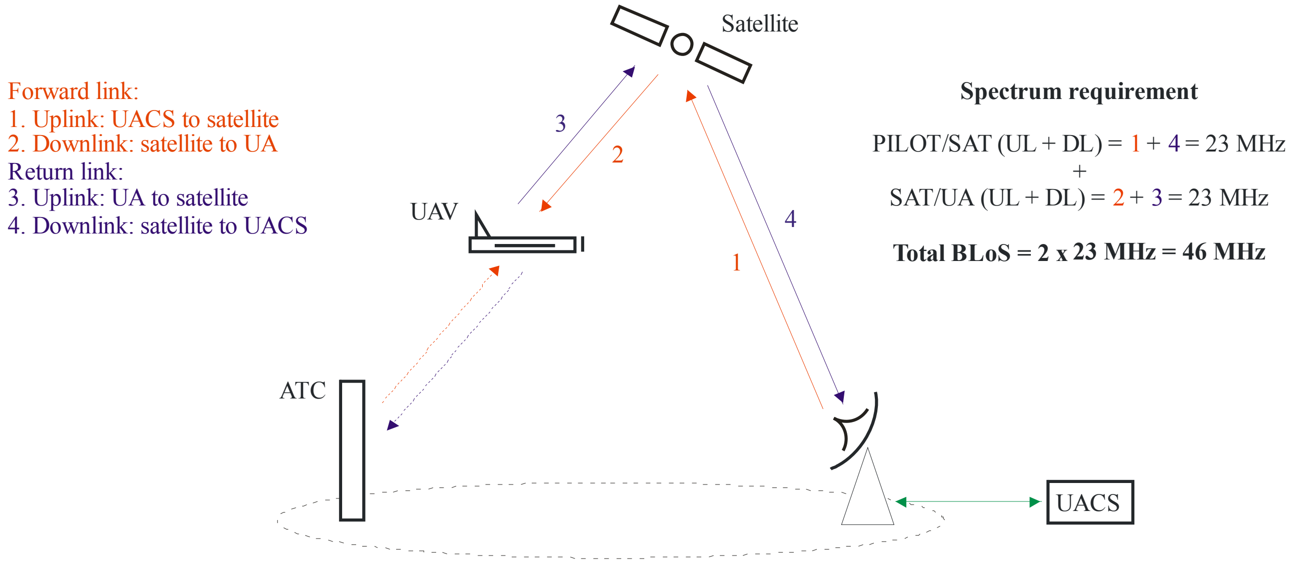
FIGURE 4

Links involved for beyond line of sight (BLoS) via satellite (without on-board processing)



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NOTE 1 – The spectrum requirements figures for BLoS cases correspond to satellite architectures with multi-spot coverage and either on-board processing as illustrated in Fig. 3 above (allowing direct connection between any UA and its UACS) or no satellite on-board processing as illustrated in Fig. 4 (in which the UACS connects to the earth station through wired/wireless line)[2].

5.3.2 Methodology 2

Table 9 summarizes the bandwidth requirements calculated for each of the three major functional communications categories (Control and navaids, ATC relay and non-payload surveillance data) in each of the three alternative system implementations (LoS, BLoS satellite spot-beam, and BLoS satellite regional-beam). Both satellite systems, particularly the regional-beam one, are clearly much more bandwidth-intensive than the terrestrial system. A hybrid system consisting of terrestrial and satellite components would have an aggregate bandwidth requirement somewhere between the “pure terrestrial” and “pure satellite” extremes. That hybrid bandwidth requirement would depend on the allocation of functions between the terrestrial and satellite components of the system, and on whether the satellite component has a spot-beam or regional-beam architecture. The assumed spot-beam system has a beam footprint of 391 km (243 miles) in radius. The regional-coverage beam has a beam footprint of 7 800 000 km^2 (3 000 000 square miles).

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[2] Wireless connections between the earth station and the UACS may be needed in some cases. In such cases the spectrum requirement may be modified.

TABLE 9

Methodology 2 – Comparison of aggregate bandwidth requirements

Functional category	Aggregate bandwidth requirement (MHz)		
	LoS terrestrial system	BLoS satellite system	
		Spot-beam	Regional-beam[1]
Command and control	1.61	9.01	6.54
ATC Relay	2.72	6.50	11.47
Sense and avoid	23.51	21.81	38.29
Total	**27.84**	**37.32**	**56.31**

(1) Regional-beam system does not support small UA.

The terrestrial spectrum requirements are divided as follows:

– UACS to UA = 2.0 MHz

– UA to UACS = 25.9 MHz.

The spot-beam satellite spectrum requirements are divided as follows:

– UA to SAT = 15.32 MHz

– UACS to SAT = 3.29 MHz

– SAT to UA = 3.29 MHz

– SAT to UACS = 15.32 MHz.

The regional-beam satellite spectrum requirements are divided as follows:

– UA to SAT = 24.05 MHz

– UACS to SAT = 4.1 MHz

– SAT to UA = 4.1 MHz

– SAT to UACS = 24.05 MHz.

6 Summary of results of Methodologies 1 and 2

Based on the assumptions and results of Methodologies 1 and 2, the total UAS spectrum requirements are:

34 MHz for a terrestrial LoS system:

– UACS to UA = 4.6 MHz

– UA to UACS = 29.4 MHz.

46 MHz for a spot-beam satellite BLoS system:

– UA to SAT = 18.9 MHz

UACS to SAT = 4.1 MHz

SAT to UA = 4.1 MHz

SAT to UACS = 18.9 MHz.

56 MHz for a regional-beam satellite BLoS system which would require multiple geostationary satellites, and operation at frequency sufficiently high to enable the use of directional antenna on the UA.

- UA to SAT = 24.05 MHz
- UACS to SAT = 4.1 MHz
- SAT to UA = 4.1 MHz
- SAT to UACS = 24.05 MHz.

7 Conclusion

The methodologies estimating the total spectrum requirements in this report addressed terrestrial and satellite requirements in a separate manner. Deployment of UAS will require access to both terrestrial and satellite spectrum.

The maximum amount of spectrum required for UAS are:

- 34 MHz for terrestrial systems,
- 56 MHz for satellite systems.

Annex 1

Throughput requirements for control and non-payload communications of a single unmanned aircraft

1 Introduction

This annex calculates the throughput requirements for control and non-payload communications (CNPC). The throughput requirements of the navigation, surveillance, and ATS systems themselves, as opposed to the UACS/UA data-relay requirements, are outside the scope of this annex and not considered here.

The throughput requirements are estimated, including overhead, for each type of service, each link direction (UACS to UA and UA to UACS), and each phase of UA operations. Five phases were analysed: pre-flight, terminal (departure), en route, terminal (arrival), and post-flight. The pre-flight and post-flight phases do not include taxiing.

Section 2 of this annex gives an overview of the internal and external non-payload information flows of a generic UAS. Section 3 of this annex presents a data-loading analysis in which we estimate the non-overhead bit rates required to support necessary information transfer between UACS and UA for each class of service. In § 4 of this annex, the estimation of the overhead burdens was made and added to the data-loading numbers to obtain values for total throughput in bps. Table 14 of this annex presents our estimates of required throughput in bit/s, for use in the Annex 3 of this report estimating the aggregate CNPC bandwidth needs of all UA.

1.1 Information flows

Figure 5 depicts the basic non-payload internal and external information-exchange requirements of a UAS. These include:

- The basic UACS/UA control links supporting command and control.
- Data from NavAids.
- Non-payload surveillance data (target tracks) provided by the UAS's S&A system.
- Other non-payload surveillance data, including weather radar data and video images.
- ATC voice messages that the UA must relay to and from the UACS.
- ATS data that the UA must also relay to and from its UACS.

Figure 6 depicts the command and control, sense and avoid and ATC relay information flows between the UACS and the UA. These are the information flows whose throughput/ data rate requirements are estimated in this annex.

They include not only the basic exchange of control data between UACS and UA, but also the relay of ATC voice and ATS data messages using the UA as a relay, and the downlink of navigational data, non-payload target tracks (from the S&A system and other sources), weather radar outputs, and video images from the UA to the UACS.

FIGURE 5

Basic internal and external non-payload information flows of a UAS

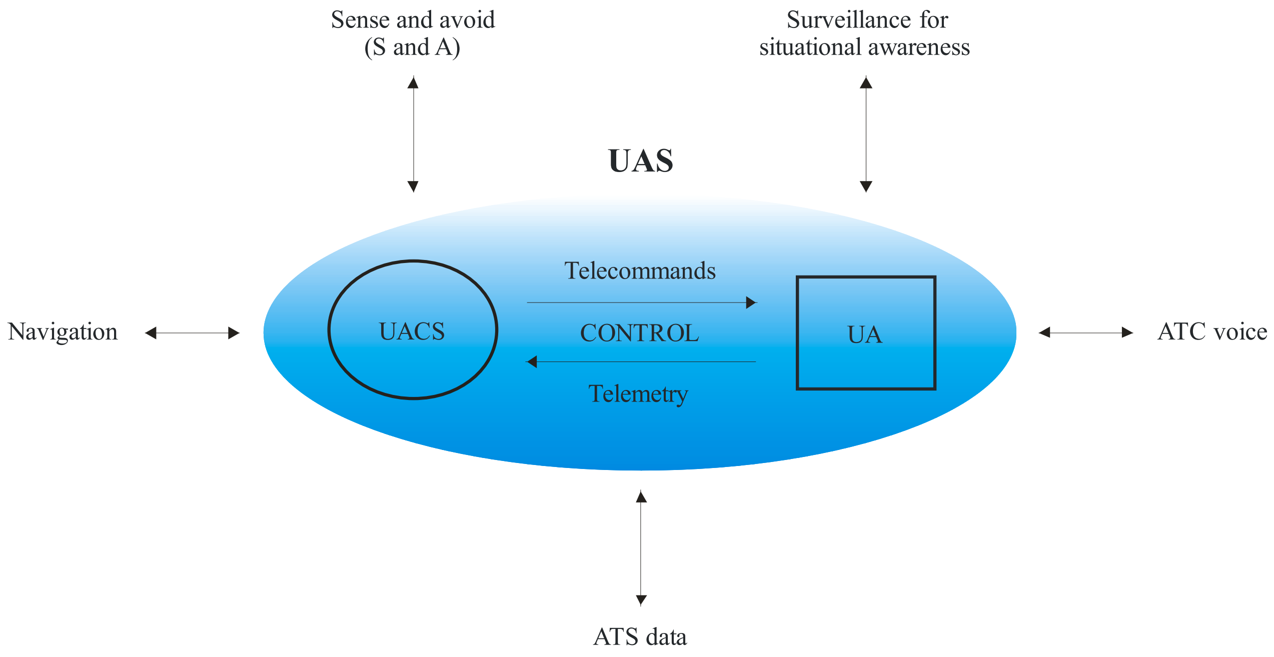

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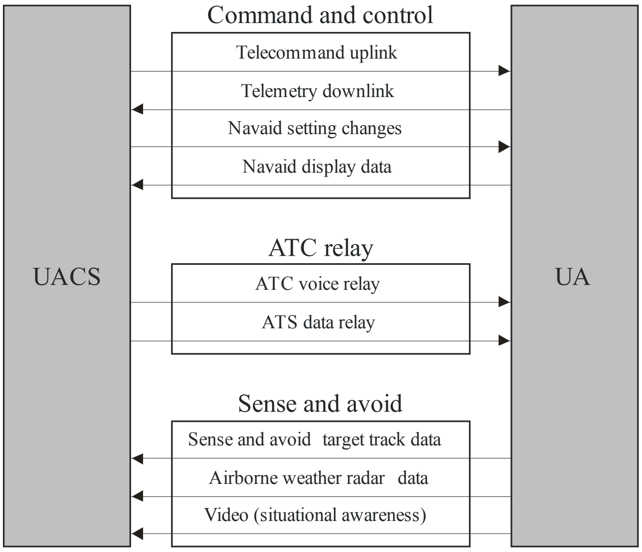
FIGURE 6

CNPC information flows between UACS and UA



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1.2 Data loading requirements

1.2.1 UACS/UA command and control links

Appendix 1 presents the details of a data-loading analysis of the basic UACS/UA command and control links. It promotes spectral efficiency by allowing the omission of unnecessary fields within particular messages and the concatenation of multiple messages into single packets.

1.2.2 Navigational aids

Appendix 2 to this annex presents a loading analysis of the UACS-to-UA uplink that will enable the UACS to control the settings of the UA's navigation receivers, and the UA-to- UACS downlink that will carry data from those receivers to the UACS display.

1.2.3 ATC voice relay

Spectrum will be required for relaying (via the UA) voice message traffic between ATC and the UACS. ATC voice messages are currently transmitted as analogue signals in 25 kHz channels, but even if that is still true in 2030 it seems certain that the relay links will have to be more spectrally efficient. If the relay links are digital, they will presumably have bit rates similar to those defined in RTCA DO-224A[3] for the VHF digital link mode 3 (VDL3), in which 4 133 bit/s of message content are supplemented by 667 bit/s of forward error correction (FEC) overhead to yield 4 800 bit/s of throughput.

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[3] *Signal-in-Space Minimum Aviation System Performance Standards (MASPS) for Advanced VHF Digital Data Communications Including Compatibility with Digital Voice Techniques*, DO-224A, RTCA, September 2000, pp. 115-116.

1.2.4 ATS data relay

A system providing ATS data services of various kinds, identified in RTCA Paper 082-08/PMC-614[4], is expected to be in place by the 2020s. It seems likely that the messages associated with those services will need to be relayed to and from the UACS via the UA. The messages contain aircraft addresses, so each UA need relay only messages addressed to it.

The analysis of the data-loading requirements for each kind of ATS message is based on the findings of the 2007 EUROCONTROL/FAA Future Communications Study Operational Concepts and Requirements Team[5]. Detailed results appear in Tables 10 and 11. Unlike other parts of this analysis, these tables take overhead into account, because overhead is embedded in the results presented in these studies. Table 10 quantifies the amount of data transmitted in each "instance" of the use of a given ATS data service. (For example, there are five 190-byte UA-to-UACS messages and three 129-byte UACS-to-UA messages per D-FLUP instance.) Table 11 combines that information with the number of instances per UA per operational phase (also given in Table 10) to quantify the data rate per UA in each phase. The values presented in Table 11 are based on the relative phase durations postulated in the UAS deployment scenarios found in Annex 2 of this report and listed in the footnotes of Table 11. Shorter or longer assumed phase durations for particular phases would yield proportionately higher or lower ATS data rates.

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[4] *Terms of Reference: Standards for Air Traffic Data Communication Services*, RTCA Paper No. 082-08/PMC-614, RTCA SC-214, 15 February 2008.

[5] *Communications Operating Concept and Requirements for the Future Radio System*, COCR Version 2.0, EUROCONTROL/FAA Future Communications Study Operational Concepts and Requirements Team, 2007.

TABLE 10

ATS data relay message rates and sizes (including overhead)

Service	Description	Message direction				Number of instances per UA in each phase				
		UA to UACS		UACS to UA						
		Msgs per instance	**Msg size (bytes)**	**Msgs per instance**	**Msg size (bytes)**	**Pre-flight**	**Terminal (departure)**	**En route**	**Terminal (arrival)**	**Post-flight**
ACL	ATC clearance	2	93	2	93	1	4(1)	5	4(1)	1
ACM	ATC communication management	1	126	1	88	1	4(2)	5(3)	4(2)	1
AMC	ATC microphone check	1	89	0	0	1	1	1	1	1
ATSA-ITP	In trail procedure	2	93	2	93	0	0	1	1	0
COTRAC	Common trajectory coordination	Subsumed in 4DTRAD								
D-ATIS (arrival)	Data link ATIS	5	100	3	93	0	0	1	1	0
D-ATIS (departure)	Data link ATIS	3	101	2	96	1	0	0	0	0
DCL	Departure clearance	1	117	2	88	1	0	0	0	0
D-FLUP	Data link flight update	5	190	3	129	1	1	1	1	0
DLIC (DLL)	DLL – data link logon	1	491	1	222	1	0	1	0	0
D-OTIS	Data link operational terminal info service	11	193	3	107	1	0	1	1	0
D-RVR	Data link runway visual range	4	116	3	121	1	0	1	1	0
D-TAXI	Data link taxi clearance	2	132	1	98	0	1	0	1	0
FLIPINT	Flight path intent	No flight crew involvement, so no need to relay data between UACS and UA								
NOTAM	Notice to airmen	4	287	2	134	1	0	2	0	0
VOLMET	Assumed to be equal to D-SIGMET	4	130	3	129	1	0	1	1	0
4DTRAD	4-D trajectory data link (COTRAC + FLIPINT)	3	1 969	4	1 380	1	1	5(3)	0	0

(1) 2 for each of 2 assumed terminal sectors.

(2) 1 in ground position, 1 in tower position, and 1 for each of 2 assumed terminal sectors.

(3) 1 for each of 5 assumed en route sectors.

TABLE 11

ATS data relay bit rates (including overhead)

Service	Description	Data rate (bit/s) per UA in each phase(1)									
		Pre-flight		**Terminal (departure)**		**En route**		**Terminal (arrival)**		**Post-flight**	
		UA to UACS	**UACS to UA**	**UA to UACS**	**UACS to UA**	**UA to UACS**	**UACS to UA**	**UA to UACS**	**UACS to UA**	**UA to UACS**	**UACS to UA**
ACL	ATC clearance	2.6	2.6	5.2	5.2	0.7	0.7	3.8	3.8	10.3	10.3
ACM	ATC communication management	1.8	1.2	3.5	2.4	0.5	0.3	2.5	1.8	7.0	4.9
AMC	ATC microphone check	1.2	0.0	0.6	0.0	0.1	0.0	0.4	0.0	4.9	0.0
ATSA-ITP	In trail procedure	0.0	0.0	0.0	0.0	0.1	0.1	0.9	0.9	0.0	0.0
COTRAC	Common trajectory coordination	Subsumed in 4DTRAD									
D-ATIS (arrival)	Data link ATIS	0.0	0.0	0.0	0.0	0.4	0.2	2.5	1.4	0.0	0.0
D-ATIS (departure)	Data link ATIS	4.2	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DCL	Departure clearance	1.6	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
D-FLUP	Data link flight update	13.2	5.4	6.6	2.7	0.7	0.3	4.8	2.0	0.0	0.0
DLIC (DLL)	DLL – Data link logon	6.8	3.1	0.0	0.0	0.4	0.2	0.0	0.0	0.0	0.0
D-OTIS	Data link operational terminal info service	29.5	4.5	0.0	0.0	1.6	0.2	10.7	1.6	0.0	0.0
D-RVR	Data link runway visual range	6.4	5.0	0.0	0.0	0.3	0.3	2.3	1.8	0.0	0.0
D-TAXI	Data link taxi clearance	0.0	0.0	1.8	0.7	0.0	0.0	1.3	0.5	0.0	0.0
FLIPINT	Flight path intent	No flight crew involvement, so no need to relay data between UACS and UA									
NOTAM	Notice to airmen	15.9	3.7	0.0	0.0	1.7	0.4	0.0	0.0	0.0	0.0
VOLMET	Assumed to be equal to D-SIGMET	7.2	5.4	0.0	0.0	0.4	0.3	2.6	2.0	0.0	0.0
4DTRAD	4-D trajectory data link (COTRAC + FLIPINT)	82.0	76.7	41.0	38.3	21.6	20.2	0.0	0.0	0.0	0.0
Total		173	113	59	49	28	23	32	16	22	15
Total by phase		286		108		51		48		37	

(1) Assumed phase durations:

- Pre-flight: 4% of total
- Terminal (departure): 8% of total
- En-route: 76% of total
- Terminal (arrival): 11% of total
- Post-flight: 1% of total.

1.2.5 Surveillance data

Non-payload surveillance data relevant to UAS operation include target track data; flight information service, broadcast (FIS-B) data; weather radar data; and video downlinks.

1.2.5.1 Target track data

Essential sources of target track data will include:

- S&A capabilities whose architecture is still undefined.
- Traffic information services, broadcast (TIS-B).
- Automatic dependent surveillance (ADS) – broadcast (ADS-B).
- ADS – rebroadcast (ADS-R).
- ADS – contract (ADS-C).

In the analysis it is assumed that no more than 60 tracks, from all the above sources combined, will ever need to appear on the UACS display at any given time. Zoom and proximity/velocity/altitude filters will be used to select targets of interest and limit the number of displayed tracks. The UA's on-board processor will provide any additional filtering necessary, and so the command and control, sense and avoid and ATC relay links will never need to carry relayed data on more than 60 tracks at a time. It is also assumed that the relayed target parameters will be as shown in Table 12, all of whose uncompressed field sizes (except for "Reserved for future use") were extracted from RTCA DO-260A[6]. The field sizes add up to 209 bits, but it should be feasible with data compression to reduce the total to about 80 bits. Assume an update rate of 1 Hz, the same as for ADS-B is assumed. The resultant maximum data rate (excluding overhead) for this class of surveillance data is (60)(80)(1) = 4 800 bit/s for a single UA.

TABLE 12

Uncompressed contents of target update message

Category	Field	Bits
General	Track ID	32
	Time stamp	40
Track category	Type	5
	Emitter category	3
3D Position	Latitude	17
	Longitude	17
	Altitude	12
3D Velocity	E/W velocity (including direction bit)	11
	N/S velocity (including direction bit)	11
	Vertical rate (including direction and sign bits)	11
Accuracy	Navigation accuracy for position	4
	Navigation accuracy for velocity	3

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[6] *Minimum Operational Performance Standards for 1 090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Services – Broadcast (TIS-B)*, DO-260A, RTCA, 2003.

TABLE 12 (*end*)

Category	Field	Bits
Integrity	Navigation integrity category	8
	Barometric altitude integrity code	1
	Surveillance integrity level	2
Reserved	Reserved for future use	32
Total		209

1.2.5.2 FIS-B

The universal access transceiver (UAT) ground segment, which supports FIS-B, occupies 176 ms of each 1 000-ms UAT frame, during which just over one Mbit/s is transmitted[7]. Thus about 180 kbit/s of capacity is devoted to FIS-B in each UAT frame. The FIS-B capacity is typically divided among approximately 9 "data channel blocks" assignable to different UAT ground-based transceivers (GBTs) in a given area, so the FIS-B portion of the average GBT's FIS-B data stream may be assumed to need about 20 kbit/s of capacity. Hence, 20 kbit/s should suffice to relay any necessary FIS-B data to the UACS – if it were necessary. However, it does not appear necessary, because FIS-B does not provide any essential service not being provided by other systems, and because its outputs are likely to be widely distributable via land lines. Consequently it is *not* recommended that spectrum be set aside for relaying FIS-B data to the UACS via the UA.

1.2.5.3 Weather radar data downlink

An airborne weather radar data downlink provides meteorological information from the UA to the UACS. To estimate the data loading requirement, a typical airborne weather radar system conforming to the ARINC 708 protocol is considered. The two operating modes are weather/turbulence detection, in which the 180° sector ahead of the aircraft is scanned every 4 s, and wind-shear detection, which covers a 120° sector every 3 s. A beamwidth of 3.5° is applied to both modes. Each data frame has one word 1 600 bits long, consisting of a header and data for a single radial scan. The data portion is organized into 512 range bins, each storing the radar reflection data in a 3-bit set.

In calculating downlink data-loading requirements, it seems reasonable to assume that an update is needed each time the beam sweeps across a single 3.5° beamwidth. It follows that the required downlink data rate is (1 600)(180)/((3.5)(4)) = 20 571 bit/s for the weather/turbulence mode and (1 600)(120)/((3.5)(3)) = 18 286 bit/s for the wind-shear mode. We assume the slightly more throughput-intensive weather/turbulence mode for the rest of this analysis.

If a 4 s downlink delay can be tolerated, the radar data for the entire coverage area can be accumulated onboard the UA and compressed before the downlink. Results presented in Lakshmanan's "Overview of Radar Data Compression"[8] suggest that a compression ratio of about 7:1 may be feasible in typical situations. Then, the required airborne weather radar downlink data rate per UA would become 20 571/7 = 2 939 bit/s.

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[7] *Minimum Operational Performance Standards for Universal Access Transceiver (UAT) Automatic Dependent Surveillance – Broadcast (ADS-B)*, DO-282A, RTCA, 2004.

[8] V. Lakshmanan, *Overview of Radar Data Compression*, Cooperative Institute of Mesoscale Meteorological Studies, University of Oklahoma & National Severe Storms Laboratory, http://www.cimms.ou.edu/~lakshman/Papers/radarcompression.pdf.

The delays associated with data compression are more likely to be acceptable in the en route phase of flight than during takeoff and landing. Consequently, for the remainder of this analysis, the airborne weather data rate requirement is assumed to be 2 939 bit/s for the en route phase (i.e. with compression), and 20 571 bit/s for the departure and arrival phases (i.e. without compression).

1.2.5.4 Non-payload video downlink

A non-payload video downlink is likely to be required intermittently by some UA for improved pilot situational awareness in certain situations such as takeoff and landing. With the latest video-compression technology[9] it is feasible to encode 5-frames/s of standard-definition video, having a resolution of 720 by 480 pixels, in a 200 kbit/s data stream. Sufficient throughput needs to be set aside to support this capability on the occasions when it is required (at surface airport and low altitude). For medium and high altitude the number of encode frames/s could be 10 times lower (20 kbit/s).

1.2.6 Summary of loading requirements

Table 13 summarizes the command and control, sense and avoid and ATC relay loading requirements that may have to be continuously supported to enable operation of a single UA in various phases.

Table 13 does not contain a “Totals” column, because, if throughput requirements of all kinds were lumped together in such a column, it would tend to exaggerate the relative significance of the intermittently operating non-payload video downlinks in determining overall throughput requirements. It must also be kept in mind that not every UA will be equipped to carry every class of traffic. Estimates of the percentages of various UA types that will be equipped to participate in each class of traffic in 2030 are presented in Annex 3 of this report.

TABLE 13

Estimated non-payload loading requirements (bit/s) of a single UA

Operational phase(1)	**Relative phase duration (percentage of total)(2)**	**Mode**	**Non-payload communications loading (bit/s)(3), (4)**									
			Command and control				**ATC relay**			**Sense and avoid**		
			Control		**navaids**		**ATC voice relay(5)**	**ATS data relay**		**Target tracks(6)**	**Airborne weather radar**	**Video(7)**
			UL	**DL**	**UL**	**DL**		**UL**	**DL**	**DL**	**DL**	**DL**
Pre-flight	4	**M**	*96*	*3*	0	0	4 133	*113*	*173*	4 800	0	0
Terminal (departure)	8	**M**	1 256	3 008	352	440	4 133	*49*	*59*	4 800	20 571	200 000
		A	408	480	74	98	4 133	*49*	*59*	4 800	20 571	200 000
En route	76	**M**	632	1 240	352	440	4 133	*23*	*28*	4 800	2 939	200 000
		A	152	280	74	98	4 133	*23*	*28*	4 800	2 939	200 000

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[9] *Information Technology – Coding of Audio-Visual Objects: Part 10, Advanced Video Coding*, H.264 (ISO/IEC 14496-10:2005).

TABLE 13 (*end*)

Operational phase(1)	**Relative phase duration (percent-age of total)(2)**	**Mode**	**Non-payload communications loading (bit/s)(3), (4)**									
			Command and control				**ATC relay**			**Sense and avoid**		
			Control		**navaids**		**ATC voice relay(5)**	**ATS data relay**		**Target tracks(6)**	**Airborne weather radar**	**Video(7)**
			UL	**DL**	**UL**	**DL**		**UL**	**DL**	**DL**	**DL**	**DL**
Terminal (arrival)	11	**M**	2 424	4 008	352	600	4 133	*16*	*32*	4 800	20 571	200 000
		A	656	672	74	123	4 133	*16*	*32*	4 800	20 571	200 000
Post-flight	1	**M**	*1*	*1*	0	0	4 133	*15*	*22*	0	0	0

(1) Pre-flight and post-flight phases do not include taxiing.

(2) Average assumed total duration of all phases = 4 h.

(3) Overhead bits not counted except for ATS data relay.

(4) Values in italics depend on assumed phase durations.

(5) Not necessarily needed in all scenarios or potential system architectures.

(6) 60 tracks assumed.

(7) Video needed only intermittently.

Abbreviations:

M: Manual operation, A: Automatic operation, UL: Uplink, DL: Downlink.

Table 13 gives different loading values for "manual" and "automatic" operation for certain operational phases and traffic classes. For the purposes of this analysis, manual operation means the pilot is steering and orienting the UA by exercising direct control, via the control link, of the UA's ailerons and other control surfaces. Automatic operation means the pilot is exercising indirect control by means of waypoints and/or course and altitude commands, which the UA's onboard processor then converts into signals that cause the control surfaces to respond in a manner that achieves the desired result.

1.3 Overhead and throughput

1.3.1 Control links, NavAids, and non-video surveillance

Messages of these types may be put together in a single packet. It allows multiple messages to be sent in a single packet that can contain up to 576 bytes (including overhead). For purposes of this analysis, we assume the following overhead burdens:

Packet overhead: The transport protocol requires 8 bytes. The network protocol requires 46 bytes. The average packet has 400 "content" bytes and contains 2 messages. Each message has a 34-byte wrapper and a 4-byte presence vector identifying the fields to be transmitted.

Encryption overhead: In a digital signature algorithm (DSA) or elliptic curve DSA system with 80-bit security (which would oblige a spoofer to try roughly 10^{24} times to crack the private key), encryption overhead is 40 bytes per packet.

With 400 content bytes, these $8 + 46 + 2(4 + 34) + 40 = 170$ bytes of overhead increase the total bit rates by 42.5%. If a 3/4 FEC coding rate is assumed, the total overhead increases another 33%, yielding a combined overhead factor of $(1.425)(4/3) = 1.9$.

1.3.2 Other types of traffic

For ATC voice relay, 667 bit/s of coding overhead as in VDL3 is assumed. This imposes a 16.1% overhead burden and increases total loading to 4 800 bit/s per voice channel. Encryption overhead is not needed here, since ATC voice is always transmitted in the clear. For ATS data relay, overhead is already included in the numbers presented in Tables 10 and 11, so those numbers do not need to be multiplied by an overhead factor here.

Since the weather-radar and video downlinks will not be packetized, their message and encryption overhead will be relatively small, leaving FEC as the only significant contributor to overhead. Thus the required overhead burden for video may be only about 35%. This yields throughput requirements of 2 939(1.35) = 3 968 bit/s for en route weather radar, 20 571(1.35) = 27 771 bit/s for weather radar in the departure and arrival phases, and 200(1.35) = 256 kbit/s for standard-definition video with a 5 Hz frame rate (at surface airport and low altitude) or 25.6 kbit/s (medium and high altitude).

1.3.3 Throughput requirements

Multiplying the data rates of Table 13 by appropriate overhead factors yields the estimated throughput requirements summarized in Table 14 for Methodology 1 and Table 16 for Methodology 2. As in Table 13, there is no “Totals” column, for the same reasons noted earlier in the discussion of Table 13.

1.3.3.1 Methodology 1

The airspace has been divided into 4 levels of UA altitudes: airport surface, low altitude, medium altitude and high altitude. From Table 14, the data rate requirements for a single UA have been derived using the terminal (departure) and terminal (arrival) for the airport surface and low altitude cases and en route for the medium and high altitude case. This is shown in Table 15.

TABLE 14

Estimated non-payload throughput requirements of a single UA for Methodology 1

	Phase(1)	**Percentage of Total**	**Mode**	**Non-payload communications throughput (bit/s)(3), (4)**									
				Command and control				**ATC relay**			**Sense and avoid**		**Video/ weather radar(8)**
				Control		**Navaids**		**ATC voice relay(5)**	**ATS data relay**		**Sense & avoid comm(6)**	**Non-S&A target tracks(7)**	
				UL	DL	UL	DL	UL&DL	UL	DL	DL	DL	DL
Airport surface and low altitude	Terminal (departure)	42%	M	2 386	5 715	669	836	4 800	*49*	*59*	4 560	4 560	270 000
				9 606				*UL: 4 849* *DL: 4 859*			9 120		
	Terminal (arrival)	58%	M	4 606	7 615	669	1 140	4 800	*16*	*32*	4 560	4 560	270 000
				14 030				*UL: 4 816* *DL: 4 832*			9 120		
	Average			**12 167** (0.42*9 606 + 0.58*14 030)				*Level used in the study* *UL=DL=* ***4 855***			**9 120**		**270 000**
Medium and high altitude	En route	100%	M	1 201	2 356	669	836	4 800	*23*	*28*	4 560	4 560	27 000
				5 062				*UL: 4 823* *DL: 4 828* *Level used in the study* *UL=DL=* ***4 855***			**9 120**		**27 000**

(1) Pre-flight and post-flight phases do not include taxiing.

(2) Average assumed total duration of all phases = 4 h.

(3) Overhead as well as content bits are considered for all classes of traffic.

(4) Values in *italics* depend on assumed phase durations.

(5) Not necessarily needed in all scenarios or potential system architectures.

(6) 60 tracks assumed.

(7) Video needed only intermittently.

(8) Pre- and post-flight phases excluded.

Abbreviations:

M: Manual operation, A: Automatic operation, UL: Uplink, DL: Downlink.

Table 15 summarizes the values used in the study:

TABLE 15

	Command and control	ATC relay	Sense and avoid	Video/weather radar
Proposal: airport surface	12 167	2 × 4 855	9 120	**270 000**
	30 997 (UL: 9 197 DL: 21 800)			
Proposal: low altitude	12 167	2 × 4 855	9 120	**270 000(1)**
	30 997 (UL: 9 197 DL: 21 800)			
Proposal: medium altitude	5 062	2 × 4 855	9 120	**27 000**
	23 892 (UL: 6 725 DL: 17 167)			
Proposal: high altitude	5 062	2 × 4 855	9 120	**27 000**
	23 892 (UL: 6 725 DL: 17 167)			

(1) A factor representing a percentage value of video and weather radar data rate used in the low altitude could be need to apply and is taken into account in Annex 3.

1.3.3.2 Methodology 2

TABLE 16

Estimated non-payload throughput requirements (bit/s) of a single UA for Methodology 2

Operational phase(1)	Relative phase duration (percentage of total)(2)	Mode	Non-payload communications throughput (bits per second)(3), (4)									
			Command and control				ATC relay			Sense and avoid		
			Control		NavAids		ATC voice relay(5)	ATS data relay		Target tracks(6)	Airborne weather radar	Video(7)
			UL	DL	UL	DL	UL&DL	UL	DL	DL		
Pre-flight	4	M	*183*	*5*	0	0	4 800	*113*	*173*	9 120	0	0
Terminal (departure)	8	M	2 386	5 715	669	836	4 800	*49*	*59*	9 120	27 771	270 000
		A	775	912	141	186	4 800	*49*	*59*	9 120	27 771	
En route	76	M	1 201	2 356	669	836	4 800	*23*	*28*	9 120	3 968	270 000
		A	289	532	141	186	4 800	*23*	*28*	9 120	3 968	
Terminal (arrival)	11	M	4 606	7 615	669	1 140	4 800	*16*	*32*	9 120	27 771	270 000
		A	1 246	1 277	141	234	4 800	*16*	*32*	9 120	27 771	
Post-flight	1	M	*1*	*2*	0	0	4 800	*15*	*22*	0	0	0

(1) Pre-flight and post-flight phases do not include taxiing.

(2) Average assumed total duration of all phases = 4 h.

(3) Overhead as well as content bits are considered for all classes of traffic.

(4) Values in *italics* depend on assumed phase durations.

(5) Not necessarily needed in all scenarios or potential system architectures.

(6) 60 tracks assumed.

(7) Video needed only intermittently.

Abbreviations:

M: Manual operation, A: Automatic operation, UL: Uplink, DL: Downlink.

Appendix 1
of Annex 1

Loading requirements for UACS/UA command and control links

The following tables provide details of the UACS/UA control-link loading analysis:

- Table 17 – Control requirements, pre-flight phase: uplink
- Table 18 – Control requirements, pre-flight phase: downlink
- Table 19 – Control requirements, terminal (departure) phase: uplink
- Table 20 – Control requirements, terminal (departure) phase: downlink
- Table 21 – Control requirements, en route phase: uplink
- Table 22 – Control requirements, en route phase: downlink
- Table 23 – Control requirements, terminal (arrival) phase: uplink
- Table 24 – Control requirements, terminal (arrival) phase: downlink
- Table 25 – Control requirements, post-flight phase: uplink
- Table 26 – Control requirements, post-flight phase: downlink.

For the pre-flight and post-flight phases, the total numbers of bits that must be transferred is estimated. It is assumed for the pre-flight uplink estimate that a 300-waypoint flight plan must be uploaded. For the departure, en route, and arrival phases, data rates (bits/s rather than total numbers of bits) for manual as well as automatic operation were estimated.

TABLE 17

Control requirements, pre-flight phase: uplink

Field	Type	Bits
VSM ID	Integer 4	32
Data link ID	Integer 4	32
Vehicle type	Unsigned 2	16
Vehicle subtype	Unsigned 2	16
CUCS subtype	Unsigned 1	8
Requested/handover access	Unsigned 1	8
Requested/handover LOI	Unsigned 1	8
Controlled station	Unsigned 4	32
CUCS type	Unsigned 1	8
Mission plan mode	Unsigned 1	8
Route type	Unsigned 1	8
Waypoint number*	Unsigned 2	300 × 16
Waypoint to latitude*	Integer 4	300 × 32
Waypoint to longitude*	Integer 4	300 × 32
Waypoint to altitude*	Integer 3	300 × 24

TABLE 17 (*end*)

Field	Type	Bits
Waypoint altitude type*	Unsigned 1	300 × 8
Waypoint to speed*	Integer 2	300 × 16
Waypoint speed type*	Unsigned 1	300 × 8
Next waypoint*	Unsigned 2	300 × 16
Contingency waypoint A*	Unsigned 2	300 × 16
Contingency waypoint B*	Unsigned 2	300 × 16
Time stamp	Unsigned 5	40
Total		55 416

* 300 waypoints are assumed to be in the UA flight plan.

TABLE 18

Control requirements, pre-flight phase: downlink

Field	Type	Bits
VSM ID	Integer 4	32
Vehicle type	Integer 4	32
Vehicle subtype	Unsigned 2	16
Tail number	Character 16	128
Data link ID	Integer 4	32
Access authorized	Unsigned 1	8
Access granted	Unsigned 1	8
LOI authorized	Unsigned 1	8
Controlled station	Unsigned 4	32
Configuration ID	Unsigned 4	32
Propulsion fuel capacity	Float	32
Maximum indicated airspeed	Integer 2	16
Latitude	Integer 4	32
Longitude	Integer 4	32
Engine temperature	Unsigned 1	8
Engine number	Integer 4	32
Engine status	Unsigned 1	8
Route type	Unsigned 1	8
Status	Unsigned 1	8
Per cent complete	Unsigned 1	100 × 8
Waypoint request	Unsigned 2	20 × 16
Time stamp	Unsigned 5	40
Total		1 664

TABLE 19

Control requirements, terminal (departure) phase: uplink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	**Data rate (bit/s)**	**Repetition rate (Hz)**	**Data rate (bit/s)**
Select flight path control mode	Unsigned 1	8	1	8	1	8
Commanded altitude or throttle command	Integer 3 or (Integer 1)	24	1	24	10	240
Altitude type	Unsigned 1	8	1	8	1	8
Heading command type	Unsigned 1	8	1	8	1	8
Heading reference	Unsigned 1	8	1	8	1	8
Commanded heading/turn rate or aileron command	Integer 2 or (Integer 1)	16	1	16	10	160
Commanded course	Integer 2	16	1	16	10	160
Commanded speed or elevator command	Integer 2 or (Integer 1)	16	1	16	10	160
Speed type	Unsigned 1	8	1	8	1	8
Set lights	Unsigned 2	16	1	16	1	16
Engine number	Integer 4	32	1	32	1	32
Engine command	Unsigned 1	8	1	8	1	8
Gear turn/brake	Integer 1	8	5	40	5	40
Time stamp	Unsigned 5	40	5	200	10	400
Total				408		1 256

TABLE 20

Control requirements, terminal (departure) phase: downlink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	Data rate (bit/s)	Repetition rate (Hz)	Data rate (bit/s)
Latitude	Integer 4	32	2	64	15	480
Longitude	Integer 4	32	2	64	15	480
Altitude	Integer 3	24	2	48	15	360
Air speed	Integer 2	16	1	16	1	16
Ground speed	Integer 2	16	1	16	1	16
Roll	Integer 2	16	1	16	15	240
Yaw	Integer 2	16	2	32	15	240
Pitch	Integer 2	16	2	32	15	240
Heading	Integer 2	16	1	16	15	240
Engine temperature	Unsigned 1	8	1	8	1	8
Engine speed	Unsigned 2	16	1	16	1	16
Remaining fuel	Unsigned 2	16	1	16	1	16
Lights state	Unsigned 2	16	1	16	1	16
Engine number	Integer 4	32	1	32	1	32
Reported engine command	Unsigned 1	8	1	8	1	8
Time stamp	Unsigned 5	40	2	80	15	600
Total				480		3 008

TABLE 21

Control requirements, en route phase: uplink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	**Data rate (bit/s)**	**Repetition rate (Hz)**	**Data rate (bit/s)**
Select flight path control mode	Unsigned 1	8	1	8	1	8
Commanded altitude or throttle command	Integer 3 or (Integer 1)	24	1	24	5	120
Altitude type	Unsigned 1	8	1	8	5	40
Heading command type	Unsigned 1	8	1	8	1	8
Heading reference	Unsigned 1	8	1	8	1	8
Commanded heading/turn rate or aileron command	Integer 2 or (Integer 1)	16	1	16	5	80
Commanded course	Integer 2	16	1	16	5	80
Commanded speed or elevator command	Integer 2 or (Integer 1)	16	1	16	5	80
Speed type	Unsigned 1	8	1	8	1	8
Time stamp	Unsigned 5	40	1	40	5	200
Total				152		632

TABLE 22

Control requirements, en route phase: downlink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	Data rate (bit/s)	Repetition rate (Hz)	Data rate (bit/s)
Latitude	Integer 4	32	1	32	5	160
Longitude	Integer 4	32	1	32	5	160
Altitude	Integer 3	24	1	24	5	120
Engine temperature	Unsigned 1	8	1	8	1	8
Engine speed	Unsigned 2	16	1	16	1	16
Air speed	Integer 2	16	1	16	5	80
Ground speed	2 × Integer 2	2 × 16	1	32	5	160
Roll	Integer 2	16	1	16	5	80
Yaw	Integer 2	16	1	16	5	80
Pitch	Integer 2	16	1	16	5	80
Heading	Integer 2	16	1	16	5	80
Remaining fuel	Unsigned 2	16	1	16	1	16
Time stamp	Unsigned 5	40	1	40	5	200
Total				280		1 240

TABLE 23

Control requirements, terminal (arrival) phase: uplink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	Data rate (bit/s)	Repetition rate (Hz)	Data rate (bit/s)
Select flight path control mode	Unsigned 1	8	1	8	1	8
Commanded altitude or throttle command	Integer 3 (or Integer 1)	24	1	24	20	480
Altitude type	Unsigned 1	8	1	8	1	8
Heading command type	Unsigned 1	8	1	8	1	8
Heading reference	Unsigned 1	8	1	8	1	8
Commanded heading/turn rate or aileron command	Integer 2 (or Integer 1)	16	1	16	20	320
Commanded course	Integer 2	16	1	16	20	320
Commanded speed or elevator command	Integer 2 (or Integer 1)	16	1	16	20	320
Speed type	Unsigned 1	8	1	8	1	8
Set lights	Unsigned 2	16	1	16	1	16
Engine number	Integer 4	32	1	32	1	32
Engine command	Unsigned 1	8	1	8	1	8
Landing gear state	Unsigned 1	8	1	8	1	8
Gear turn/brake	Integer 1	8	10	80	10	80
Time stamp	Unsigned 5	40	10	400	20	800
Total				656		2 424

TABLE 24

Control requirements, terminal (arrival) phase: downlink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	Data rate (bit/s)	Repetition rate (Hz)	Data rate (bit/s)
Latitude	Integer 4	32	2	64	20	640
Longitude	Integer 4	32	2	64	20	640
Altitude	Integer 3	24	2	48	20	480
Air speed	Integer 2	16	2	32	2	32
Ground speed	2 × Integer 2	2 × 16	2	64	2	64
Roll	Integer 2	16	2	32	20	320
Yaw	Integer 2	16	2	32	20	320
Pitch	Integer 2	16	2	32	20	320
Heading	Integer 2	16	2	32	20	320
Engine temperature	Unsigned 1	8	1	8	1	8
Engine speed	Unsigned 2	16	1	16	1	16
Remaining fuel	Unsigned 2	16	1	16	1	16
Lights state	Unsigned 2	16	1	16	1	16
Landing gear state	Unsigned 1	8	1	8	1	8
Speed brake deployment angle	Integer 1	8	1	8	1	8
Time stamp	Unsigned 5	40	5	200	20	800
Total				672		4 008

TABLE 25

Control requirements, post-flight phase: uplink

Field	**Type**	**Bits**
Select flight path control mode	Unsigned 1	8
Set lights	Unsigned 2	16
Commanded flight termination state	Unsigned 1	8
Flight termination mode	Unsigned 1	8
Time stamp	Unsigned 5	40
Total		80

TABLE 26

Control requirements, post-flight phase: downlink

Field	**Type**	**Bits**
Select flight path control mode	Unsigned 1	8
Latitude	Integer 4	32
Longitude	Integer 4	32
Lights state	Unsigned 2	16
Reported flight termination state	Unsigned 1	8
Reported flight termination mode	Unsigned 1	8
Time stamp	Unsigned 5	40
Total		144

Appendix 2
of Annex 1

Loading requirements for NavAid data links

The following tables provide details of our loading analysis of UACS /UA NavAid data links:

– Table 27 – NavAid requirements, terminal (departure) phase: uplink
– Table 28 – NavAid requirements, terminal (departure) phase: downlink
– Table 29 – NavAid requirements, en route phase: uplink
– Table 30 – NavAid requirements, en route phase: downlink
– Table 31 – NavAid requirements, terminal (arrival) phase: uplink
– Table 32 – NavAid requirements, terminal (arrival) phase: downlink

TABLE 27

NavAid requirements, terminal (departure) phase: uplink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	Data rate (bit/s)	Repetition rate (Hz)	Data rate (bit/s)
Set NavAid radio state	Unsigned 1	8	0.1	0.8	1	8
Set NavAid frequency	Unsigned 2	16	0.1	1.6	1	16
VOR radial	Signed 2	16	1	16	5	80
Radial to/from	Unsigned 1	8	1	8	5	40
Radio unit	Unsigned 1	8	1	8	1	8
Time stamp	Unsigned 5	40	1	40	5	200
Total				74.4		352

TABLE 28

NavAid requirements, terminal (departure) phase: downlink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	Data rate (bit/s)	Repetition rate (Hz)	Data rate (bit/s)
VOR NavAid state	Unsigned 1	8	1	8	1	8
NavAid frequency	Unsigned 2	16	0.1	1.6	1	16
NavAid receiver state	Unsigned 1	8	0.1	0.8	1	8
Radio unit	Unsigned 1	8	1	8	1	8
VOR azimuth	Signed 2	16	1	16	5	80
DME	Signed 3	24	1	24	5	120
Time stamp	Unsigned 5	40	1	40	5	200
Total				98.4		440

TABLE 29

NavAid requirements, en route phase: uplink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	Data rate (bit/s)	Repetition rate (Hz)	Data rate (bit/s)
Set NavAid radio state	Unsigned 1	8	0.1	0.8	1	8
Set NavAid frequency	Unsigned 2	16	0.1	1.6	1	16
VOR radial	Signed 2	16	1	16	5	80
Radial to/from	Unsigned 1	8	1	8	5	40

TABLE 29 (*end*)

Field	**Type**	**Bits**	**Automatic mode**		**Manual mode**	
			Repetition rate (Hz)	**Data rate (bit/s)**	**Repetition rate (Hz)**	**Data rate (bit/s)**
Radio unit	Unsigned 1	8	1	8	1	8
Time stamp	Unsigned 5	40	1	40	5	200
Total				74.4		352

TABLE 30

NavAid requirements, en route phase: downlink

Field	**Type**	**Bits**	**Automatic mode**		**Manual mode**	
			Repetition rate (Hz)	**Data rate (bit/s)**	**Repetition rate (Hz)**	**Data rate (bit/s)**
VOR NavAid state	Unsigned 1	8	1	8	1	8
NavAid frequency	Unsigned 2	16	0.1	1.6	1	16
NavAid receiver state	Unsigned 1	8	0.1	0.8	1	8
Radio unit	Unsigned 1	8	1	8	1	8
VOR azimuth	Signed 2	16	1	16	5	80
DME	Signed 3	24	1	24	5	120
Time stamp	Unsigned 5	40	1	40	5	200
Total				98.4		440

TABLE 31

NavAid requirements, terminal (arrival) phase: uplink

Field	**Type**	**Bits**	**Automatic mode**		**Manual mode**	
			Repetition rate (Hz)	**Data rate (bit/s)**	**Repetition rate (Hz)**	**Data rate (bit/s)**
Set NavAid radio state	Unsigned 1	8	0.1	0.8	1	8
Set NavAid frequency	Unsigned 2	16	0.1	1.6	1	16
VOR radial	Signed 2	16	1	16	5	80
Radial to/from	Unsigned 1	8	1	8	5	40
Radio unit	Unsigned 1	8	1	8	1	8
Time stamp	Unsigned 5	40	1	40	5	200
Total				74.4		352

TABLE 32

NavAid requirements, terminal (arrival) phase: downlink

Field	Type	Bits	Automatic mode		Manual mode	
			Repetition rate (Hz)	Data rate (bit/s)	Repetition rate (Hz)	Data rate (bit/s)
VOR NavAid state	Unsigned 1	8	1	8	1	8
NavAid frequency	Unsigned 2	16	0.1	1.6	1	16
NavAid receiver state	Unsigned 1	8	0.1	0.8	1	8
Radio unit	Unsigned 1	8	0.1	0.8	1	8
VOR azimuth	Signed 2	16	1	16	5	80
DME	Signed 3	24	1	24	5	120
LOC/glideslope valid	Unsigned 1	8	1	8	5	40
LOC	Signed 1	8	1	8	5	40
Glideslope	Signed 1	8	1	8	5	40
Marker	Unsigned 1	8	1	8	5	40
Time stamp	Unsigned 5	40	1	40	5	200
Total				123.2		600

Annex 2

UAS deployment scenario

Two UAS deployment scenarios (see Methodologies 1 and 2) have been developed separately and lead to the same order of UAS density.

1 Methodology 1

Studies indicate that the estimated Peak Instantaneous Aircraft Count (PIAC) around 2030 would typically be around:

– 44 in a TMA,

– 62 in a medium en route,

– 204 in a large en route area.

This methodology assumes that 10% of these estimations would be UA.

Further information on this methodology is contained in Annex 3.

This leads at an average density presented in the table below:

			UA		
			Small	Medium	Large
UA in operation by 2030			8336	2028	837
		%	60%		
Density of UA/km^2	Low altitude	< 1 500 m	0.000641	–	–
	Medium altitude	> 1 500 m – < 6 000 m	–	0.000156	–
	High altitude	> 6 000 m	–	–	0.000064
LoS scenario			Based on above densities		
BLoS scenario (spot-beam)		per spot	0	75	31

2 Methodology 2

2.1 Introduction

This methodology begins by describing the UA operations that are anticipated and the characteristics and phases of UA missions.

This methodology then discusses the projected UA population by the 2030 time-frame. This time-frame has been chosen to align with the time-frames being considered by standards development bodies such as RTCA SC-203 and EUROCAE WG 73 as well as being far enough into the future to provide projected quantities that are significant enough to establish a good estimate of the long term spectrum need.

This methodology then describes scenarios which represents not only typical use and mission profiles for UA but which also exemplify maximum aircraft densities in given volumes of air space and as such should represent maximum bandwidth requirements.

2.2 UAS operations and UA categorization

Operational concepts for UAS are as varied as their systems. These variations result from a balance of considerations including mission needs, desired capabilities, risk tolerance, environmental conditions, economic cost/benefits, and rules governing operations.

This section provides a general description and categorization of UAS operational concepts. These concepts are organized by surface and airborne environments, as well as by participation or non-participation with ATC. Additionally, there are two categories of flight profiles described that relate to UAS airborne operational behaviours. These high-level descriptions address, in generic terms, the what, where, who, and how of UAS operations.

The term “ATC participating” for this subsection, assumes operations engaging air traffic control services. An ATC-participating operation encompasses all operations under IFR rules and VFR operations where ATC services are provided. In contrast, a non-ATC participating operation refers to operations receiving no ATC services. Non-ATC participating encompass all VFR operations that occur in uncontrolled airspace in Classes F and G and those within Class E airspace where ATC services are not provided or required.

2.2.1 Primary operational functions

Four functions in vertical columns within each operational view are identified. **Communicate, Control, Navigate**, and **Avoid**. These functions represent the primary operations that must take place for safe flight. The **Communicate** function refers to voice, data and light signal exchanges between ATC and the UACS to communicate instructions and responses. The **Control** function relates to the control link between the UA and Unmanned Aircraft Control Station, and includes telemetry information confirming aircraft control status and health. The **Navigate** function pertains to any reference cues used by the UA or pilot to determine orientation. The **Avoid** function refers to any action taken by the aircraft to keep safely away from moving and stationary objects (e.g. terrain, clouds, aircraft, people, structures, etc.) and from unauthorized surface areas or airspace.

Common to the above four operational functions is the **Manage** function. This function, depicted by the bottom row of each graphic, refers to the human or automated ability to plan, monitor, assess, decide, react and re-task or re-plan based on changing system status and/or environmental inputs. It is reliant on information exchanges. The **Manage** function may reside solely in the UA, Unmanned Aircraft Control Station, and ground support element or, more likely, allocated among them.

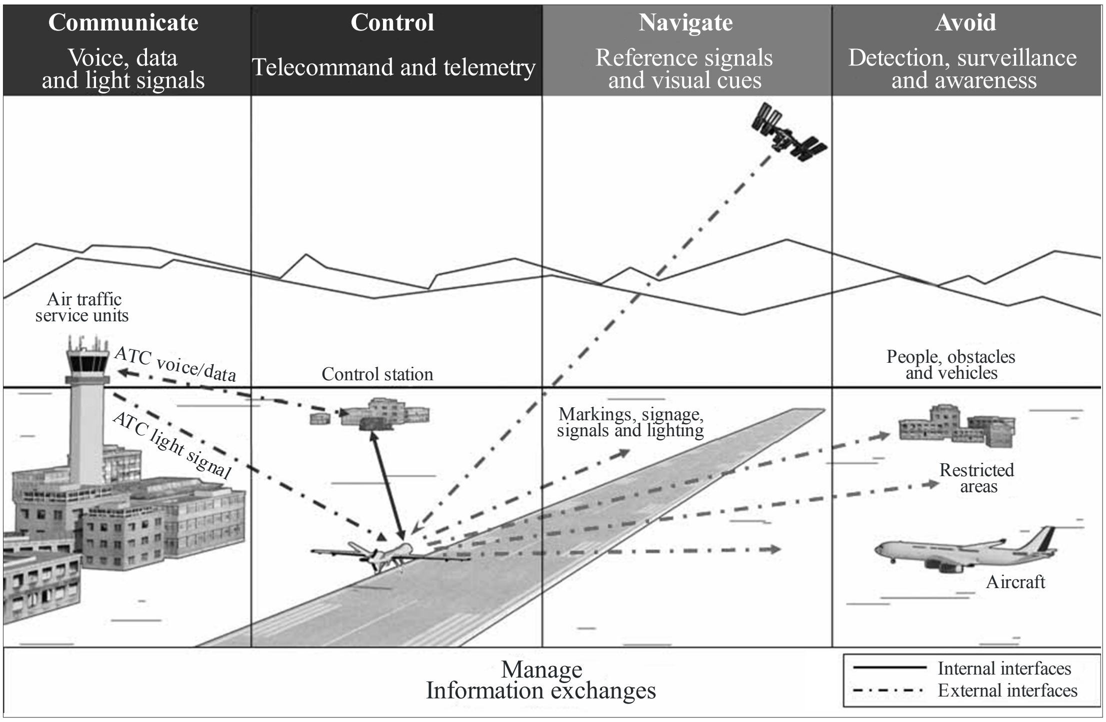
2.2.2 Surface environment

The surface environment encompasses all operations related to mission planning, system preparations, pre-flight checks and aircraft movement on the surface that occur just prior to takeoff/launch and immediately following landing/recovery. This environment includes airport and off-airport operations. All surface operations require an awareness and ability to stay safely clear of persons, obstructions, structures, vehicles, and aircraft on the surface.

2.2.2.1 ATC participating airport

The participating surface environment represents UAS operations at towered airports and seaports where ATC services are required for movement. This environment exists only during ATC operating hours.

ATC participating airport operational view



Report M.2171

In this environment, UAS performs the following operations:

Communicate with ATC via voice or data link at controlled airports or, in the absence of voice communications, to see and comply with ATC light signals. This function relies on radio and visual sight of light signals.

Control the movement of the aircraft and monitor status. This function relies on the control link and telemetry feedback for remote controls, pre-programmed navigation for autonomous control, or by physical movement of the aircraft (e.g. towing).

Navigate on the airport surface as instructed by ATC. This function is accomplished by visual compliance with markings, signage, lighting, and signals that guide or restrict movement on the aprons, taxiways and runway surface. This function may be augmented using appropriate internal or external navigational capabilities, such as an inertial navigation system or satellite system.

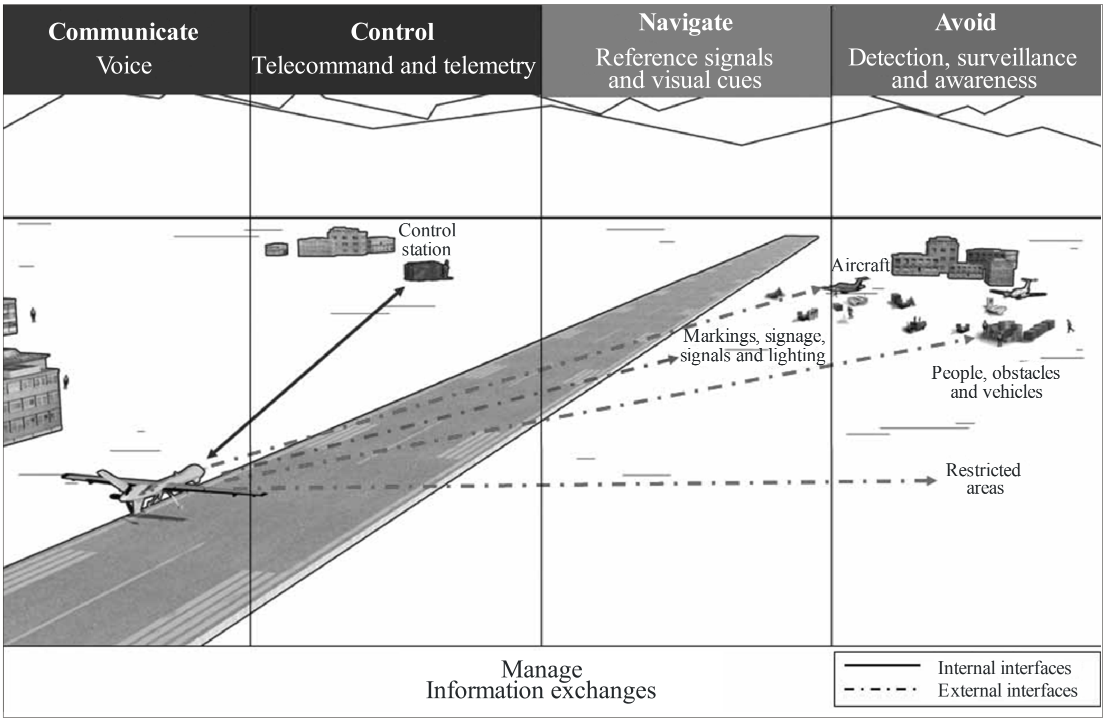
Avoid all people, aircraft, vehicles, buildings and natural and man-made obstacles on or near the designated surface movement areas. Also avoid object free areas and areas restricted or not intended for aircraft. This function is enabled by surveillance, detection, and other systems or methods – internal or external to the UAS – that are capable of providing sufficient awareness and resolution to maintain safe separation and avoid collision.

Manage all planning, pre-flight, and surface movement activities. Safely and efficiently manoeuvre, space, sequence, and align with other aircraft as expected by ATC and other airport users. Changing conditions or states on the surface are assessed, decided upon, and acted on, if appropriate, to maintain safety, situational awareness, and navigational compliance. This function relies on information exchanged between the operational personnel, UAS, ATSU, and environment.

2.2.2.2 Non-ATC participating airport

The non-ATC participating airport environment represents UAS operations at any public non-towered airport or at towered airports when ATC services are not offered.

Non-ATC participating airport operational view



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In this environment, UAS perform the following operations:

Communicate flight intentions with local traffic where common traffic advisory frequency (CTAF) frequencies are available. This function is accomplished via voice radio.

Control the movement of the aircraft and monitor status. This function relies on the control link and telemetry feedback for remote control, pre-programmed navigation for autonomous control, or physical control of the aircraft (e.g. towing).

Navigate on the airport surface. This function is accomplished by visual compliance with markings, signage, lighting, and signals that guide or restrict movement on the aprons, taxiways and runway surface. This function may be augmented using appropriate internal or external navigational capabilities, such as an inertial navigation system or satellite system.

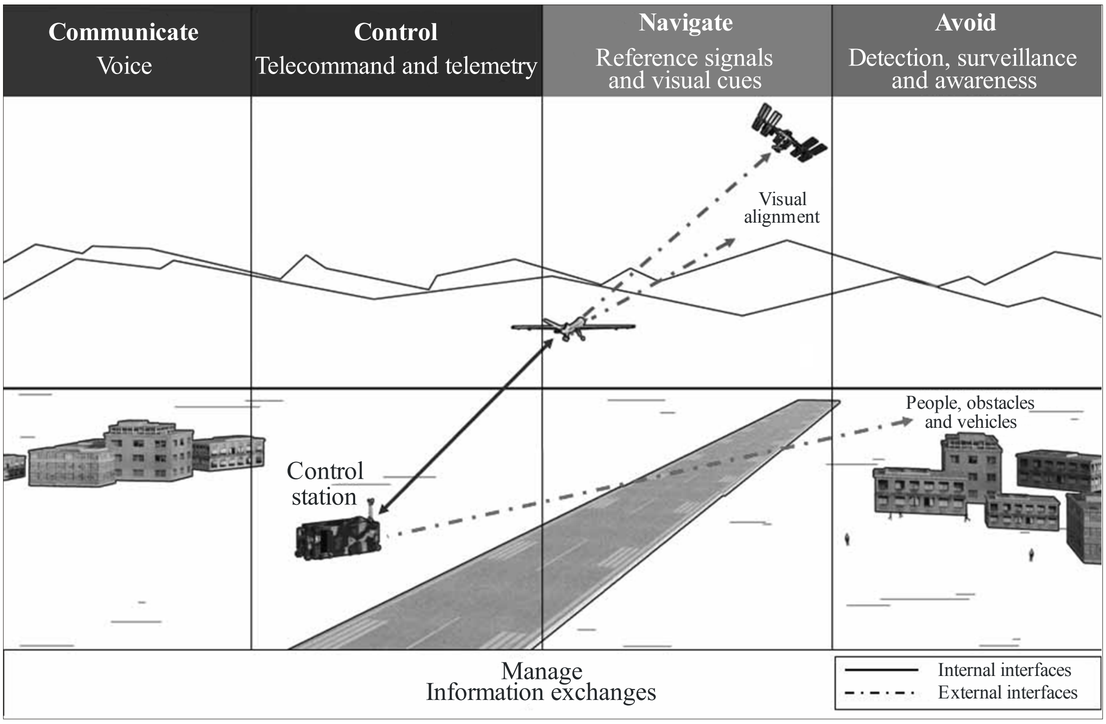
Avoid all people, aircraft, vehicles, buildings and natural and man-made obstacles on or near the designated surface movement areas. Also avoid object free areas and areas restricted or not intended for aircraft. This function is enabled by surveillance, detection, and other systems or methods – internal or external to the UAS – that are capable of providing sufficient awareness and resolution to maintain safe separation and avoid collision.

Manage all planning, pre-flight, and surface movement activities. Safely and efficiently manoeuvre, space, sequence, and align with other aircraft as expected by other airport users. Changing conditions or states on the surface are assessed, decided upon, and acted on, if appropriate, to maintain safety, situational awareness, and navigational compliance. This function relies on information exchanged between the operational personnel, UAS, airport users, and the environment.

2.2.2.3 Non-ATC participating surface

The non-ATC participating surface environment represents UAS operations at any off-airport location, privately-owned airfield, open water (other than seaports) or airports that can be temporarily cleared (or "sterilized") to allow for UAS operations.

Non-ATC participating surface operational view



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In this environment, UAS perform the following operations:

Communicate flight intentions with local traffic where CTAF frequencies are available. This function is accomplished via voice radio.

Control the movement of the aircraft and monitor status. This function relies on the control link and telemetry feedback for remote controls, pre-programmed navigation for autonomous control, or by physical movement of the aircraft (e.g. towing).

Navigate on the operating surface unless the UA is capable of vertical lift or being launched or recovered without need for surface movement. This function is accomplished through visual alignment with the terrain and may be further augmented using GNSS signals.

Avoid all people and obstacles on or near the surface movement area. This function is enabled by surveillance, detection, and other systems or methods capable of providing sufficient awareness and resolution to maintain safe separation and avoid collision.

Manage all surface movement and launch/recovery activities. Surface movement is continuously monitored, changes assessed, and actions taken to ensure the safety of the aircraft, and persons and property in its proximity. This function relies on information exchanges among the operational personnel, UAS and environment.

2.2.3 Airborne environment

The airborne environment encompasses all operations from takeoff/launch to landing/recovery. This environment includes ATC-controlled airspace (Class A, B, C, D and E) and uncontrolled airspace (Class F and G). The number of external interfaces is greatest when flown in controlled airspace. All airborne operations require an awareness and ability to stay safely clear of severe weather, aircraft, obstructions and terrain.

2.2.3.1 ATC participating airborne

The ATC participating airborne environment represents UAS operations interacting with the ATC system under instrument flight rules (IFR) or visual flight rules (VFR) while under air traffic control.

In this environment, UAS perform the following operations:

Communicate with ATC via voice or data link and light signals from ATC when in the vicinity of an active towered airport. This function relies on radio communications and visual observation of ATC light signals.

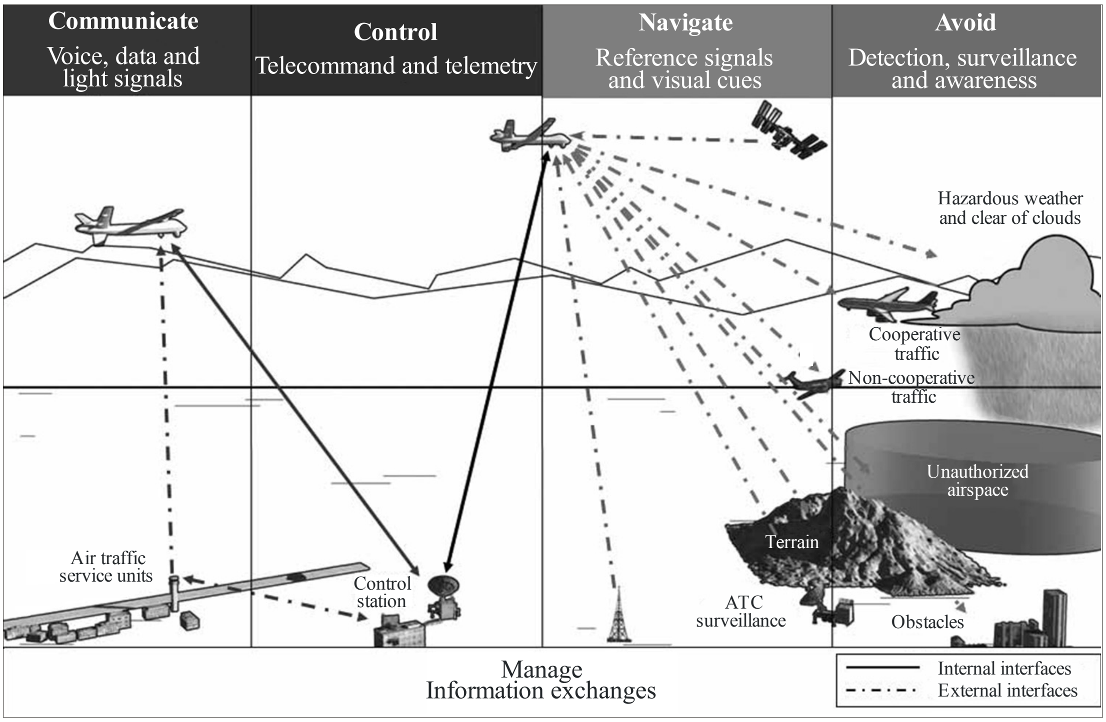
Control movement of the aircraft and monitor status. This function relies on the control link and telemetry feedback and automated or remotely activated flight controls aboard the UA.

Navigate along pre-designated routes or within assigned areas and assigned altitudes. This function relies on satellite and/or ground-based NavAids acceptable to ATC.

Avoid hazardous weather, cooperative and non-cooperative aircraft, unauthorized airspace, terrain and obstacles. The UAS maintains safe separation from cooperative traffic via ATC surveillance. This function relies on transponders, procedures, sensory systems, databases and/or other systems or methods capable of providing sufficient awareness and resolution to avoid collisions.

Manage all flight movements through continuous monitoring of UA and its environment. Changing conditions or states are assessed and acted on, if appropriate, to maintain safety, situational awareness, and navigational compliance. This function relies on information exchanges among the operational personnel, UAS, ATSU, airspace users and environment.

ATC participating airborne operational, environment and system interfaces



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2.2.3.2 Non-ATC participation airborne

The non-ATC participation airborne environment represents UAS operations that occur under VFR in Class G and E airspace outside of ATC control.

In this environment, UAS perform the following operations:

Communicate flight intentions with local traffic where CTAF frequencies where available. This function is accomplished via voice radio within protected spectrum.

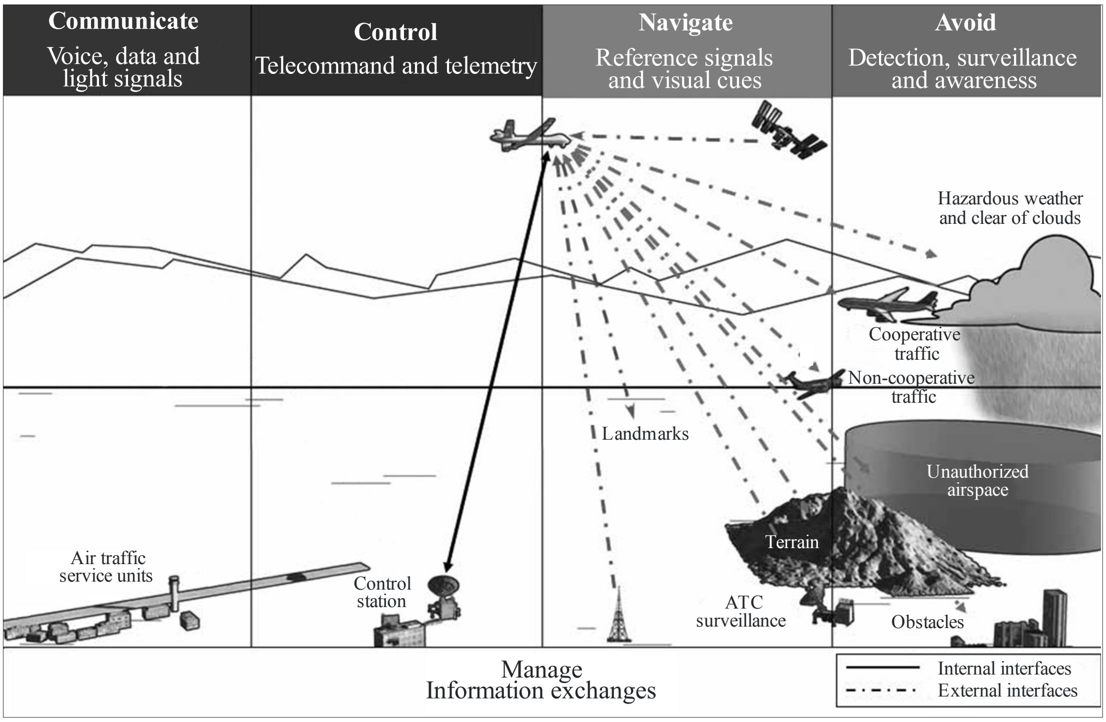
Control the movement of the aircraft and monitor status. This function relies on the control link and telemetry feedback and automated or remotely activated flight controls aboard the UA.

Navigate in areas and at altitudes required of VFR operations. This function is accomplished using pilotage and/or satellite or ground-based NavAids.

Avoid hazardous weather, cooperative and non-cooperative aircraft, unauthorized airspace, terrain and obstacles. The UAS maintains VFR separation from clouds, and remain at a safe horizontal and vertical separation from congested areas. This function relies on procedures, visual observation, sensory systems, databases and/or other systems or methods capable of providing sufficient awareness and resolution to avoid collisions.

Manage all flight movements through continuous monitoring of UA and its environment. Changing conditions or states are assessed and acted on, if appropriate, to maintain safety, situational awareness, and navigational compliance. This function relies on information exchanges among the operational personnel, UAS, ATSU, and environment.

Non-ATC participating airborne operational view



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2.2.4 UAS mission characteristics and phases of flight

Understanding how UAS intend to fly is not only important in assessing compatibility with the ATM system, in characterizing UAS flights relative to other airspace users, in developing collision encounter models and assessing safety risks associated with these flight profiles but is also important in evaluating the spectrum required to support UAS operations.

The UAS flight profiles that represent the operational behaviour of UA in the airborne environment are divided into two categories: planned aerial work, and unplanned aerial work.

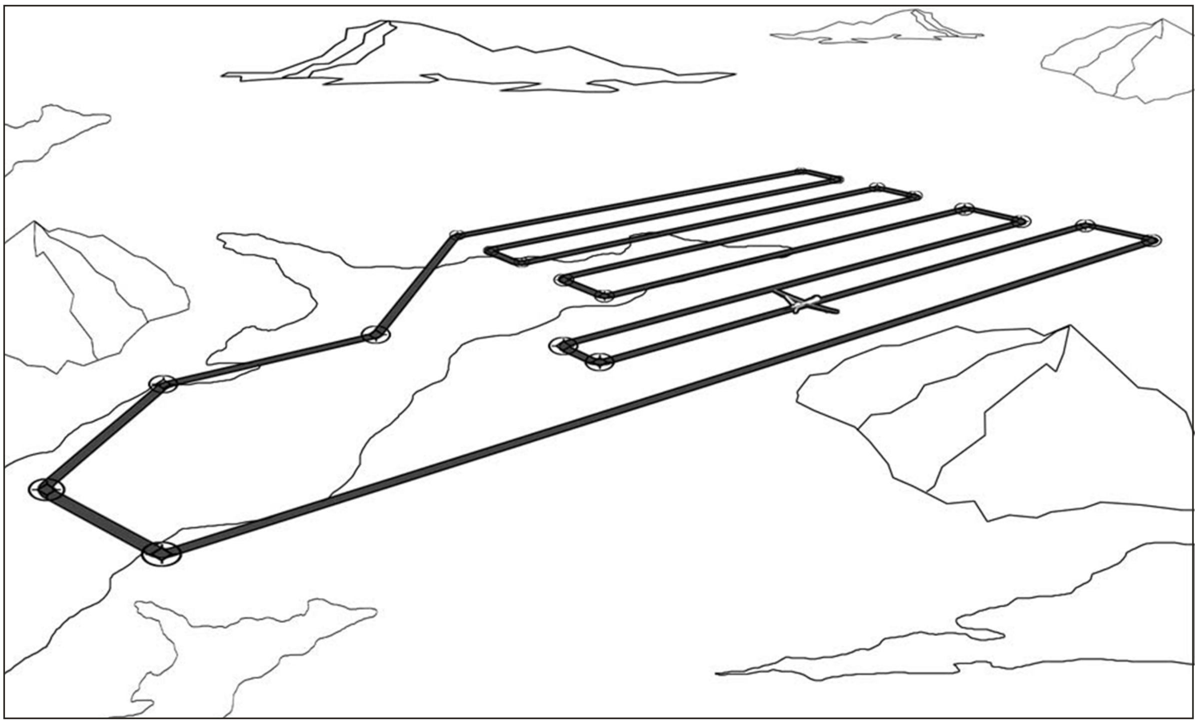
2.2.4.1 Planned aerial work

UAS Planned Aerial Work operations generally refer to orbiting, surveillance and tracking flights using pre-defined waypoints. Planned Aerial Work is usually conducted for surveillance or communications relay operations, and is anticipated to represent a significant percentage of UAS operations in the 2030 time-frame. Planned tracking flights include surveillance of natural or political geographic features (such as shorelines, borders, buildings, roads, or pipelines). Orbiting and tracking operations occur using a range of UAS platforms within low, medium, and high altitude airspace and encompass VFR and IFR operations.

Point-to-point UAS operations represent a subset of planned aerial work. They are very similar to the majority of commercial manned aircraft operations. They represent flights to an airfield or any other non-terminal area other than the departure airfield. Point-to-point operations are characterized by the direct nature of the flight and do not include aerial work or delays that may occur during the en-route phase of the flight.

Point-to-point operations will require use of airports located primarily within controlled facilities, private airports, or civil towered-airports located in Class C or D airspace. UAS surface operations within Class B jurisdiction may occur in limited circumstances, but it is doubtful that point-to-point operations will originate or end in close proximity to major commercial hub airports any time soon.

Planned aerial work



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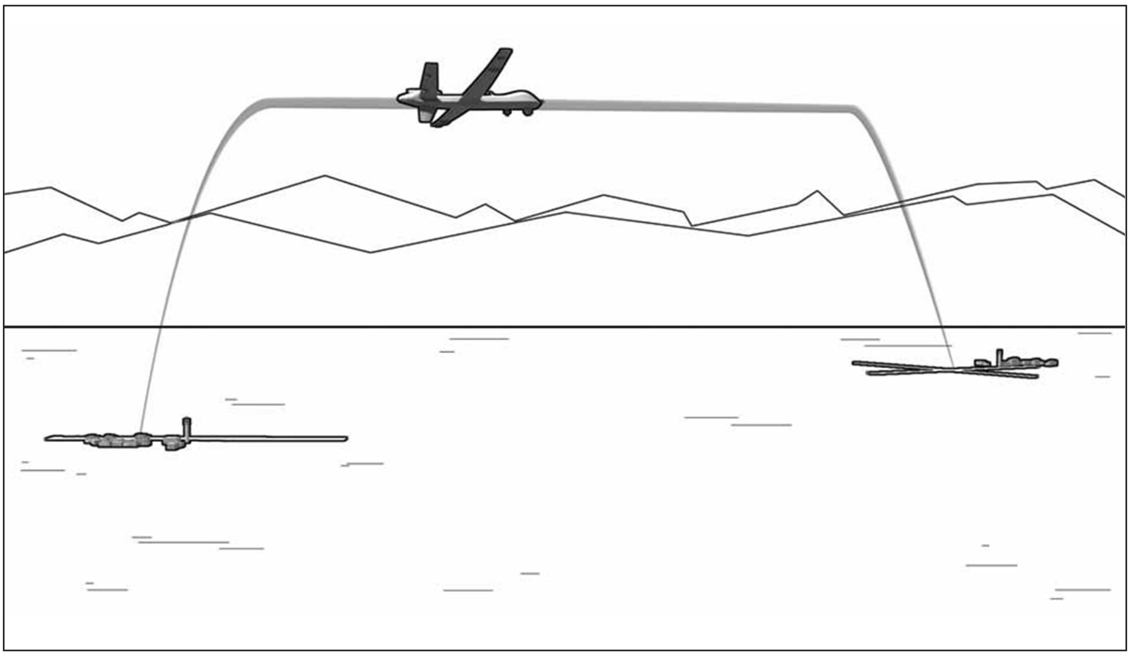
Point-to-point aerial work



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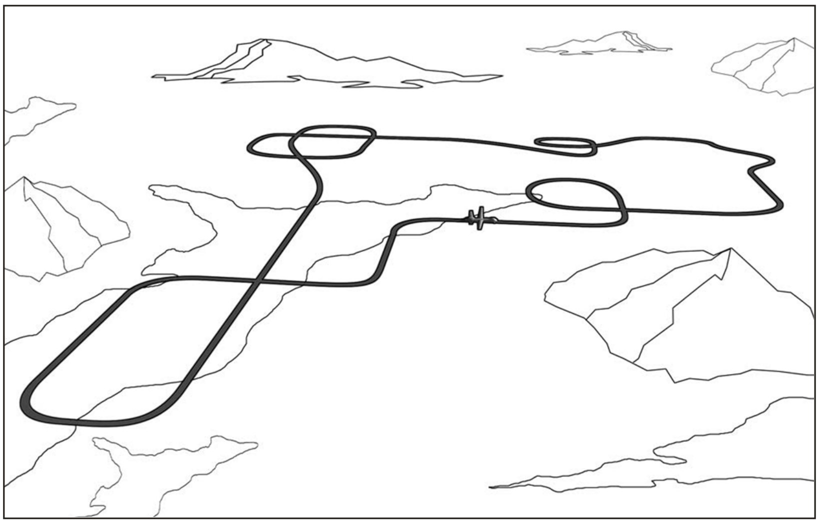
2.2.4.2 Unplanned aerial work

Unplanned aerial work operations are ad hoc in nature. Typical examples are tracking a ground vehicle or performing intermittent orbits to observe specific areas of interest. In such cases, UAS cannot predict their intended flight path but they can provide a general indication of their area of flight. For manned aircraft, these unplanned aerial work flights are usually conducted under VFR, though they can be accommodated in IFR depending on circumstances and a controller's willingness to block airspace to allow these operations. These operations are normally only allowed for government missions. Air traffic control has the discretion to allow such deviations for commercial activities but they may require cancellation of the IFR plan.

Unplanned aerial work



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2.2.4.3 Phases of flight

In subsequent analysis the phases of flight for the previously described operations will also be required. In this respect UA operate very similarly to manned aircraft where the phases of flight are determined by which part of the air traffic management system is supporting the flight. A typical flight will consist of the following phases:

Pre-flight – This phase includes operations conducted on the surface including flight planning and aircraft/pilot preparations. Pre-flight concludes with clearance delivery or when ground control communications are established.

Terminal departure – This phase includes taxi, takeoff and departure initially under supervision of the airport tower controller and then the terminal radar approach control facility (TRACON) once the aircraft has left the vicinity of the airport. This phase is concluded when communications are transferred to an en-route communications facility (air route traffic control centre – ARTCC).

En-route – This phase includes flight in national airspace as well as international and oceanic air space and terminates when the UA returns to TRACON or terminal supervision.

Terminal arrival – This phase includes approach, landing and taxiing clear of the runway initially under supervision of the terminal radar approach control facility (TRACON) and then the airport tower controller as the aircraft enters the vicinity of the airport. This phase concludes when ground control communications have been established.

Post-flight – This phase includes shutdown, securing of the UA and debriefing activities and is performed clear of airport surface movement areas.

Although the phases of flight are similar to manned aircraft, UA will often operate in distinctly different ways particularly during the en-route phase. The UA may in fact not "en-route" at all but may loiter in the terminal area or return to the same airport as it departed. The UA may also not be able to follow a predetermined flight plan if it is performing ad hoc surveillance activity but will only be able to provide a general area of operation for flight planning purposes. UA may also loiter for considerable time (measured in periods of months for some airship style UA) where they are being used as communications relay platforms for example. Finally many UA operations will not take place in the jetways and airways associated with current manned aircraft commercial and general aviation traffic flows but the UA may well fly in remote locations on the borders, littoral regions and remote areas.

2.2.5 UA categorization

There have been a number of different methods used to categorize UA. Weight has often been used, as it is in the manned aircraft industry, as it has a close correlation with safety assessments. The following table shows the categorization used in this methodology. From this methodology's perspective the key parameters that differentiate small, medium and large UA are not their weight but their maximum altitude and maximum range, since these have a direct bearing on the disposition of UA and hence the amount of spectrum required to support UA operations.

Table 33 groups UA into the three categories described above (small, medium and large) and gives some of the key parameters of these three categories that will be required in the subsequent spectrum assessments in Annex 3.

TABLE 33

UA categories from a spectrum perspective

UA Category	Weight (kg)	Maxime altitude (m)	Cruise speed (km/h)	Endurance (hours)	Maximum range (km)
Small	< 25	< 300	< 111	< 5	Visual LoS < 3
Medium	25-2 000	300-5 500	111-185	5-30	RF LoS 150-250
Large	> 2 000	> 5 500	> 185	> 30	Beyond RF LoS

Once standards are in place it is expected that Small UA will typically operate in Class G airspace, medium UA will typically operate in all airspace except Class A and large UA will operate in any class of airspace.

NOTE 1 – For the remainder of this annex the terms LoS and BLoS will refer to RF line-of-sight and beyond RF line-of-sight and the term Visual LoS will be used explicitly to differentiate RF LoS from visual LoS.

Endurance and cruise speed also have some bearing on the spectrum required as they determine the amount of time a UA will spend in any specific region.

Even though small and medium UA fly over short ranges it may be necessary to operate small and medium UA using a BLoS satellite system, when such UA are outfitted with satellite communication capability and no terrestrial LoS spectrum is available.

2.3 Projected UA population

This section contains a description of the current and potential uses for UAS. It takes forecast information from surveys and develops a projection for the number of UA available for operation. This assessment will be used to support the scenarios developed in § 2.2.4 of this methodology.

Data used for this assessment was taken from UAS manufacturers, operators, published reports, articles, and subject matter expert opinion projections from the Teal Group's *World Unmanned Aerial Vehicle Systems*: *Market Profile and Forecast, 2008* indicate that the USA will spend an estimated 73% of the worldwide research, development, test and evaluation (RDT&E) over the next decade and represent the vast majority of UAS that will likely be operated through the 2030 time-frame that is the focus of this methodology .

Demand for UAS results from the desire for a UAS capability against the economic costs and any legal, technological, political, or social constraints. The decision to purchase, use, operate, and maintain UAS are made based on a balance of the strengths and weaknesses of these factors. In forecasting UAS quantities, it is generally useful to make projections based on past trends. For the UAS industry, however, these trends are not well established. The underlying technologies, practices, and governing rules are evolving and resolution of economic, legal, political, and social barriers remain in question. The result is a degree of uncertainty both positive and negative associated with any forecast.

General assumptions made when conducting this UAS assessment include:

– Government-sponsored UAS operations will take place despite a lack of standards and regulations. This will be accomplished through special arrangements with the Aviation authorities that will confine the place, times and types of operations.

– No technological breakthrough or extraordinary demand will significantly accelerate the introduction of UAS beyond the constraints imposed by the established regulations.

– Growth rates for all UAS use segments will follow a common S-curve growth progression, or sigmoid function (slow initial increases followed by a steep climb then a gradual levelling as saturation occurs).

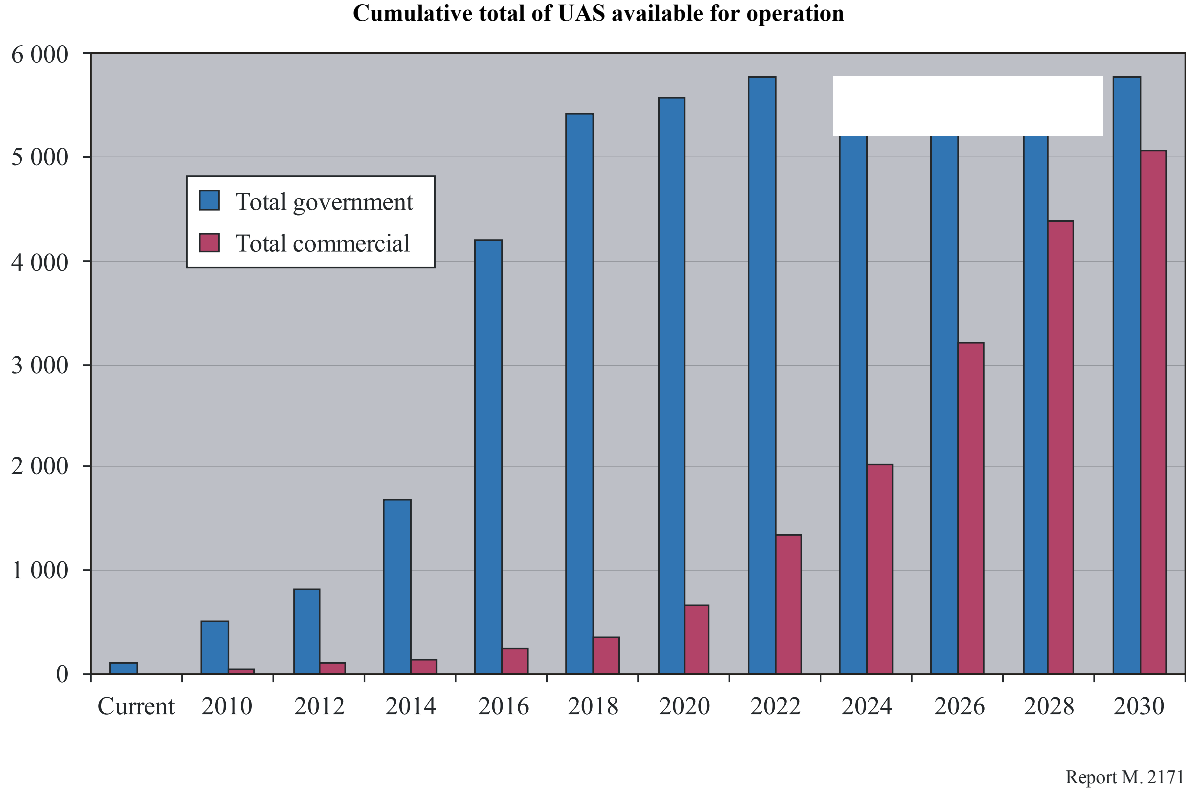
– UAS technologies will continue to mature and associated prices of those technologies decrease over time.

– The cost of operating personnel will remain constant over time.

– The cost of UAS systems, operations, and continued maintenance will decline over time due to economies of scale, standards, and technological maturity.

2.3.1 UAS use segments

In its broadest context, there are two major UAS use segments, government and commercial. The distribution of UAS among use segments is, today, highly skewed to the government use segment. Currently, according again to the Teal Group *World Unmanned Aerial Vehicle Systems: Market Profile and Forecast, 2008*, there are no commercial UAS operating. Studies predict that by 2018 the Government use segment will have completed its ramp up and be at a reasonably constant level through future years. The commercial use segment will not likely begin to grow significantly until sometime after certification standards become available in the 2020 time frame. The following figure is an example of a cumulative total of UAS available for operation in a specific area illustrates the growth of these two use segments using data developed through the remainder of this section.



Translating UAS use segment size into usage data of UA (e.g. flight hours) requires a more complete understanding of intended missions and will be discussed further in §§ 2.3.4 and 2.4 of this methodology.

While drivers and dynamics between these two use segments differ significantly, they both share a common objective of providing a service that cannot either be accomplished by manned aircraft, and/or can be perform by a UAS at a lower cost. Development of UAS business therefore depends on the unique characteristics and costs of UAS products and services relative to their manned counterparts. This general rule applies to each use segment. For the government use segment, usage is primarily influenced by a combination of budget priorities, perceived mission needs and priorities, and socio-political considerations. For the commercial use segment, potential UAS operators will need to build a sufficient business case, demonstrating to investors that the potential returns outweigh the risks. The business case for individual missions will vary significantly depending on a number of factors such as demand for the proposed service(s), the cost of system acquisition and operation, level of competition, regulatory impediments, and insurance liability.

The following subsections describe prospective uses for government and commercial UAS.

2.3.2 Government use segment

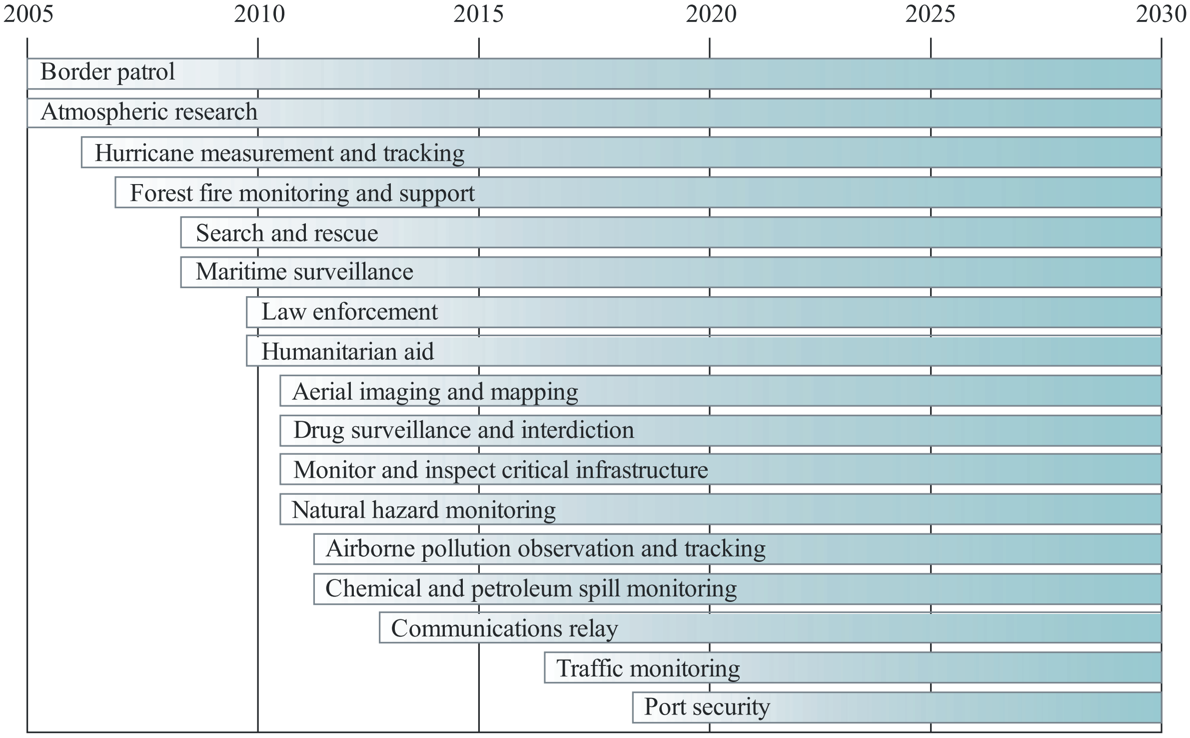
The government use segment includes all federal, state, and local government organizations, including government-funded entities such as state-funded universities. Current government missions for UAS include border patrol, forest fire support, and a variety of technology tests and scientific missions.

Government UA applications will likely substitute for current manned aircraft missions where greater mission effectiveness and endurance can be gained, risks reduced, or costs lowered. Some UAS applications will be new, such as those supporting flights in proximity of dangerous areas, such as chemical spills or radiation releases. The following figure represents current and potential government applications for UAS (excluding UAS operated exclusively within VLoS).

Primary factors affecting the growth of the government use segment include:

- proven technology and utility of UAS gained from government experience;
- ability to self-certify UAS and operator personnel;
- interim allowance for airspace access;
- surface operations restricted or very limited at public-use airports;
- some access to protected communication frequencies for operational use;
- continued government interest in the advancement of unmanned technologies; and
- public acceptance for use of UAS for the public good (e.g. climate research, humanitarian relief);
- continued limited airspace access due to regulatory constraints;
- high cost of UAS acquisition and operations relative to manned aircraft;
- limitations in the use of protected communication frequencies and bandwidths;
- manned aircraft alternatives;
- lack of public funding;
- changing mission or national priorities.

Current and potential government applications



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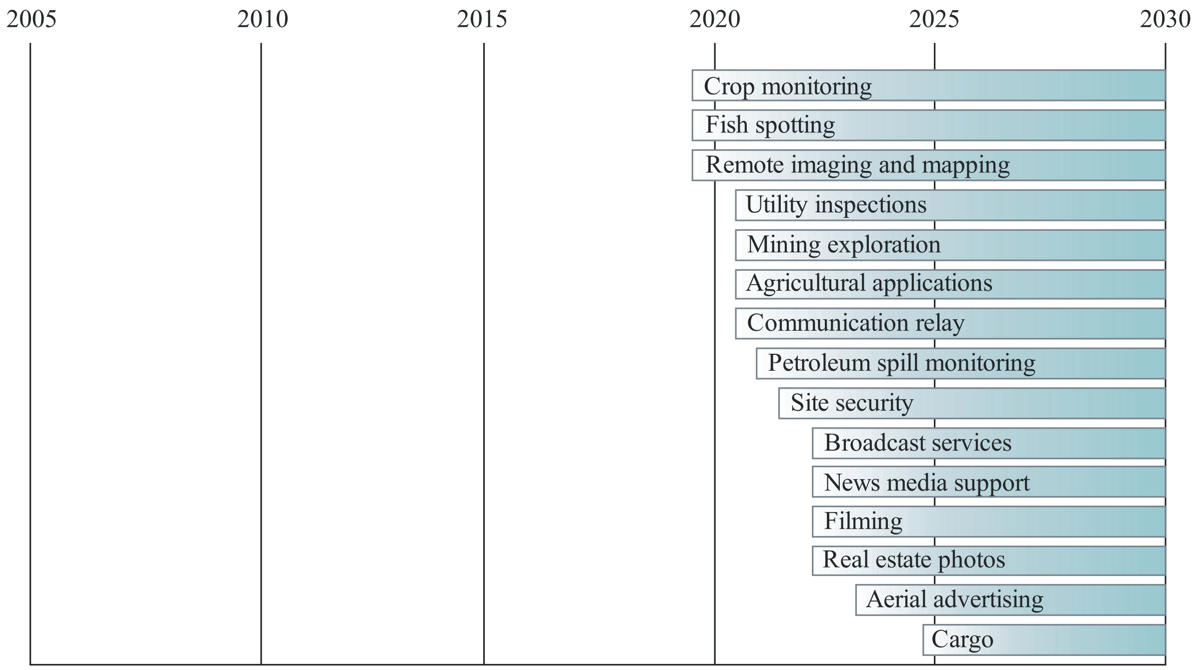
2.3.3 Commercial use segment

The greatest challenge facing commercial growth remains the establishment of standards and regulations that define system and operational requirements. Currently there exists no legal way to conduct commercial UAS operations. Lack of available spectrum will also severely impact growth in this use segment.

Depending on the eventual requirements imposed on UAS and their operators, the costs may, in many instances, be uncompetitive when compared to manned aircraft. However, there are likely to be cost reductions, technological maturity, and other innovations stemming from the government use segments that facilitate the emergence of a strong commercial use segment.

Potential commercial applications for UAS are illustrated in the following figure:

Potential commercial applications



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Primary factors affecting the growth of the commercial use segment include:

- promulgation of regulations for the certification and operation of UAS;
- proven technology and utility of UAS gained from Defense-government and government experience;
- established industry base;
- investor willingness to supply capital;
- potential cost reductions resulting from economies of scale;
- continued limited airspace access due to regulatory constraint;
- economic viability compared to manned aircraft;
- available spectrum for commercial use;
- lack of investment funds due to use segment uncertainties;
- high insurance liability costs;
- specific regulations restrictions can limit development and trade of UAS technology.

2.3.4 Example of quantity of UAS available to operate by 2030

Current government UAS inventory is mostly operating inside segregated airspace, however over the next decade more government UA will be used for training, transitioning from one segregated airspace to another, security/surveillance and support in emergency disaster relief. The following table assumes a continuance of government operation inside segregated airspace as well as the increased operation described in § 2.3.2 of this methodology.

Because unrestricted entry into non-segregated airspace is still some distance in the future predicting commercial UAS quantities is dependent on a number of factors that are not precisely predictable. This methodology predicts growth of the commercial use segment at the same rate as the government use segment which itself was and is manufacturing limited. This leads to an approximately similar quantity of commercial UA by the 2030 time-frame as government UA. It is also probably reasonable to assume that a similar ratio of small, medium and large UAS will emerge in the commercial use segment as is currently predicted for government use. Demand already exists for commercial operation, particularly in the small category of UAS. This is reflected in early slow growth of the small commercial use segment starting in 2010. The following table uses the previously reference sources as well as the above-described factors to predict the quantity of UAS that will be available for operation.

It is very clear from the above analysis that a significant demand exists for UAS operations and that there are a wide range of valuable missions that both government and commercial operators can perform. The UAS industry can support this demand with technology and manufacturing capability but growth could be constrained until regulations for commercial airworthiness certification exist and spectrum is available to support UAS control and communications. Even if regulations or spectrum availability are delayed the demand for the unique capabilities and benefits that UAS can provide will still exist so the total UAS quantities predicted above may be delayed but are unlikely to be diminished.

Cumulative total UA available for operation

YEAR (end)	Current	2010	2012	2014	2016	2018	2020	2022	2024	2026	2028	2030
Government small	78	230	287	821	2 980	3 993	4 143	4 343	4 343	4 343	4 343	4 343
Government medium	23	240	462	737	971	1 121	1 121	1 121	1 121	1 121	1 121	1 121
Government large	7	34	71	133	231	305	305	305	305	305	305	305
Commercial small	0	50	100	150	250	350	500	1 000	1 500	2 500	3 500	4 000
Commercial medium	0	0	0	0	0	0	150	300	450	600	750	900
Commercial large	0	0	0	0	0	0	25	50	75	100	125	150
Total small	78	280	387	971	3 230	4 343	4 643	5 343	5 843	6 843	7 843	8 343
Total medium	23	240	462	737	971	1 121	1 271	1 421	1 571	1 721	1 871	2 021
Total large	7	34	71	133	231	305	330	355	380	405	430	455
Total government	108	503	819	1 691	4 182	5 418	5 568	5 768	5 768	5 768	5 768	5 768
Total commercial	0	50	100	150	250	350	675	1 350	2 025	3 200	4 375	5 050
Total	108	553	919	1 841	4 432	5 768	6 243	7 118	7 793	8 968	10 143	10 818

2.4 Deployment and disposition of projected UAS population

The key factor needed to calculate the total bandwidth required to support UAS operation is the maximum number of aircraft that are in an area where they can interfere with each other if they simultaneously use the same frequency under the worst case deployment scenario (which will be discussed later in this section of this methodology) based on the operations described in § 2.2 of this methodology and the quantities available for operation described in § 2.3 of this methodology.

The UAS RF control link between the UACS and the UA can be supported by either a terrestrial LoS link or a satellite based BLoS link. So the analysis will need to be performed for both types of link. However, small and possibly some medium UA may not have the capability to support a satellite antenna or modem so this must also factor into the analysis.

From a terrestrial perspective, where propagation distance increases with altitude (at the altitudes being considered in this methodology) the distance between two UAS that can use the same frequency simultaneously will be determined by interference between two aircraft not between two ground control stations or between one UA and a control station controlling a second UA.

Satellite antenna footprints are designed to either cover a large geographic area (regional-beam) or a small geographic area (spot-beam). In the spot-beam case the satellite may support multiple spot-beams to provide wide geographic coverage. In either the regional-beam or spot-beam case the distance between two UAS that can use the same frequency simultaneously will be determined by them interfering in the satellite transponder, so all aircraft in the footprint of the satellite's antenna (regional-beam or spot-beam) must use different frequencies to operate simultaneously. In this deployment scenario the regional-beam is defined to cover 7 800 000 km^2 (3 000 000 square miles) and the spot-beam is defined to cover 480 000 km^2 (185 000 square miles). These coverage areas are typical for many mobile satellite and fixed satellite services systems footprints in use today.

2.4.1 Geographically uniform deployment scenario

Even though a Geographically uniform distribution of UAS may at first appear not to be representative of actual UAS use it is very unlikely that UAS will only fly in the airways and jetways currently used by manned aircraft. Many UAS operations will occur in geographic areas where no manned flights currently take place and so this methodology will focus on a homogeneous deployment scenario as being a good representation of UAS deployment and then discuss when higher densities might occur and if they impact the bandwidth required.

It is unlikely that small UA will fly at night and likewise a percentage of medium UA will also not be able to fly at night, due to equipment limitations, so daytime operation is assumed in this deployment scenario. Not all UA will fly everyday due to weather so the scenario also assumes clear weather in the area of the deployment. It is also assumed that the operations being performed are all maximizing the number of aircraft flying, as is typical the case of a government or commercial type operation. By 2030 there will also be enough UA available that there will be no time when the operation is not being supported; but a certain percentage of aircraft will be non-operational due to maintenance and repair and over sizing of the operator's fleet to ensure continuity of operation. This percentage of non-operational aircraft varies depending on the type of operation. This methodology assumes on average 25% of any fleet will be non-operational during the time (clear weather, daytime) when the deployment scenario is being evaluated. From § 2.8 of this methodology it was predicted that 8 343 small, 2 021 medium and 455 large UA would be available for operation by 2030. So on a clear day 75% of the UA available for operation would correspond to 6 257 small, 1 515 medium and 341 large UA.

This methodology uses an area of approximately 7 800 000 km^2 (3 000 000 square miles). So if it is assumed that all of the UA population is distributed evenly throughout this area this will result in a UA density of:

- Small – 0.0008031 UA/km^2 (0.00208 UA per square mile)
- Medium – 0.0001950 UA/km^2 (0.000505 UA per square mile)
- Large – 0.0000440 UA/km^2 (0.000114 per square mile).

Additional spectrum could be required by some UA for video transmission from the UA to the UACS for pilot situational awareness enhancement (N.B. this is not payload video). This video would be used during takeoff and landing, during weather avoidance and during collision avoidance manoeuvring.

Not all UA simultaneously operating will require this video all of the time. If it is assumed that UA would use this video while in the climb out phase of takeoff and while in the pattern preparing to land and during landing itself then the percentage of time each UA is in this phase of flight needs to be estimated. This total time is somewhat dependent on the category of UA but as a percentage of its endurance the figure is typically 19% for the LoS and 2.5% for BLoS taking into account the one using BLoS are equipped with additional equipment (e.g. navigation aids). This figure is based on analysis of over 70 responses to RTCA Special Committee 203's questionnaire sent to a large number of UA manufacturers and operators (*Guidance Material and Considerations for Unmanned Aircraft RTCA DO-304 March 2007 Appendix F*). The percentage of UA performing weather avoidance on the clear day in this deployment scenario and collision avoidance is significantly lower than the number taking off or landing so does not materially impact this percentage. However, not all UA will need to provide the pilot with situational awareness enhancement using video since they will operate almost autonomously.

The final factor required to calculate the total bandwidth required to support UAS operation is how many UA are flying in each phase of flight in the deployment scenario being analysed. See § 2.2.4.3 of this Annex for definitions of phases of flight. Because of the wide range of UA categories, capabilities and mission profiles it is not possible to define precise quantities of UA in each phase of flight. However, based again on the analysis of over 70 responses to RTCA Special Committee 203's questionnaire sent to a large number of UA manufacturers and operators (*Guidance Material and Considerations for Unmanned Aircraft RTCA DO-304 March 2007 Appendix F*) the average percentage of time spent in each phase of flight has been used to develop the following table:

Disposition of total number of UA interferers by phase of flight

UA QUANTITY PER PHASE OF FLIGHT					
	Pre-flight	**Terminal departure**	**En-route**	**Terminal arrival**	**Post-flight**
Percentage of time in phase	**4%**	**8%**	**76%**	**11%**	**1%**

2.4.2 Non-geographically uniform deployment scenarios

The analysis in the previous section assumed a homogeneous distribution of UA. In case of disaster support and search and rescue as well as takeoff and landing at airports the quantity of UA in a particular area is higher and accordingly the associated spectrum requirement could be larger.

As an example, statistics of the hurricane Katrina which occurred in 2005, show that at a peak approximately 400 helicopters were operating in an area 480 by 480 km (300 by 300 miles) rescuing over 33 000 people in a period of approximately eight days. This equates to 0.0017 helicopters/km^2 (0.0043 helicopters per square mile), near 3 times the density of small UA calculated for the geographically uniform distribution scenario in § 2.4.1 of this methodology. It is certainly conceivable that under similar circumstances at least one or two small UA could be assigned to support and provide direction for each helicopter or could be used instead of helicopters for rapid and continuous search operations. Taking this analysis to an extreme where each small UA is operating inside a circle whose radius is equivalent to its operation range (visual LoS from the UACS for small UA is 3.2 km (2 miles) see UA Category table in § 2.2.5 of this annex) and that adjacent small UA are spaced on 6.4 km (4 miles) centres, to give contiguous coverage of the search area, then the density of small UA could rise to 0.024 small UA/km^2 (0.0625 small UA per square mile). This density is approximately thirty times more than the density for the geographically uniform distribution scenario. However this density may not occur due to the limited availability of qualified UA pilots. Using a similar analysis for the medium and large UA where the UA are separated such that their operating areas are arranged in a uniform grid whose size is equivalent to their operating range yields significantly lower densities than the geographically uniform distribution scenario. Even if the UA are flown closer together to provide high density surveillance the number of medium and large UA per square mile will not exceed the geographically uniform distribution scenario until the aircraft spacing becomes less than 65 km (40 miles) for a medium and 153 km (95 miles) for a large UA. Using the helicopter statistics from the hurricane used in this example the average helicopter separation was approximately 24 km (15 miles) so using this spacing the number of medium UA would increase to 0.0017/km^2 (0.0043 per square mile) approximately ten times more than the geographically uniform distribution scenario with a corresponding increase in spectrum required to support them. It is unlikely that large UA will be flown in this close proximity to each other as their manoeuvrability compared to helicopters is significantly less, requiring larger separations for safe operation other than during more orderly flight, such as during takeoff and landing.

This methodology assumed that by 2030 not all of the airports will be equipped to support UAS operation. Assuming approximately 100 airports will be equipped for medium and large UA operations and that small UA will operate from non-ATC participating surface locations then the average number of UA based at each airport will be approximately 15 medium and 4 large (based on the 1 515 medium and 341 large UA predicted to be available for operation).

Based on the UA quantity per phase of flight table in this methodology the percentage of aircraft operating in the terminal departure and terminal arrival phases of flight is 19% (8% departure, 11% arrival). Using the average number UA per airport calculated above these results in approximately three medium and just less than one large UA being in these phases of flight at any one time. Assuming these four aircraft are all concentrated in the takeoff and landing patterns in close vicinity of the airport, within 8 km (5 miles) radius from the runway, results in a UA density of 0.019 UA/km^2 (0.05 UA per square mile).

If there are 100 UA ready airports equally distributed throughout the area used in this methodology then they will be separated by approximately 278 km (173 miles). This distance exceeds the RF interference radii of the aircraft at the altitudes associated with takeoff and landing so airports are effectively isolated from each other. So the number of UA/km^2 calculated above will not persist outside the airport 8 km (5 miles) radius takeoff and landing area. In consequence takeoff and landing operations will not require more than approximately four additional channels in the overall spectrum assessment. Even if more airports are equipped to support UA operations the number of aircraft per airport will be reduced (since the total quantity of UA is fixed). The density of UA in takeoff and landing exceed the density for the geographically uniform distribution scenario once the number of airports equipped for UA operations approaches 6 000.

In summary the most spectrally demanding non-geographically uniform deployment scenario is associated with small and medium UA performing high density surveillance operations. However, it is unrealistic to expect these UA densities to exist over very large geographic areas due to other logistical and operational constraints. If the overall area of high density surveillance is reduced to more typical areas of only a few km in radius then this additional local capacity increase can be easily accommodated by limiting or stopping UAS operations outside the area of intense activity for the temporary period of these high density surveillance activities.

From an airport takeoff and landing perspective even if UA are operated in large quantities from single airports the demand for spectrum will still be low until UAS certified airports are close together and then it is unlikely that the UA volumes will be high at all airports within a neighbourhood since the total number of UA available to operate is bounded.

This methodology concludes that the number of UA/km^2 predicated in the geographically uniform distribution scenario be used to assess the aggregate bandwidth requirement to support UAS operation. These values are recalled in the table below:

			UA		
			Small	Medium	Large
UA in operation by 2030			8343	2021	455
		%	75%		
Density of UA/km^2	Low altitude	< 300 m	0.000803	–	–
	Medium altitude	300-5 500 m	–	0.000195	–
	High altitude	> 5 500 m	–	–	0.000044
LoS scenario			Based on above densities		
BLoS scenario (spot-beam)		Per spot	385	93	21
BLoS scenario (single regional-beam)		Total	0	1515	341

Annex 3

Aggregate bandwidth requirements for command and control, for support of sense and avoid, and ATC relay of unmanned aircraft

1 Methodology 1

1.1 General description of the approach

For the purpose of assessing spectrum requirement, six phases of UA operations are considered. These phases are:

- Taxiing
- Takeoff
- Initial climb
- Cruise/en-route
- Approach
- Landing.

It is noted that some UA may not use all these phases of flight.

For each phase of flight the methodology for assessing the spectrum requirement has four main steps:

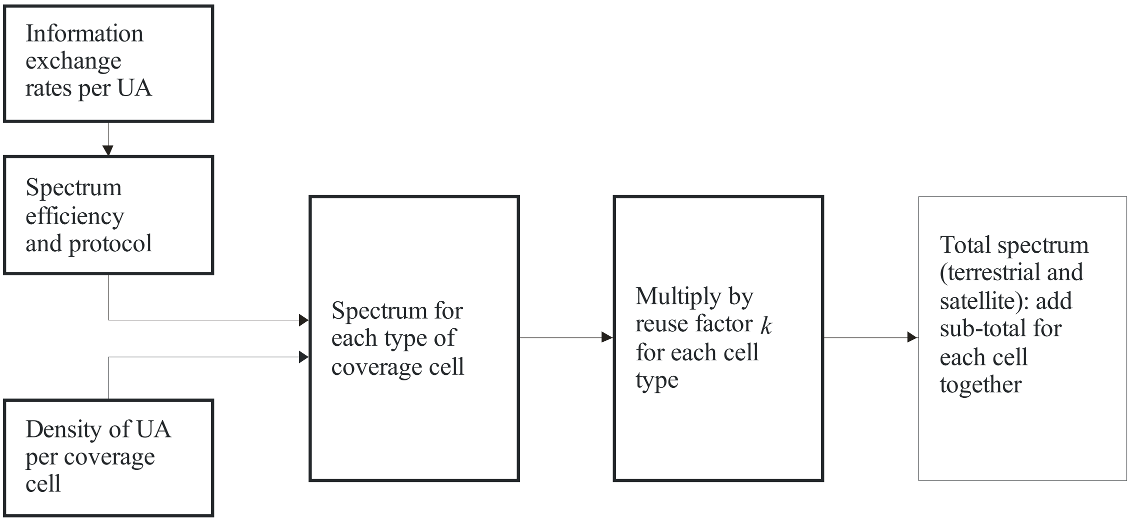
Step 1: From the estimated information exchange rate, calculate the spectrum required for a single UA.

Step 2: From the estimated density of UA in each type of coverage cell, calculate the per-cell spectrum requirement using (1).

Step 3: Calculate the re-use factor for each type of coverage cell.

Step 4: Use (2) and (3) to estimate the sub-total spectrum required for each cell type, and add sub-totals together to determine the total spectrum required (terrestrial and satellite).

Spectrum for each type of coverage cell



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1.2 Redundancy factor, utilization factor and system wide frequency assignment efficiency

The aggregate bandwidth requirement *W* (kHz) of any of the first three classes of traffic can be expressed as:

$$W = K\,B\,M\,R\,/\,(U\,E)$$

where:

K: the cellular network frequency reuse factor

B: the data rate requirement (kbit/s) of a single UA for this class of traffic (see Annex 1)

M: the number UA per cell or spot.

R is a redundancy factor (≥ 1) to allow for spectrum needed by dual and/or backup links. ($R = 1$ if there are no dual or backup links. $R = 2$ in a "dual-link" system where every primary link has a dedicated backup. If primary links share backups, then $1 < R < 2$).

U is the utilization factor. This is a margin factor (≤ 1) applied to each class of communications traffic to ensure that adequate bandwidth is available for the entire system to accommodate temporary traffic surges.. For example in a packetized system, *U* must be significantly less than 1 to enable the system to handle fluctuations in levels of traffic without introducing excessive delays. Short latency values require relatively low values of *U* (and hence wider RF channels to enable those lower *U* values).

E is the spectral efficiency (bit/s/Hz) of 0.75 for all data types. This level of spectral efficiency is feasible for a robust modulation scheme. As an example in VDL3, a time-division multiple access (TDMA) system, a single 25-kHz radio-frequency (RF) channel can carry a maximum of four

4 800-bit/s voice circuits on separate time slots. This gives a spectral efficiency of (0.768=4*4 800/25 000). Hence we assume that a spectral efficiency of 0.75 is possible for the voice relay link as well as for all the other links. Larger values of *E* may be feasible for satellite systems.

Terrestrial	**C2**	**ATC relay**	**S&A low latency**	**S&A medium latency**	**Video/weather radar**
R	2	2	2	1.5	1
U	0.5	1	0.5	0.75	1
E (bit/s/Hz)	0.75	0.75	0.75	0.75	0.75
Ratio R/UE	5.33	2.66	5.33	2.66	1.33

Satellite	**C2**	**ATC relay**	**S&A low latency**	**S&A medium latency**	**Video/weather radar**
R	2	2	2	1.5	1
U	1	1	1	1	1
E (bit/s/Hz)	0.75	0.75	0.75	0.75	0.75
Ratio R/UE	2.66	2.66	2.66	2	1.33

1.3 Reuse factor

1.3.1 Terrestrial

In order to determine the most efficient reuse factor (*k*) for each type of cell, the following iterative process must be applied:

- Starting with a high *k* factor (e.g. 12) calculate the Edge-of-Cell (EOC)-to-EOC distance (Du).

$$D_u = R_C\sqrt{3.K} - 2R_C = R_c(\sqrt{3.K} - 1)$$

- Calculate the radio horizon (R_H) associated with operation at maximum altitude within the cell.

$$R_H = 4.130 \times \sqrt{h(\text{m})} \qquad \text{km}$$

- If the EOC-to-EOC plus cell radius (Rc) distance is greater than the radio horizon, the *k* factor may be reduced to the next available integer value (see table below), and the process re-starts.

  The available K are determined by the following equation:

$$K = i^2 + ij + j^2 \qquad \text{with } i,j \in N$$

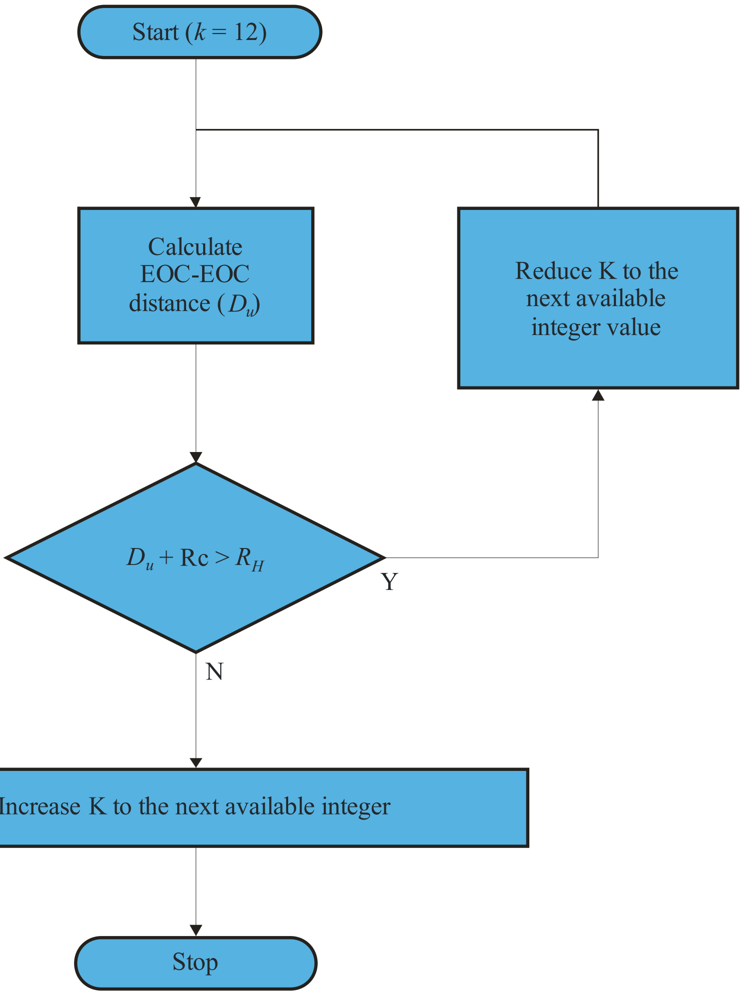
  Therefore the following table gives the possible value of *k*.

Reuse pattern (*k*)	1 ($i = 1, j = 0$)	3 ($i = 1, j = 1$)	4 ($i = 2, j = 0$)	7 ($i = 2, j = 1$)	9 ($i = 3, j = 0$)	12 ($i = 2, j = 2$)	13 ($i = 3, j = 1$)

- If the EOC-to-EOC plus cell radius (Rc) distance is less than the radio horizon, the *k* factor must be increased to the next available integer.

– The current *k* factor can be applied.

– This process can be summarized with the following flowchart:



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Results of K factor calculation

For cell A:

	$D_u + Rc$ (km)	R_H (km)	$D_u + Rc > R_H$
K = 12	324	160	Yes
K = 9	272	160	Yes
K = 7	232	160	Yes
K = 4	160	160	No

For cell B:

	$D_u + Rc$ (km)	R_H (km)	$D_u + Rc > R_H$
K = 4	388	320	Yes
K = 3	315170	320	No

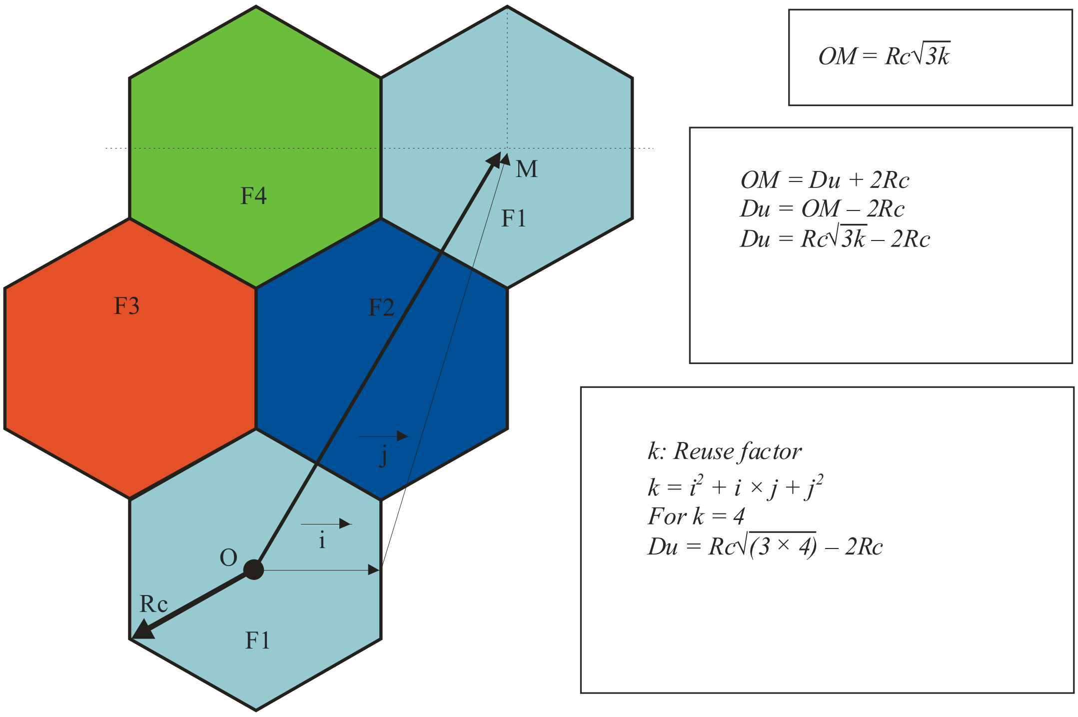
For cell C:

	$D_u + Rc$ (km)	R_H (km)	$D_u + Rc > R_H$
K = 3	630	480	Yes
K = 1	230.5	480	No

For cell D :

	$D_u + Rc$ (km)	R_H (km)	$D_u + Rc > R_H$
K = 3	698	640	Yes
K = 1	352	640	No

Cell planning: An example with a reuse factor $k = 4$



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Networked cells

For the networked cells (Type C, D, E and F) the process gives frequency reuse patterns as follows:

Cell Type	Cell radius (km)	Cell altitude (m)	R_H (km)	K applied	Reuse distance (km)	EOC-to-EOC distance (km)
A	65	0-1 500	160	**7**	298	168
B	157	1 500-6 000 (FL195)	320	**4**	544	230
C	315	6 000-13 500 (FL450)	480	**3**	945	315
D	480	13 500-24 000	640	**3**	1 440	480

1.3.2 Satellite

A reuse factor K of 4 is used for the satellite case (spot type E).

1.4 Results of the aggregate spectrum requirement

Two different links are needed for terrestrial communications:

- From UA to UACS (for all communications including video)
- From UACS to UA (for all communications).

Four different links are needed for satellite communications:

- From UA to satellite (for all communications including video)
- From satellite to UACS (for all communications including video)
- From UACS to satellite (for all communications)
- From satellite to UA (for all communications).

Spectrum requirements for terrestrial infrastructure without video/weather radar

Cell Type	Number of UA per cell M	Frequency reuse factor K	B.R/UE (kHz)	Spectrum needs = M.B.K.R/UE (MHz)
At surface	3	1	127.4	0.38
A	5	7	127.4	4.46
B	12	4	89.5	4.30
C	20	3	89.5	5.37
D	5	3	89.5	1.34
Total				**15.9**

Spectrum requirements for terrestrial infrastructure with video/weather radar

Cell Type	Number of UA per cell M	Frequency reuse factor K	B.R/UE (kHz)	Spectrum needs = M.B.K. R/UE (MHz)
At surface	3	1	486.2	1.46
A	5	7	486.2	17.02
B	12	4	125.3	6.01
C	20	3	125.3	7.52
D	5	3	125.3	1.88
Total				**33.9**

Spectrum requirements for satellite infrastructure without video/weather radar

Spot Type	Number of UA per spot M	Frequency reuse factor K	B.R/UE (kHz)	Spectrum needs = M.B.K. R/UE (MHz)
E	106	4	60.6	25.7

From the infrastructure point of view (satellite needs 4 links compared with terrestrial, which needs 2 links) the spectrum requirement for satellite infrastructure except video is 51.4 MHz.

Spectrum requirements for satellite infrastructure with video/weather radar

Cell Type	Number of UA per cell M	Frequency reuse factor K	B.R/UE (kHz)	Spectrum needs = M.B.K. R/UE (MHz)
E	106	4	96.6	40.95

As the satellite infrastructure needs 2 links compared to 1 for the terrestrial infrastructure, the satellite spectrum requirement with video is 81.9 MHz

75% of UA flying in the medium or high altitude is assumed to be equipped with BLoS capability among which 25% are considered to use their LoS capability. Therefore an additional ratio of 0.56 should be applied to satellite needs.

The following table provides the UAS spectrum needs summary:

	Except video/ weather radar	Video/weather radar only	Total
Terrestrial needs (MHz)	15.9	18.1	34
Satellite needs (MHz)	29	17	46

The terrestrial spectrum requirements are divided as follows:

– UACS to UA = 4.6 MHz

– UA to UACS = 29.4 MHz.

The satellite spectrum requirements are divided as follows:

– UA to SAT = 18.9 MHz

– UACS to SAT = 4.1 MHz

– SAT to UA = 4.1 MHz

– SAT to UACS = 18.9 MHz.

Appendix 1
to Methodology 1

Coverage cells

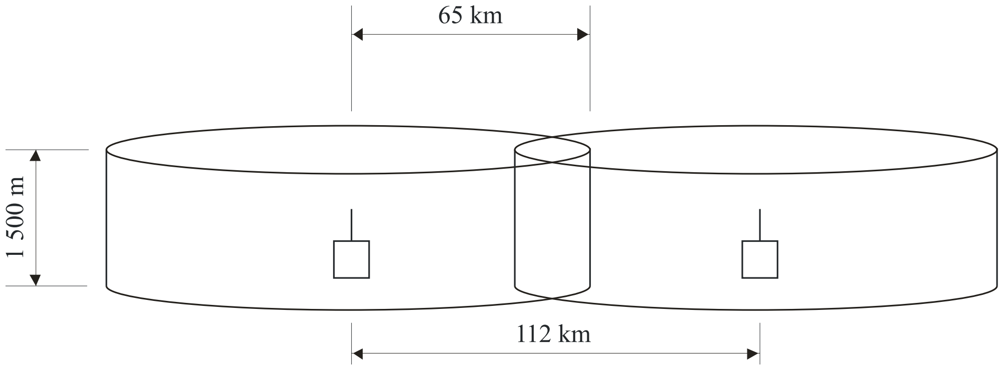
For the purpose of this exercise, 5 types of coverage cell assumed. These can provide coverage to UA operating at different altitudes ranging from the surface to FL800 (approximately 24 000 m) to meet the wide range of UAS applications that are expected to evolve. The coverage cells are defined in terms of radius and altitude range. The upper altitude range is necessary to minimize the frequency re-use factor (k) that has to be applied to overcome adjacent cell interference received by elevated platforms.

The types of airspace cell used within this process are defined in the following sections:

Cell Type “A”

This type of cell is intended to cater for UA that may be operating below 1 500 m. These UA are most likely to be en-route, engaged in a task (e.g. surveying), departure flight phase or arrival flight phase.

To ensure LoS coverage at minimum operating heights of 300 m, the UA must never be more than 70 km from a base station. It shall be assumed therefore that these cells shall have a radius of 65 km and shall be spaced 112 km apart.



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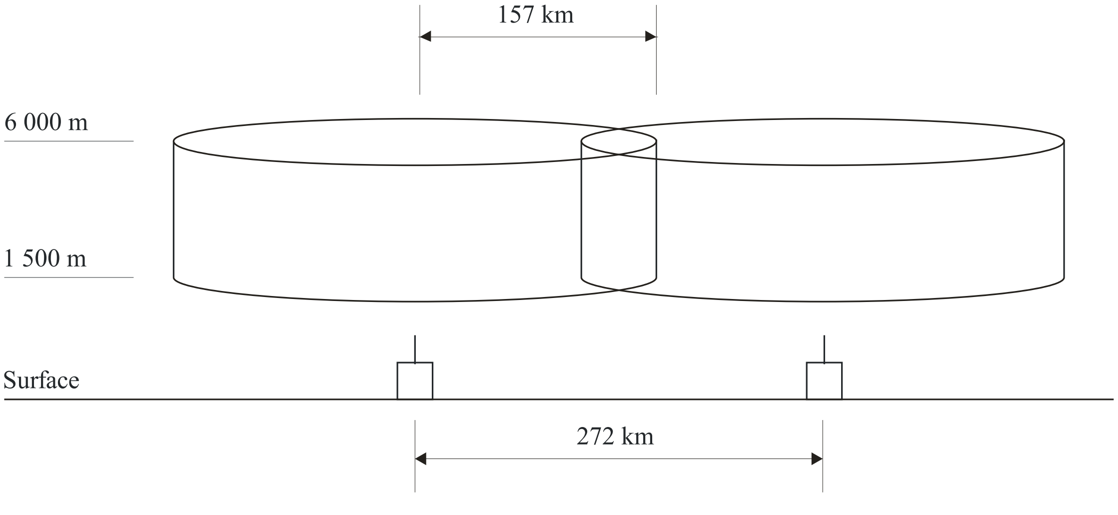
Cell Type “B”

This type of cell is intended to cater for UA operating in the height range 1 500 m to flight level 195 (FL195) (approximately 6 000 m). The UA in this height band will most likely be in an en-route phase of flight.

To ensure LoS coverage at minimum operating heights of 1 500 m, the UA must never be more than 160 km from a base station. It shall be assumed therefore that these cells shall have a radius of 157 km and shall be spaced 272 km apart.



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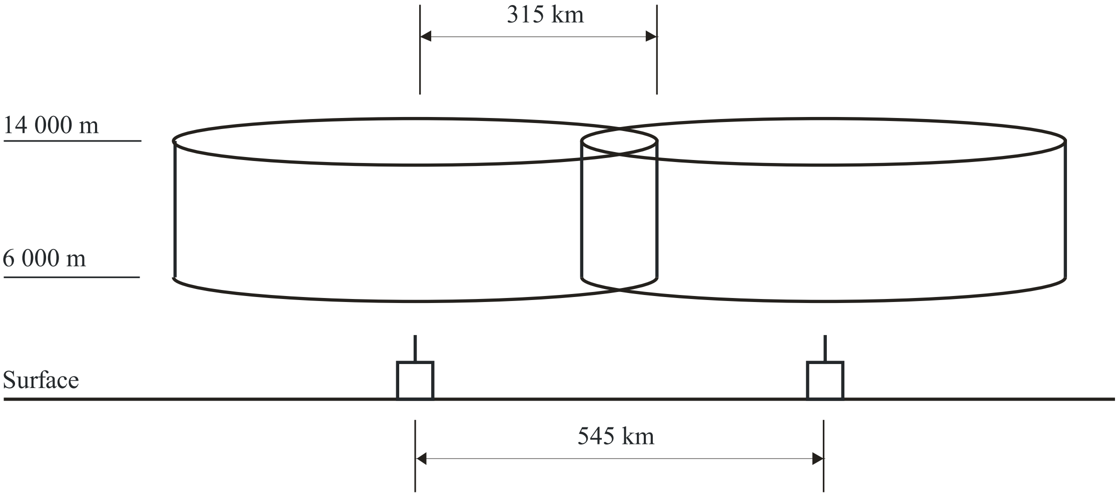
Cell Type "C"

This type of cell is intended to cater for UA operating in the altitude range FL195 to FL450 (approximately from 6 000 m to 14 000 m). The UA in this height band will most likely be in an en-route phase of flight.

To ensure LoS coverage at minimum operating heights of 6 000 m, the UA must never be more than 320 km from a base station. It shall be assumed therefore that these cells shall have a radius of 315 km and shall be spaced 545 km apart.



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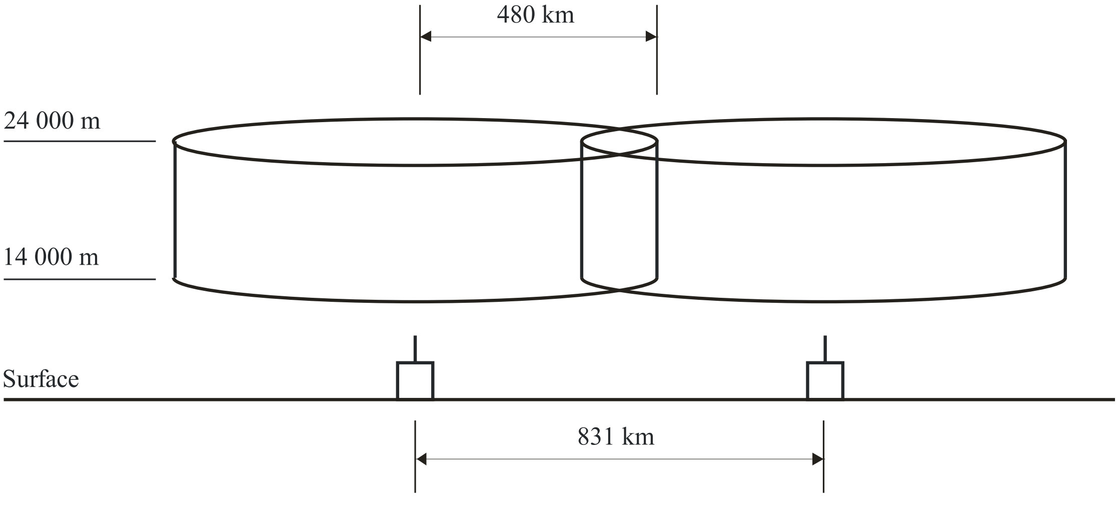
Cell Type "D"

This type of cell is intended to cater for high altitude UA operating above the normal air routes at altitudes of between FL450 and FL800 (approximately between 14 000 m and 24 000 m). The UA in this height band will most likely be used as a high altitude platform, or to perform scientific/environmental research.

To ensure LoS coverage at minimum operating heights of 12 000 m, the UA must never be more than 480 km from a base station. It shall be assumed therefore that these cells shall have a radius of 480 km and shall be spaced 831 km apart.



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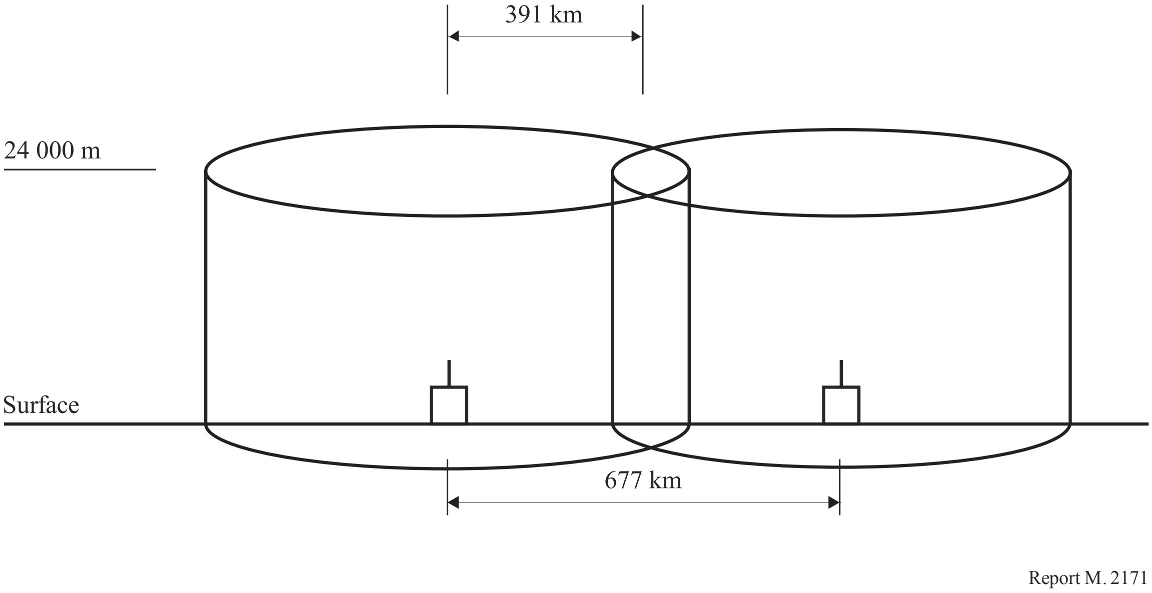
Spot Type "E" – Satellite using spot-beam

This type of spot is intended to cater for all altitude UA operation (0 to 24 000 m).



1 Methodology 2

1.1 Introduction

The CNPC loading, throughput and bandwidth requirements of a single generic unmanned aircraft (UA) in 2030 were analysed in Annex 1. The present analysis provides estimates of the aggregate bandwidth requirements of all UAS operating in U.S. airspace and requiring the use of protected aeronautical spectrum in the same time-frame. These results will support the objectives of ITU-R's WP 5B work plan for studies required for WRC-12 Agenda item 1.3.

This analysis, like Annex 1 to this report, deals only with requirements for non-payload information flow between UACS and the UA they are controlling. The bandwidth will be needed for the telecommand uplinks, the non-payload telemetry downlinks, and the relay of navigational data, non-payload surveillance data, ATC voice messages, and air traffic services (ATS) data between each UA and the UACS. The bandwidth needs of the navigation, surveillance, and ATS systems themselves, as opposed to the UACS/UA relay requirements, are outside the scope of this paper and not considered here.

Table 34, except for its last three rows, has been extracted from Annex 1. It summarizes the estimated CNPC throughput requirements of a fully equipped generic UA in 2030 for each of seven traffic classes: control data, NavAid data, ATC voice relay, ATS data relay, target tracks, airborne weather radar data, and non-payload video.

The new "weighted average" rows have been added to give an indication of average throughput requirements over a typical UA flight. Those rows take into account the relative durations of operational phases and show separate results for manual and automatic modes of UA operation. In this analysis, manual operation means the pilot is steering and orienting the UA by exercising direct control, via the control link, of the UA's ailerons and other control surfaces. Automatic operation means the pilot is exercising indirect control by means of waypoints and/or course and altitude commands, which the UA's onboard processor then converts into signals that cause the control surfaces to respond in a manner that achieves the desired result.

The "overall average" row shows the weighted averages for manual and automatic operation combined. The overall averages are based on the assumption that in every flight phase, 80 per cent of all UAS operation in the area under consideration in 2030 will be automatic and 20% will be manual. This assumption affects only the values for command and control, since the throughputs for the other traffic classes are independent of whether operation is automatic or manual.

Like its counterpart in Annex 1, Table 34 lacks a "Totals" column because, if the throughput requirements of all traffic classes were lumped together in such a column, it would tend to exaggerate the relative significance of the intermittently operating non-payload video downlinks in determining overall bandwidth requirements.

TABLE 34

Estimated non-payload throughput requirements (bit/s) of a single UA

Operational phase[1]	**Relative phase duration (percent-age of total)**[2]	**Mode**	**Non-payload communications throughput (bit/s)**[3], [4]									
			Command and control				**ATC relay**			**Sense and avoid**		
			Control		**NavAids**		**ATC voice relay**[5]	**ATS data relay**		**Target tracks**[6]	**Airborne weather radar**	**Video**[7]
			UL	**DL**	**UL**	**DL**		**UL**	**DL**	**DL**		
Pre-flight	4	M	*183*	*5*	0	0	4 800	*113*	*173*	9 120	0	0
Terminal (departure)	8	M	2 386	5 715	669	836	4 800	*49*	*59*	9 120	27 771	270 000
		A	775	912	141	186	4 800	*49*	*59*	9 120	27 771	270 000
En route	76	M	1 201	2 356	669	836	4 800	*23*	*28*	9 120	3 968	270 000
		A	289	532	141	186	4 800	*23*	*28*	9 120	3 968	270 000
Terminal (arrival)	11	M	4 606	7 615	669	1 140	4 800	*16*	*32*	9 120	27 771	270 000
		A	1 246	1 277	141	234	4 800	*16*	*32*	9 120	27 771	270 000
Post-flight	1	M	*1*	*2*	0	0	4 800	*15*	*22*	0	0	0
Weighted average of flight phases[8]		M	*1 695*	*3 248*	*669*	*871*	4 800	*24*	*31*	9 120	8 729	270 000
		A	*441*	*650*	*141*	*192*	4 800	*24*	*31*	9 120	8 729	270 000
Overall average[8], [9] 0.8A + 0.2M			*692*	*1 170*	*247*	*328*	4 800	*24*	*31*	9 120	8 729	270 000

[1] Pre-flight and post-flight phases do not include taxiing.

[2] Average assumed total duration of all phases = 4 h.

[3] Overhead as well as content bits are considered for all classes of traffic.

[4] Loading values in *italics* depend on assumed phase durations.

[5] Not necessarily needed in all scenarios or potential system architectures.

[6] 60 tracks assumed.

[7] Video needed only intermittently.

[8] Pre- and post-flight phases excluded.

[9] Automatic operation assumed to be in effect 80% of the time in all flight phases; manual operation, 20%.

Abbreviations:

M: Manual operation, A: Automatic operation, UL: Uplink, DL: Downlink.

For each of the seven traffic classes, this methodology provides aggregate bandwidth estimates for each of the three alternative system implementations discussed in Annex 2 to this report for CNPC coverage of the area under consideration:

1 A LoS terrestrial system serving all UA classes (large, medium, and small).

2 A BLoS spot-beam satellite system serving all UA classes.

3 A BLoS satellite system using a single regional-coverage beam to serve medium and large UA (but not small UA, which cannot carry the necessary satellite terminals).

The estimated bandwidths derived in this methodology are based upon the geographically uniform UA deployment scenario presented in Annex 2 to this report. Table 35 presents the key parameters of that scenario. For simplicity, the scenario postulates three separate types of UA flying above the area under consideration in 2030: large UA at an altitude of 9 144 m (30 000 feet) above ground level (AGL), medium UA at 5 486 m (18 000 feet) AGL, and small UA at 305 m (1 000 feet) AGL. Each UA class is assumed to be uniformly distributed across this area with the geographical densities shown in the table. If they were arranged in a quasi-hexagonal array, the UA in each of the three classes would be separated from their nearest neighbours of the same class by the average spacing shown for that class in the table.

TABLE 35

Geographically uniform UA deployment scenario

UA Type	**Postulated characteristics**		
	Altitude (m) AGL	**Geographical density (UA/km^2)**	**Average spacing between nearest neighbours (km)**
Large	9 144	0.0000440	161.9
Medium	5 486	0.0001950	76.9
Small	305	0.0008031	38.0

Individual UA on board equipment is not stipulated in Annex 2 to this report, but in the present analysis it is necessary to consider the fact that not all UA will be equipped or required to carry every class of traffic in protected aeronautical spectrum. A summary of assumed on board equipment statistics for each UA type appears in Table 36.

TABLE 36

Postulated on board equipment of each UA type

Functional category	**Traffic class**	**Assumed percentage of each UA type equipped to participate in this traffic class in protected aeronautical safety spectrum**		
		Large	**Medium**	**Small**
Command and control	Control data	100	100	50
	NavAid data	100	50	0
ATC relay	ATC voice relay	100	75	0
	ATS data relay	100	75	0

TABLE 36 (*end*)

Functional category	Traffic class	Assumed percentage of each UA type equipped to participate in this traffic class in protected aeronautical safety spectrum		
		Large	**Medium**	**Small**
Sense and avoid	Target tracks	100	100	0
	Airborne weather radar data	100	0	0
	Non-payload video	100	100	0

As indicated in Table 36, every large UA is assumed to be fully equipped and thus capable of participating in every class of traffic. However, only 50% of the medium UA will be assumed to have selectable (non-GPS) navigation receivers that would require the significant throughputs identified in the "NavAids" columns of Table 34. Only 75% of the medium UA are assumed to have a need for ATC/UACS communication requiring the use of the UA as an ATC relay. All of the medium UA are assumed to be exchanging target track data and to be equipped with non-payload video for safety purposes, but none of them are assumed to be flying high enough and far enough from their control stations to need onboard weather radars.

Every UA must be equipped to carry UACS/UA control data, but it is assumed here that only 50% of the small-UA control links will be operating in protected aeronautical safety spectrum. The other half of the small-UA control links are assumed to be operating in industrial, scientific and medical (ISM) or other unprotected bands, making their bandwidth requirements irrelevant to the aggregate estimates discussed in this methodology. Finally, it is assumed that small UA will not be equipped to participate in any of the other traffic classes, at least not in protected aeronautical bands.

1.2 Aggregate bandwidth requirements of a LoS terrestrial system

Since the seven classes of CNPC traffic have substantially different requirements for latency, redundancy and other relevant operational parameters, their bandwidth requirements must be computed separately. The aggregate nationwide bandwidth requirement W (MHz) of any given class of traffic in a LoS terrestrial system may be expressed as:

$$W = V\,M/E \qquad \text{MHz} \tag{1}$$

where:

V is a link bandwidth factor defined as:

$$V = 0.001\ T\,F\,R/(U\,S) \qquad \text{MHz} \tag{2}$$

T is the throughput requirement (kbit/s) of a single UA for the traffic class in question. This is the "overall average" value shown in Table 34 for this traffic class. Where uplink and downlink values are shown separately, T is their sum.

F is the average fraction of the subset of UA equipped to participate in this traffic class which is actually participating at a given time during flight. This is assumed to be 1 for all traffic classes except for video downlinks, which are assumed (as postulated in Annex 2) to be sharing a bandwidth-on-demand system with $F = 0.19$.

R is a redundancy factor (≥ 1) to allow for spectrum needed by dual and/or backup links. $R = 1$ if there are no dual or backup links. $R = 2$ in a "dual-link" system where every primary link has a dedicated backup. In this analysis, R is assumed to be 2 for all traffic classes except airborne weather-radar data and video, for which $R = 1$.

U is the utilization factor. This is a margin factor ($\leq$ 1)applied to each class of communications traffic to ensure that adequate bandwidth is available for the entire system to accommodate temporary traffic surges. Short latency times require relatively low values of *U*, and hence wider RF channels to enable those lower *U* values. For packetized data (i.e. control and NavAid data, ATS data relay, and target tracks), *U* must be significantly less than 1 to enable the system to handle fluctuations in levels of traffic without introducing excessive delays. *U* should also be less than 1 for video downlinks, to allow for occasions when larger-than-average numbers of UA in a given area may need to use their video downlinks simultaneously. Since ATC voice relay links must provide guaranteed immediate access to the air traffic controller, each voice channel must always be available for use as if it were fully loaded, and so $U = 1$ for that class of traffic. Weather-radar downlinks are assumed to operate continuously and so $U = 1$ for that traffic class as well.

S is the link spectral efficiency (kbit/s/kHz) achievable for this class of traffic. For data, this is assumed to be 1.0, a value that is feasible for a robust modulation scheme such as quadrature phase-shift keying (QPSK) with a 3/4 FEC coding rate and a *S*/*N* ratio of at least 8 dB. For ATC voice relay a value of 0.5 is conservatively assumed, to ensure that enough bandwidth will be available to maintain stringent ATC latency and voice-quality requirements in the face of potential degradation introduced by the additional hop between the UA and the UACS.

Table 37 shows the assumed parameters and the calculated values of the link bandwidth factor *V* for each class of traffic. These values are indicative of the bandwidth needed by each equipped UA to carry each of the seven CNPC traffic classes.

TABLE 37

Calculation of link bandwidth factor for each traffic class

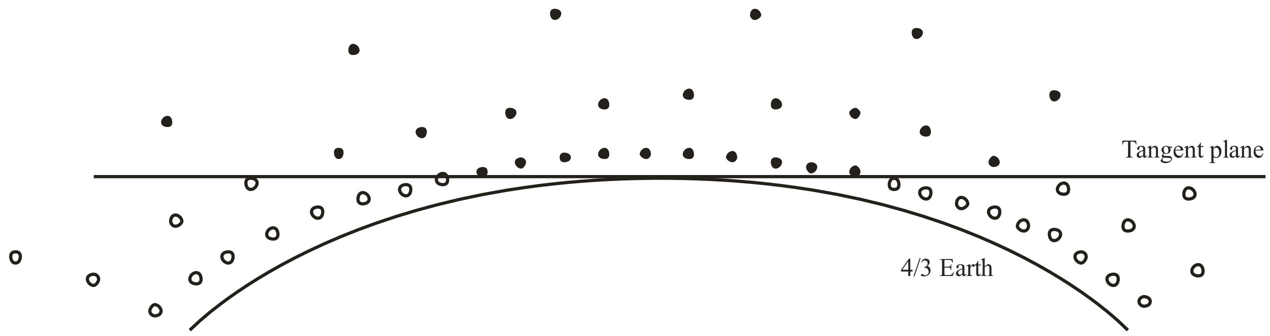
Traffic class	**Through-put *T* (kbit/s)**	**Average fraction (*F*) of equipped UA participating simultaneously**	**Redun-dancy factor *R***	**Utilization factor *U***	**Link spectral efficiency *S* (kbit/s/kHz)**	**Link bandwidth factor *V* = 0.001 *TFR/US* (MHz)**
Control data	1.862	1.000	2	0.5	1.0	0.007448
NavAid data	0.575	1.000	2	0.5	1.0	0.002300
ATC voice relay	4.800	1.000	2	1.0	0.5	0.019200
ATS data relay	0.055	1.000	2	0.5	1.0	0.000220
Target tracks	9.120	1.000	2	0.5	1.0	0.036480
Weather radar data	8.729	1.000	1	1.0	1.0	0.008729
Non-payload video	270.000	0.19	1	0.5	1.0	0.102600

Two other factors that were introduced in equation (1), *M* and *E*, are also needed to ascertain the aggregate bandwidth requirements of the nationwide system.

M is the largest number of mutually visible UA (each with a LoS to all the others) equipped for a given class of traffic. This constitutes a lower bound on the number of channels needed to prevent co-channel interference (CCI) among the equipped UA. Figure 7 illustrates the physical significance of *M*. Each dot in the Fig. 7 represents a UA. If an imaginary geometrical plane (shown edge-on in the figure) is placed tangent to any point on a standard 4/3 Earth, then a direct radio LoS exists between every pair of UA above the plane. The *M* UA above the plane (shown in the figure as black dots) thus constitute a mutually visible subset of UA, no two of whose members can use the same radio channel without risking mutual CCI. UA below the tangent plane, shown as white dots, do not belong to the subset, since any given UA below the plane is invisible to at least some of the UA above the plane. Thus any UA below the plane may be able to reuse a channel being used by one of the *M* UA in the subset. It can also potentially reuse a channel used by any non-member of the subset, if that non-member happens to be hidden from the UA in question. Note that the separate groups of white dots at the left and right sides of Fig. 1 are hidden from each other, so the groups of UA they represent may be able to share channels.

FIGURE 7

Mutually visible UA above a 4/3 Earth



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Ideally, a system could operate free of CCI by efficiently reusing the *M* channels needed by its largest mutually visible subset. If such an optimal frequency plan could be devised, the system could be said to have a system-wide frequency-assignment efficiency (*E*) of 1. However, no practical technique currently exists for developing truly optimal frequency plans for large deployments of mobile radios. In practice, *E* must always be less than 1 except for sparse UA deployments in which *M* is quite small.

An automated frequency-planning tool has been used to estimate *M* and *E* for each of the seven traffic classes in the uniform deployment scenario postulated in Annex 2 and described in Table 35 of this methodology. The deployment was simulated by setting up a database in which the nationwide population of each UA class (large, medium, and small) was arranged in a quasi-hexagonal array, each hexagon containing a UACS and a single UA free to roam at the specified altitude throughout a circle circumscribing the hexagon. Each array of hexagons covered virtually all of the considered area and certain adjacent areas.

The simulation for each traffic class took into account the postulated percentage of on board equipment shown in Table 36. If only 50% of a given UA class were equipped to carry a given class of traffic, every other UA in that class was deleted from the database. If 75% were equipped, every fourth UA was deleted. In each case, the deletions were distributed as uniformly as possible in order to preserve the overall geographical uniformity of the deployment scenario.

Using the assumption of a standard 4/3 Earth, and taking UA altitudes into account, the simulation tool ascertained which roaming circles in this scenario have mutual direct radio LoS. The tool was then used to identify a quasi-maximal subset of UA, each of whose *M* members were at least partially visible to all of the *M* – 1 others. This value of *M* constitutes a lower bound on the number of radio channels that would be needed to enable all of the equipped UA to carry the given traffic class without CCI.

The tool then constructed a strawman frequency plan for the hypothetical nationwide system by assigning an RF channel to each of the equipped UA, without ever assigning the same channel to any two UA whose roaming circles were within LoS of each other. Table 38 presents the results for each class of traffic. These consist of the calculated value of *M*, the total number (*C*) of channels the tool needed to generate the nationwide frequency plan, and the resultant system-wide spectral efficiency *E*, calculated as *M*/*C*. The calculated values of *E* ranged from 0.77 to 0.82.

TABLE 38

Results of terrestrial LoS simulations

Functional category	**Traffic class**	**Number (*M*) of equipped UA that are mutually visible**	**Number (*C*) of channels needed for nationwide frequency plan**	**Calculated system-wide frequency-assignment efficiency *E* = *M*/*C***
Command and control	Control data	128	156	0.82
	NavAid data	77	100	0.77
ATC relay	ATC voice relay	98	126	0.78
	ATS data relay	98	126	0.78
Sense and avoid	Target tracks	116	149	0.78
	Airborne weather radar data	37	48	0.77
	Non-payload video	116	149	0.78

Aggregate bandwidth requirements for each traffic class have been computed for each traffic class by substituting into equation (1) its calculated link bandwidth factor *V* from Table 37 and its *M* value from Table 5. However, since frequency-assignment efficiencies as high as those observed in the LoS simulations cannot always be guaranteed, a conservative value of 0.7 has been assumed for *E* throughout this set of computations, to provide a safety margin. The results appear in Table 39. They indicate that target tracks will consume nearly half of the total CNPC bandwidth requirement of 27.84 MHz, with ATC voice relay and non-payload video accounting for most of the remainder.

TABLE 39

Aggregate bandwidth requirements in a LoS terrestrial system

Functional category	**Traffic class**	**Number (*M*) of mutually visible equipped UA**	**Assumed frequency-assignment efficiency *E***	**Aggregate bandwidth (MHz) *W* = *VM/E***
Command and control	Control data	128	0.7	1.36
	NavAid data	77	0.7	0.25
ATC relay	ATC voice relay	98	0.7	2.69
	ATS data relay	98	0.7	0.03
Sense and avoid	Target tracks	116	0.7	6.05
	Airborne weather radar data	37	0.7	0.46
	Non-payload video	116	0.7	17.00
Total				**27.84**

The terrestrial spectrum requirements are divided as follows:

– UACS to UA = 2.0 MHz

– UA to UACS = 25.9 MHz.

Two caveats need to be considered here. First, the CNPC architecture's multiple-access scheme(s), currently undefined, would determine whether the "channels" are separated in frequency, time, and/or code space. A frequency-division multiple access (FDMA) scheme was assumed in the simulations, but many of the same principles would also apply in determining the numbers of channels needed by other schemes such as time-division multiple access (TDMA) and, perhaps, orthogonal FDMA (OFDMA).

Second, the foregoing analysis has implicitly assumed that every class of traffic will have its own set of channels, to be assigned as necessary to prevent CCI among the UA participating in that traffic class. This may well be true of ATC voice relay, airborne weather-radar data, and non-payload video, but the four other classes are expected to use packetized data, and some or all of them may use a common sub-band and channelization scheme. That could affect some of the aggregate bandwidth values shown in Table 39, although the impact on total bandwidth would probably be fairly modest.

1.3 Aggregate bandwidth requirements of a BLoS spot-beam satellite system

In a BLoS system using spot-beam satellites, the aggregate nationwide bandwidth requirement of a given class of traffic can be expressed as:

$$W = V\,B\,L\,K\,P \qquad \text{MHz} \tag{3}$$

where:

V is a link bandwidth factor defined as:

$$V = 0.001\ T\,F\,R/(U\,S) \qquad \text{MHz}$$

B is the number of UA, equipped to participate in the traffic class under consideration, in the footprint of a single spot-beam. In the spot-beam scenario postulated in Annex 2, each such footprint is assumed to be circular, with an area of 480 000 km^2 (185 000 square statute miles). For any given traffic class, the number of equipped UA in that area can easily be calculated from information in Tables 35 and 36 of this methodology.

In the BLoS analyses of this annex a value of 0.025 is assumed for the factor F for video downlinks. In the LoS analysis of § 1.2 the value of 0.19 was assumed for video downlinks because most video traffic is expected to be low-latency and thus will use LoS links. That results in a value of 0.0135 for link bandwidth factor V for the BLoS analyses, rather than the value of 0.1026 that was used in the LoS analysis.

P is the assumed maximum fraction of UA using the spot-beam satellite system at any given time. P depends on two factors. First, the number of simultaneously operating UA that are equipped to use satellite communication, and second, the amount of time in their overall flight during which those equipped will use satellite communication.

In this methodology for spot-beam operation we assume all large and medium UA will be equipped to use satellites as well as 50% of small UA. With reference to the quantities of UA available for operation from § 2.4.1 of Annex 2 Methodology 2 this equates to a total of:

$$341\ (\text{large}) + 1\,515\ (\text{medium}) + 6\,257\ (\text{small}) \times 50\% = 4\,984$$

A total of 4 984 UA represents:

$$4\ 984/(341+1\ 515+6\ 257) \times 100\% = 61\% \text{ of all of the UA available to operate.}$$

Assuming satellite equipped UA only use satellites for control and non-payload communications during the en-route phase of flight, then with reference to the disposition of the total number of UA by phase of flight table in § 2.4.1 of Annex 2 Methodology 2, this constitutes 76% of the simultaneously operating UA.

So the factor P for the spot-beam case is therefore:

$$P = 0.61 \times 0.76 = 0.46$$

In this analysis L is the necessary number of two-way paths (Earth-to-space and space-to-Earth) between either the UA and the satellite, or the UACS and the satellite, or an intermediate earth station and the satellite.

In this analysis a value of 2 is assigned to L for the spot-beam and regional-beam cases.

K is the frequency reuse factor required to prevent CCI between adjacent beams. A scheme, like the one in Fig. 2, where each colour represents one of the four sub-bands keeps each footprint (a circle circumscribing any of the hexagons) from overlapping any of its co-channel neighbours. In this analysis, $K = 4$ will be assumed to provide adequate protection against CCI in a spot-beam system.

FIGURE 8

Spot-beam frequency plan with four sub-bands

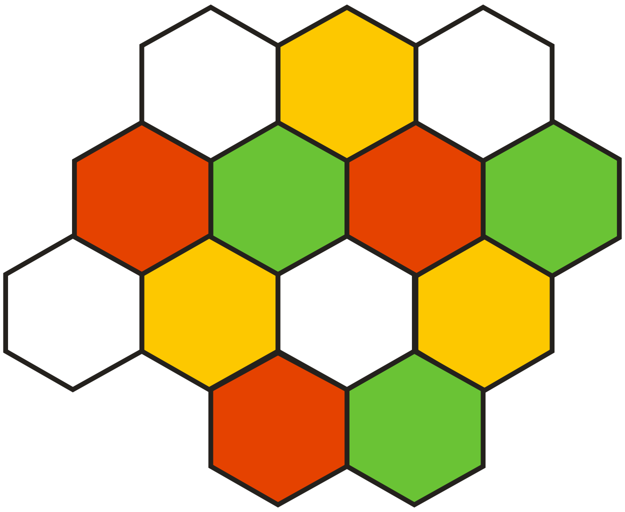

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Table 40 applies equation (3) to compute the aggregate bandwidth requirement of each class of traffic in a spot-beam satellite system. The combined requirement, 37.32 MHz, is slightly more than for the corresponding requirement for the LoS terrestrial system.

TABLE 40

Aggregate bandwidth requirements in a BLoS spot-beam satellite system

Functional category	**Traffic class**	**Number (B) of equipped UA in beam**	**Number of links (L)**	**Necessary number of sub-bands (K)**	**Aggregate bandwidth (MHz) $W = VBLKP$**
Command and control	Control data	308	2	4	8.44
	NavAid data	68	2	4	0.57
ATC relay	ATC voice relay	91	2	4	6.43
	ATS data relay	91	2	4	0.076
Sense and avoid	Target tracks	115	2	4	15.44
	Airborne weather radar data	21	2	4	0.66
	Non-payload video	115	2	4	5.71
Total					**37.32**

The spot-beam satellite spectrum requirements are divided as follows:

– UA to SAT = 15.32 MHz

– UACS to SAT = 3.29 MHz

– SAT to UA = 3.29 MHz

– SAT to UACS = 15.32 MHz.

1.4 Aggregate bandwidth requirements of a BLoS regional-beam satellite system

In a BLOS satellite system using a single regional-beam (7 800 000/km^2 (3 000 000 square miles) coverage), the aggregate nationwide bandwidth requirement of a given traffic class can be expressed as

$$W = V\,B\,L\,P \tag{4}$$

where:

V and L: defined as in the spot-beam analysis

B: number of UA, equipped to participate in the traffic class under consideration, in the footprint of the single regional-coverage beam.

Since only a percentage of the medium UA will be equipped to support a regional-beam control and non-payload communications system (assumed to be 74% in this analysis) and small UA will not be served by the regional-beam system at all, the factor P for the regional-beam case, again with reference to the quantities of UA available for operation in § 2.4.1 of Annex 2 Methodology 2 will be:

341 (large) + 1 515 (medium) × 74% = 1 464

A total of 1 464 UA represents:

1 464/ (341 +1 515) × 100% = 79% of all of the UA available to operate.

Assuming satellite equipped UA only use satellites for control and non-payload communications during the en-route phase of flight, then with reference to the disposition of the total number of UA by phase of flight table in § 2.4.1 of Annex 2 Methodology 2, this constitutes 76% of the simultaneously operating UA.

So the factor P for the spot-beam case is therefore:

$$P = 0.79 \times 0.76 = 0.6$$

For any traffic class, the number of equipped large and medium UA in the footprint can be calculated from the postulated equipage percentages in Table 36 of this methodology.

The sub-banding factor K is absent from equation (4) because potential CCI between adjacent beams is unlikely to be an issue in a regional-beam system, and consequently sub-banding is not required.

Table 41 applies equation (4) to calculate the aggregate bandwidth requirement of each class of traffic in a regional-beam satellite system. The combined requirement, 168.93 MHz, is approximately six times the corresponding requirement for the LoS terrestrial system. As already noted, the regional-beam system would not support small UA. Extending coverage to small UA would require additional spectrum for a supplementary system, perhaps a lower-bandwidth version of the LoS terrestrial system analysed in § 1.2 of this Methodology 2.

TABLE 41

Aggregate bandwidth requirements in a BLoS regional-beam satellite system

Functional category	**Traffic class**	**Number (B) of equipped UA in beam**	**Number of links (L)**	**Aggregate bandwidth $W = VBLP$ (MHz)**
Command and control	Control data	1 856	2	16.59
	NavAid data	1 099	2	3.03
ATC relay	ATC voice relay	1 477	2	34.03
	ATS data relay	1 477	2	0.39
Sense and avoid	Target tracks	1 856	2	81.25
	Airborne weather radar data	341	2	3.57
	Non-payload video	1 856	2	30.07
Total				**168.93**

NOTE 1 – Regional-beam system does not support small UA.

This BLoS regional-beam analysis assumes that only one satellite will be used to support all UAS control and communications activity within the region being considered. This is unlikely to be the case for reasons of redundancy/availability and economics. If two additional regional-beam satellites could reuse the same spectrum (assuming adequately narrow beamwidth antennas are used on the UA so that it can differentiate between satellites spaced on the geostationary arc), then the total amount of spectrum required (using regional-beams) will reduce to approximately 56 MHz. If lower frequencies are needed, where reuse of the spectrum is not possible due to limited antenna discrimination for small antennas, then the regional-beam spectrum requirement could increase to the 169 MHz maximum.

The regional-beam satellite spectrum requirements are divided as follows:

- UA to SAT = 24.05 MHz
- UACS to SAT = 4.1 MHz
- SAT to UA = 4.1 MHz
- SAT to UACS = 24.05 MHz.

2 Summary of Methodology 2 results

Table 42 summarizes the bandwidth requirements calculated above for each of the three major functional categories of CNPC traffic.

TABLE 42

Comparison of aggregate bandwidth requirements

Functional category	**Aggregate bandwidth requirement (MHz)**		
	LoS terrestrial system	**BLoS satellite system**	
		Spot-beam	**Regional-beam[1]**
Command and control	1.61	9.01	6.54
ATC relay	2.72	6.50	11.47
Sense and avoid	23.51	21.81	38.29
Total	**27.84**	**37.32**	**56.31**

[1] Regional-beam system does not support small UA.

Annex 4

Airspace classes, services and flight requirements

Annex 11 of the Convention on International Civil Aviation – Air Traffic Services provides general information concerning requirements of flights within each class of airspace. An example of these classes of airspace, as described in Table 43, is illustrated by the Fig. 9.

FIGURE 9

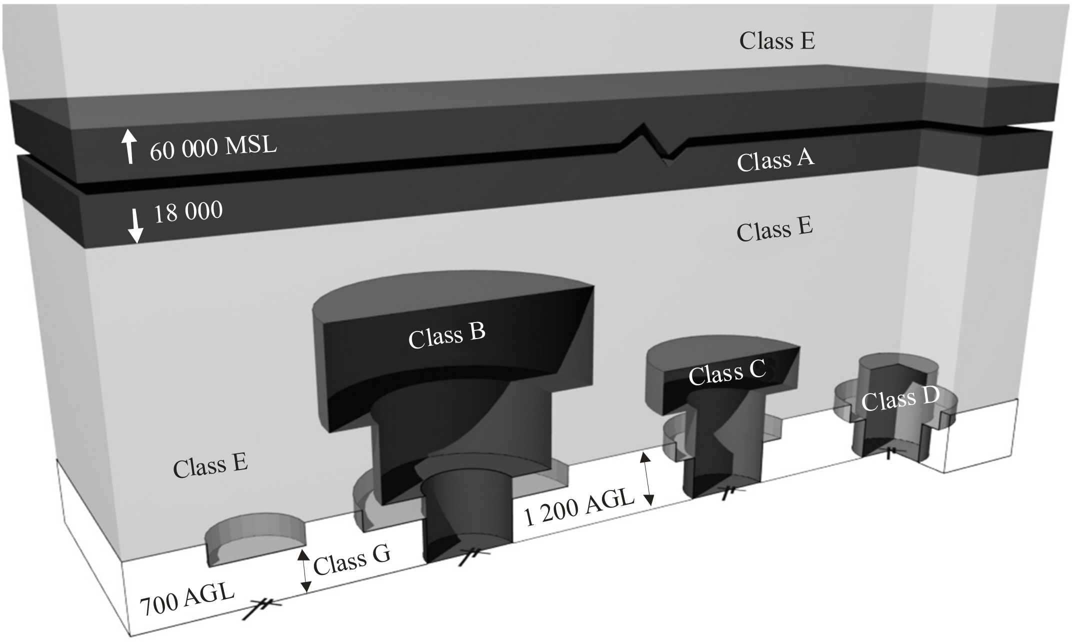

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TABLE 43

Airspace classes, services provided and flight requirements

Class	Type of flight	Separation provided	Service provided	Speed limitation*	Radio communication requirement	Subject to an ATC clearance
A	IFR only	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
B	IFR	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
	VFR	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
C	IFR	IFR from IFR IFR from VFR	Air traffic control service	Not applicable	Continuous two-way	Yes
	VFR	VFR from IFR	1) Air traffic control service for separation from IFR; 2) VFR/VFR traffic information (and traffic avoidance advice on request)	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	Yes
D	IFR	IFR from IFR	Air traffic control service, traffic information about VFR flights (and traffic avoidance advice on request)	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	Yes
	VFR	Nil	IFR/VFR and VFR/VFR traffic information (and traffic avoidance advice on request)	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	Yes

TABLE 43 (*end*)

Class	Type of flight	Separation provided	Service provided	Speed limitation*	Radio communication requirement	Subject to an ATC clearance
E	IFR	IFR from IFR	Air traffic control service and, as far as practical, traffic information about VFR flights	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	Yes
	VFR	Nil	Traffic information as far as practical	250 kt IAS below 3 050 m (10 000 ft) AMSL	No	No
F	IFR	IFR from IFR as far as practical	Air traffic advisory service; flight information service	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	No
	VFR	Nil	Flight information service	250 kt IAS below 3 050 m (10 000 ft) AMSL	No	No
G	IFR	Nil	Flight information service	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	No
	VFR	Nil	Flight information service	250 kt IAS below 3 050 m (10 000 ft) AMSL	No	No

* When the height of the transition altitude is lower than 3 050 m (10 000 ft) AMSL, FL 100 should be used in lieu of 10 000 ft.

Annex 5

Acronyms

A	Automatic operation
ACL	ATC clearance
ACM	ATC communication management
ADS-B	Automatic dependent surveillance – broadcast
ADS-C	Automatic dependent surveillance – contract
ADS-R	Automatic dependent surveillance – rebroadcast
AGL	Above ground level
AM	Amplitude modulation
AMC	ATC microphone check
ATC	Air traffic control
ATM	Air traffic management
ATS	Air traffic services
ATSA-IP	Air traffic situational awareness – In trail procedure
AV	Air vehicle

BLoS	Beyond LoS
CCI	Co-channel interference
CNPC	Control and non-payload communications
COCR	Communications operating concepts and requirements
COTRAC	Common trajectory coordination
CUCS	Core UAS control system
D-ATIS	Data link automatic terminal information service
DCL	Departure clearance
D-FLUP	Data link flight update
DL	Downlink
DLIC	Data link initiation capability
DLL	Data link logon
DME	Distance measuring equipment
D-OTIS	Data link operational terminal information service
D-RVR	Data link runway visual range
DSA	Digital signature algorithm
D-SIGMET	Data link significant meteorological information
D-TAXI	Data link taxi clearance
E/W	East/West
FDMA	Frequency division multiple access
FEC	Forward error correction
FIS-B	Flight information services – broadcast
FLIPINT	Flight path intent
FL	Flight level
GEO	Geostationary earth orbit
GNSS	Global navigation satellite system
IFR	Instrument flight rules
ITU	International Telecommunication Union
LEO	Low earth orbit
LOC	Localizer
LoS	Line of sight
LOI	Level of interoperability
M	Manual operation
Msg(s)	Message(s)
N/S	North/South
NavAid	Navigational aid

NOTAM	Notice to airmen
OFDMA	Orthogonal FDMA
QPSK	Quadrature phase-shift keying
RF	Radio frequency
RTCA	Radio Technical Commission for Aeronautics
S&A	Sense and avoid
TDMA	Time division multiple access
TIS-B	Traffic information services – broadcast
UA	Unmanned aircraft
UACS	Unmanned aircraft control station
UAS	Unmanned aircraft system
UL	Uplink
VDL3	Very high frequency digital link mode 3
VFR	Visual flight rules
VOLMET	Meteorological information for aircraft in flight
VOR	Very high frequency omnidirectional range
VSM	Vehicle specific module
WRC	World Radiocommunication Conference
3D	Three-dimensional
4DTRAD	Four-dimensional trajectory