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(11/2011)

Compatibility study to support the line-of-sight control and non-payload communications link(s) for unmanned aircraft systems proposed in the frequency band 5 030-5 091 MHz

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REPORT ITU-R M.2237

Compatibility study to support the line-of-sight control and non-payload communications link(s) for unmanned aircraft systems proposed in the frequency band 5 030-5 091 MHz

(2011)

1 Introduction

Significant growth is forecast in the unmanned aircraft systems (UAS) sector of aviation. The current state of the art in UAS design and operation is leading to the rapid development of UAS applications to fill many diverse requirements. The ability of UA to effectively support long duration and hazardous missions, are key drivers in the development and deployment of increasing numbers of UAS applications.

Though UA have traditionally been used in segregated airspace where separation from other air traffic can be assured, some administrations anticipate broad deployment of UA in non-segregated airspace shared with manned aircraft. If UA operate in non-segregated civil airspace, they must be integrated safely and adhere to operational practices that provide an acceptable level of safety comparable to that of a conventional manned aircraft. In some cases, those practices will be identical to those of manned aircraft.

It should be noted that in certain countries a wide range of frequency bands have been used for control of the UA in segregated airspace for both line-of-sight (LoS) and beyond line-of-sight (BLoS). Many of these bands do not have currently the safety aspect required to enable UA flight in non-segregated airspace.

Thus, it is envisioned that UA will operate alongside manned aircraft in non-segregated airspace using methods of control that could make the location of the pilot transparent to air traffic control (ATC) authorities and airspace regulators.

Because the pilot is located remotely from the UA, radio-frequency (RF) communications links will be required to support, among other things, UA telemetry data, telecommand messages, and the relay of ATC communications. Since this connection will be used to ensure the safe flight of UAS, reliable communications links and associated spectrum are required. It is also expected that the characteristics of the information will necessitate user authentication, and interference resilience. As UA technology advances, it can be expected that more autonomous flight capability will be incorporated into UA. Even for autonomous UAS operations, RF communications links with the same performance characteristics will be required for emergencies as well as for selected operating conditions. If the spectrum requirements of UAS operations cannot be accommodated within existing aviation spectrum allocations, additional appropriately allocated spectrum may be necessary to support UAS operations.

The goal of airspace access for appropriately equipped UAS requires a level of safety similar to that of an aircraft with a pilot onboard. The safe operation of UAS outside segregated airspace requires addressing the same issues as manned aircraft, namely integration into the air traffic control system. Because some UAS may not have the same capabilities as manned aircraft to safely and efficiently integrate into non-segregated airspace, they may require communications link performance that exceeds that which is required for manned aircraft. In the near term, one critical component of UAS safety is the communication link between the remote pilot's control station (UACS) and the UA.

Radiocommunication is the primary method for remote control of the unmanned aircraft. Seamless operation of unmanned and manned aircraft in non-segregated airspace requires high-availability communication links between the UA and the UACS. In addition, radio spectrum is required for various sensor applications that are integral to UAS operations including on-board radar systems used to track nearby aircraft, terrain, and obstacles to navigation.

The objective of this study is to identify potential new allocations in which the control and non-payload communications (CNPC) links of future UAS can operate reliably without causing harmful interference to incumbent services and systems.

Annex 1 of this Report deals with the sharing studies in the band 5 030-5 091 MHz between aeronautical-mobile (route) service (AM(R)S) with both aeronautical radionavigation service (ARNS) and aeronautical-mobile satellite (route) service (AMS(R)S) and the adjacent compatibility studies with AM(R)S and radionavigation-satellite service (RNSS) feeder links in the band 5 010-5 030 MHz.

The technical information given in this paper is not relevant for operational purposes.

2 Terminology

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

UA control station (UACS): Facility from which a UA is controlled remotely.

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

Unmanned aircraft system (UAS): Consists of the following subsystems:

– UA subsystem (i.e. the aircraft itself);

– UACS subsystem;

– air traffic control (ATC) communication subsystem (not necessarily relayed through the UA);

– S&A subsystem; and

– payload subsystem (e.g. video camera…)[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, S&A target track data, airborne weather radar downlink data, and non-payload video downlink data.

Forward link: Communication from the UACS to the UA through a satellite (see Fig. 1).

Return link: Communication from the UA to the UACS through a satellite (see Fig. 1).

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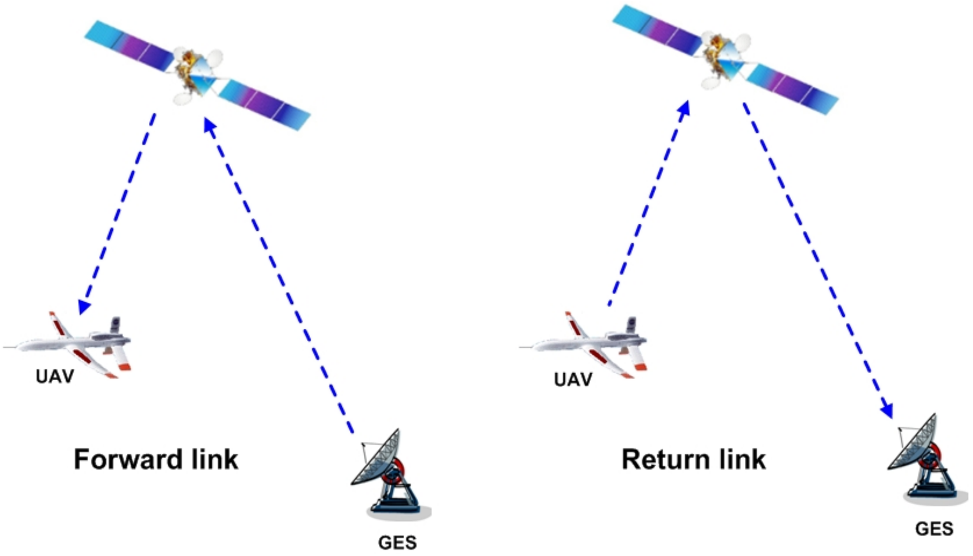
[1] UAS payload communications are not covered in this Report.

FIGURE 1

Definition – forward link and return link



3 Review of radiocommunication spectrum requirements

In order to ascertain the amount of spectrum needed for UAS control links, it is necessary to estimate the non-payload UAS control link spectrum requirements for safe, reliable, and routine operation of UAS. The estimated throughput requirements of generic UA and long-term spectrum requirements for UAS non-payload control link operations through 2030 have previously been studied and can be found in Report ITU-R M.2171[2].

The Report provides the analyses for determining the amount of spectrum required for the operation of a projected number of UAS sharing non-segregated airspace with manned air vehicles as required by World Radiocommunication Conference (WRC) Resolution 421 (WRC-07).

The Report estimates the total spectrum requirements covering both terrestrial and satellite requirements in a separate manner. Deployment of UAS will require access to both terrestrial and satellite spectrum.

The Report estimates the maximum amounts of spectrum required for UAS are:

– 34 MHz for terrestrial systems;

– 56 MHz for satellite systems.

Figure 2 illustrates the kinds of terrestrial LoS links in the system.

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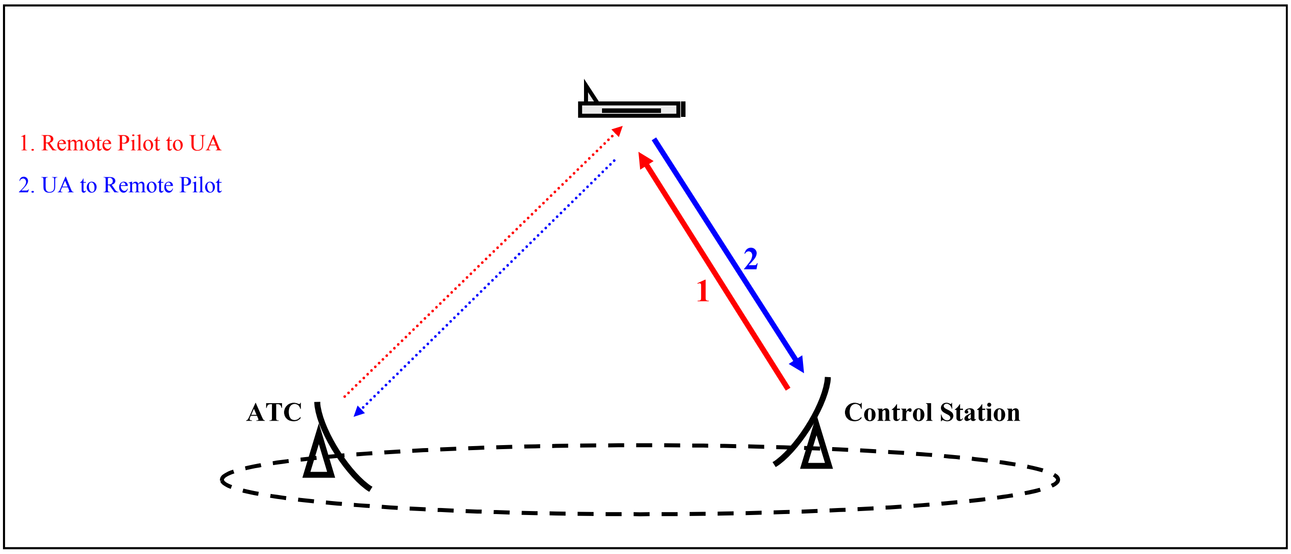
[2] Report ITU-R M.2171 – Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace, December 2009.

FIGURE 2

Links involved in LoS communications



For LoS links:

– the remote pilot stations satisfy the definition No. 1.81 (aeronautical station) of the Radio Regulations (RR);

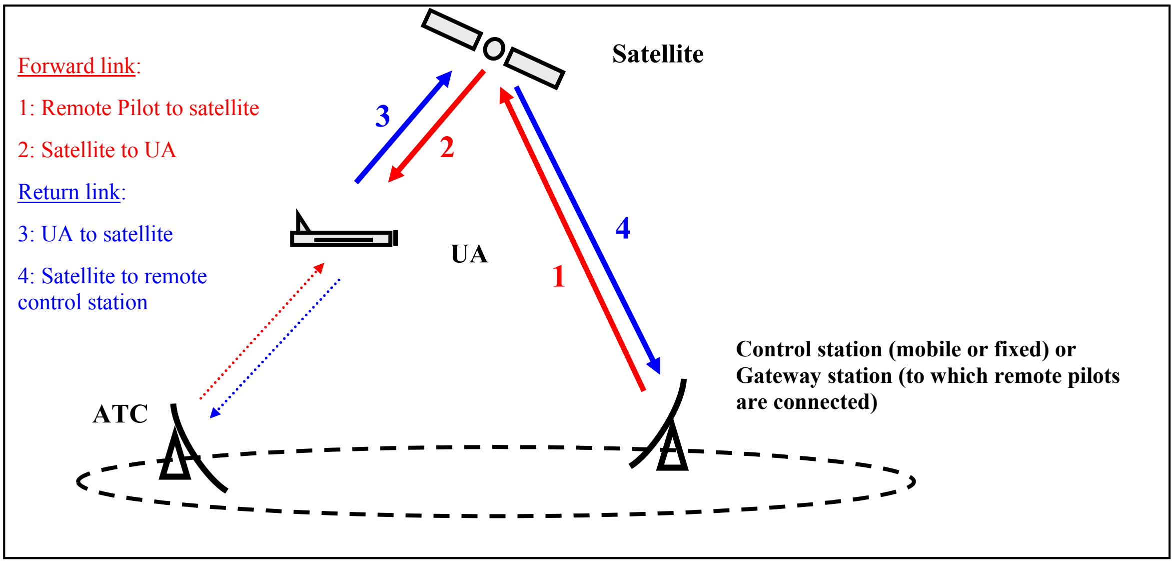
– the UA corresponds to definition RR No. 1.83 (aircraft station).

Therefore the AM(R)S, the aeronautical-mobile service (AMS) and the mobile service (MS) could be considered for links 1 and 2.

Figure 3 depicts the various kinds of satellite links in the system.

FIGURE 3

Links involved in BLoS communications via satellite



Case 1: Mobile UACS

– the UA corresponds to definition No. 1.84 (aircraft earth station) of the RR;

– the satellite corresponds to definition No. 1.64 (space station) of the RR;

– the mobile UACS corresponds to definition No. 1.68 (mobile earth station) of the RR.

Therefore, from the Radio Regulations point of view, AMS(R)S, the aeronautical-mobile satellite service (AMSS), and the mobile-satellite service (MSS) for links 2 and 3 could be considered if the allocation is on a primary basis. MSS for links 1 and 4 could also be considered if allocated on a primary basis. In the case of mobile UACS located on the Earth's surface, MSS except aeronautical for links 1 and 4 could be considered if the allocation is on a primary basis. Additionally for links 1, 2, 3 and 4, FSS allocations can also be considered if sharing studies with other services allocated in the bands, have been successfully completed which also require appropriate modifications of the Radio Regulations taking into account International Civil Aviation Organization (ICAO) requirements.

Case 2: Fixed UACS

– the UA corresponds to definition No. 1.84 (aircraft earth station) of the RR;

– the satellite corresponds to definition No. 1.64 (space station) of the RR;

– the fixed UACS corresponds to definition No. 1.63 (earth station) of the RR.

Therefore, from the Radio Regulations point of view, the services AMS(R)S, AMSS and MSS for links 2 and 3 could be considered. For links 1 and 4, the fixed-satellite service (FSS) could be considered taking also into account ICAO requirements. Additionally for links 2 and 3, FSS allocations can also be considered if sharing studies with other services allocated in the bands, have been successfully completed which also require appropriate modifications of the Radio Regulations taking also into account ICAO requirements.

Case 3: Control station providing feeder-link station functions

– the UA corresponds to definition No. 1.84 (aircraft earth station) of the RR;

– the satellite corresponds to definition No. 1.64 (space station) of the RR;

– the UACS corresponds to definition No. 1.82 (aeronautical earth station) of the RR.

Therefore, from the Radio Regulations point of view, the services AMS(R)S, AMSS and MSS for links 2 and 3 could be considered. The services FSS, AMSS, AMS(R)S for links 1 and 4 could be considered taking also into account ICAO requirements. Additionally for links 2 and 3, FSS allocations can also be considered if sharing studies with other services allocated in the bands, have been successfully completed which also require appropriate modifications of the Radio Regulations taking into account ICAO requirements.

4 Criteria for consideration of the possible frequency bands

The following criteria have been used for the consideration of the possible frequency bands for UAS operation:

Controlled-access spectrum: Each of the potential solutions should be evaluated on whether they will operate in spectrum that has some type of controlled access to enable the limitation and prediction of levels of interference.

ICAO position on AM(R)S and AMS(R)S spectrum: The ICAO position is to ensure that allocations used, in particular for UAS command and control, ATC relay and S&A in non-segregated airspace are in the AM(R)S, AMS(R)S and/or aeronautical radionavigation service (ARNS) and do not adversely affect existing aeronautical systems.

Worldwide spectrum allocation: It will be advantageous if global harmonization is achieved and the equipment needed by a UA could thus be the same for operation anywhere in the world.

Potentially available bandwidth: Under this criterion a favourable rating is more likely to be awarded to a candidate band whose incumbent RF systems currently leave a substantial amount of spectrum unoccupied, and have technical and/or operational characteristics that would facilitate coexistence with future in-band UAS control systems. Many BLoS systems share the control link and the payload return link on one common carrier, so the wide bandwidth needs of the payload return link may drive this choice more than the lower data rate needs of the control link.

Link range: This criterion evaluates the distance that the unmanned aircraft can fly away from its control station without the support of additional control stations.

Link availability: Weather-dependent availability of the link is also a very important evaluation criterion. Therefore, each candidate band should be evaluated according to the approximate availability associated with the frequency of operation. Higher frequency ranges are more susceptible to signal degradation due to rainfall and therefore receive less favourable ratings.

Satellite transmission characteristics: In order to determine whether satellite systems can provide the integrity and reliability needed to satisfy the link availability required for communications through satellite platforms to and from the UAS certain transmission characteristics need to be defined in sufficient detail. The following is a list of such information that is needed to make this determination.

1) The frequency band to be used.
2) Minimum and maximum antenna sizes, and the corresponding transmitting and receiving antenna gains of the earth station and of the airborne station.
3) Minimum and maximum equivalent isotropically radiated powers (e.i.r.p.) and e.i.r.p. densities of the earth station and of the airborne station.
4) Minimum ratio of receiving-antenna gain to receiver thermal noise temperature in Kelvins (G/T) of the receiving earth station and of the airborne station.
5) The rain conditions (i.e. rain rates) in which the link must operate, and any other propagation conditions that need to be considered.
6) Minimum required availability for the total (up and down) link (both outbound and inbound); or, alternatively, the minimum required availability in the uplink and the minimum required availability in the downlink. Note should be also taken of certain double-hop links (e.g. ATC-to-UA communications relayed through a UA-to-UACS link).
7) Off-axis gain patterns of the transmitting and receiving antennas of the earth station and the airborne station.
8) Pointing accuracies of the antennas of the control station and the airborne station.
9) Geographical coverage area where the UAS requirements will have to be met.
10) Carrier characteristics:
    a) Information rates.
    b) Occupied bandwidth.
    c) Allocated bandwidth.
    d) Modulation type.
    e) Forward error correction rate.

f) Minimum required carrier-to-(interference + noise) ratio ($C/(I+N)$) for the satellite/UA link and the satellite/control-station link.

g) The minimum and maximum acceptable latency in the transmission to and from the UA and UACS.

Co-site compatibility: This metric evaluates the relative feasibility of operating future UAS control-link radios in the band under consideration, without causing harmful interference to the collocated receivers of incumbent systems in the same UA or UACS.

Airborne equipment size, weight, and power: The driving factor for applying this criterion is the size of the antennas on board the unmanned aircraft. Credit should be given to frequency bands in which control links could operate using omnidirectional antennas.

5 Frequency band under consideration

In this Report, the frequency band 5 030-5 091 MHz is studied for the terrestrial component.

6 Conclusions

In the band 5 030-5 091 MHz, based on methodologies 1 and 2 detailed in Annex 1, it can be concluded that the sharing between AM(R)S with both ARNS and AMS(R)S is possible with mitigation techniques such as frequency planning, geographical separation and power control as appropriate. In case of operation of UAS in the same occupied bandwidth (150 kHz) with MLS in the band 5 030-5 091 MHz, it would be difficult to achieve compatibility between these two systems.

The adjacent band compatibility with RNSS feeder links is possible with appropriate geographical separation. Potential interference from the terrestrial CNPC system into RNSS service links in the band 5 010-5 030 MHz was not considered.

Annex 1

Sharing study for terrestrial line-of-sight UAS communications in the 5 030-5 091 MHz band

1 Introduction

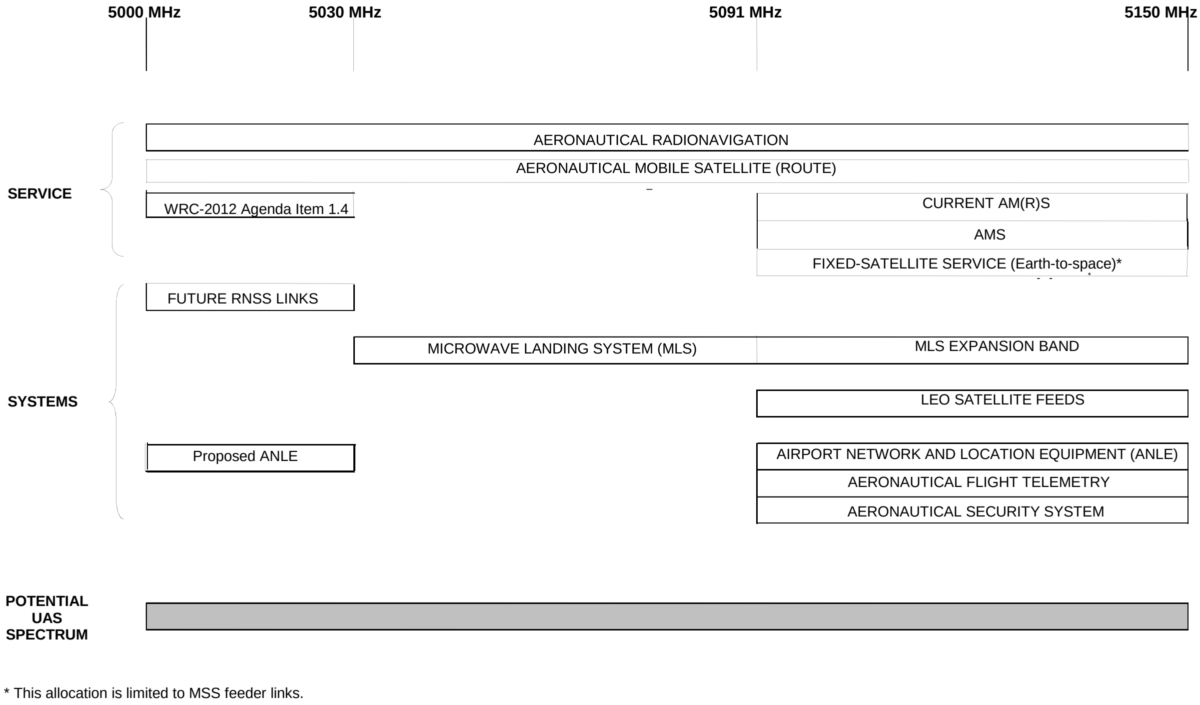
The Table of Frequency Allocations of the Radio Regulations lists the ARNS and the AMS(R)S as primary services from 5 000 to 5 150 MHz. Figure 4 provides an overview of services in this band, with examples of systems using those services. The band comprises three principal sub-bands:

- The 5 000-5 030 MHz sub-band is also allocated to the RNSS.
- The 5 030-5 091 MHz sub-band currently used (although not heavily) by the Microwave Landing System (MLS).
- The 5 091-5 150 MHz sub-band, which was originally reserved as an expansion band for MLS but now is also allocated to the FSS for use by MSS Earth-to-space feeder links. The design of FSS networks has long been based on anticipating an interference contribution

from other primary allocated services in the same band equivalent to no more than 6% $\Delta T/T$. During WRC-07, three per cent was apportioned to aeronautical mobile telemetry (AMT), aeronautical security systems and airport network and location equipment (ANLE) with the other 3% expected from the primary ARNS. Existing and planned systems in the band include low-Earth orbit (LEO) satellite feeder uplinks, the ANLE, AMT, and aeronautical security systems.

FIGURE 4

Aeronautical, RNSS, and satellite frequency use in the 5 000-5 150 MHz band



NOTE - This chart does not completely depict all systems or allocations in this band.

2 Systems characteristics

2.1 UA systems characteristics

The following tables give example for the UAS characteristics that are used in the sharing studies. e.i.r.p. for UAS can be lower than that depending on the scenarios envisaged. Appendix 1 also contains assumptions on the CNPC link characteristics, as well as budget links.

TABLE 1

UAS characteristics for the medium and large UA

Parameter	UACS	UA
Transmitter cable loss (dB)	1	2
Equivalent isotropically radiated power (e.i.r.p.) (dBm)	52	40
Receiving antenna gain (dBi)	10/24	3
Receiver cable loss (dB)	1	2
Bandwidth (kHz)	37.5	37.5/300

TABLE 2

UAS characteristics for small UA

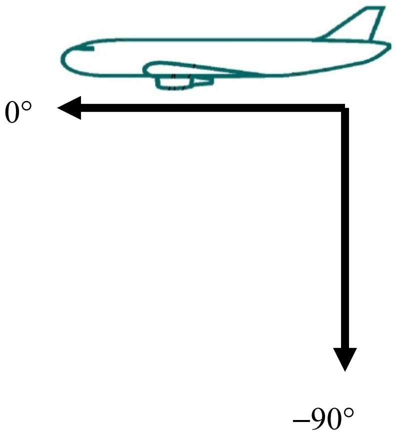
Parameter	UACS	UA
Transmitter cable loss (dB)	1	2
Equivalent isotropically radiated power (e.i.r.p.) (dBm)	35.5	25.5
Receiving antenna gain (dBi)	10	3
Receiver cable loss (dB)	1	2
Bandwidth (kHz)	37.5	37.5/300

NOTE – The second table gives parameters that are expected for small UA operations in LoS.

In this study, it is considered to take a UA's antenna similar to the DME's antenna referred in Recommendation ITU-R M.1642 but with maximum antenna gain of 0 dBi. The figure below gives the relevant UA's antenna gain for elevation angles between 0° and 90°

TABLE 3

Medium and large UA antenna gain definition

	Extract from Rec. ITU-R M.1642	**Elevation angle definition**
Elevation angle (degrees)	Antenna gain $G_r/G_{r,\,max}$ (dB)	
–90	–17.22	
–80	–14.04	
–70	–10.51	
–60	–8.84	
–50	–5.4	
–40	–3.13	
–30	–0.57	
–20	–1.08	

	Extract from Rec. ITU-R M.1642	**Elevation angle definition**
–10	0	
–5	–1.21	
–3	–1.71	
–2	–1.95	
–1	–2.19	
0	–2.43	
5	–4.69	
10	–7.22	
20	–10.52	
30	–11.36	
40	–11.79	
50	–13.21	
60	–15.82	
70	–20.08	
80	–23.44	
90	–22.57	

In the case of small aircrafts, the fuselage attenuation is expected to be lower and therefore, the UA antenna pattern considered in the studies is taken from Table 4.

TABLE 4

Small UA antenna gain definition

Elevation angle (degrees)	**Antenna gain $G_r/G_{r,max}$ (dB)**	**Elevation angle (degrees)**	**Antenna gain $G_r/G_{r,max}$ (dB)**
–90	–9.2	–1	–2.19
–80	–7.5	0	–2.43
–70	–5.6	5	–2.5
–60	–4.7	10	–3.8
–50	–2.9	20	–5.6
–40	–1.7	30	–6.0
–30	–0.57	40	–6.3
–20	–1.08	50	–7.0
–10	0	60	–8.1
–5	–1.21	70	–10.7
–3	–1.71	80	–12.5
–2	–1.95	90	–12

The pattern of the ground antenna used for the study is defined by Recommendation ITU-R F.1336-2, §§ 2.1 and 2.1.1 and is recall below:

$$G_r(\theta) = -12\left(\frac{\theta}{10.8}\right)^2 \qquad \text{for} \qquad 0 \leq |\theta| < 10.8$$

$$G_r(\theta) = -12 + 10\log\left[\left(\frac{|\theta|}{10.8}\right)^{-1.5}\right] \qquad \text{for} \qquad 10.8 \leq |\theta| \leq 90$$

where:

$G_r(\theta)$: AM(R)S ground antenna gain relative to $G_{r,\,max}$ (maximum gain);

θ: absolute value of the elevation angle relative to the angle of maximum gain (degrees).

2.2 RNSS receivers characteristics in the band 5 010-5 030 MHz

Tables 5 to 8 give the RNSS receivers characteristics for respectively GALILEO, GPS and QZSS systems.

TABLE 5

Protection criteria for Galileo receiving earth stations operating in the band 5 010-5 030 MHz

Parameter	RNSS parameter description
Signal frequency range (MHz)	5 010-5 030
Maximum receiver antenna gain (dBi)	4
RF filter 3 dB bandwidth (MHz)	20
Pre-correlation filter 3 dB bandwidth (MHz)	20
Receiver system noise temperature (K)	530
Tracking mode threshold power level of aggregate narrow-band interference at the passive antenna output (dBW)	–157.1
Acquisition mode threshold power level of aggregate narrow-band interference at the passive antenna output (dBW)	–160.1
Tracking mode threshold power density level of aggregate wideband interference at the passive antenna output (dB(W/MHz))	–147.1
Acquisition mode threshold power density level of aggregate wideband interference at the passive antenna output (dB(W/MHz))	–150.1

TABLE 6

Service link characteristics and protection criteria of GPS receiving user ground stations for operation in the band 5 010-5 030 MHz

Parameter	Parameter value
Signal frequency range (MHz)	5 019.861 ± 9.86
Maximum receiver antenna gain in upper hemisphere (dBi)	3
Maximum receiver antenna gain in lower hemisphere (dBi)	3 (see Note 2)
Receiver RF filter 3 dB bandwidth (MHz)	20
Receiver pre-correlation 3 dB bandwidth (MHz)	20
Receiver system noise temperature (K)	500
Tracking mode threshold power level of aggregate narrow-band interference at the passive antenna output (dBW)	−154.6 (see Note 1)
Acquisition mode threshold power level of aggregate narrow-band interference at the passive antenna output (dBW)	−157.6 (see Note 1)
Tracking mode threshold power density level of aggregate wideband interference at the passive antenna output (dB(W/MHz))	−144.6 (see Note 1)
Acquisition mode threshold power density level of aggregate wideband interference at the passive antenna output (dB(W/MHz))	−147.6 (see Note 1)

NOTE 1 – Narrow-band continuous interference is considered to have a bandwidth of less than 700 Hz in the 5 010-5 030 MHz band. Wideband continuous interference is considered to have greater than 1 MHz bandwidth in the 5 010-5 030 MHz band. Threshold power levels for interference bandwidths between 700 Hz to 1 MHz are derived by log-linear interpolation between the narrow-band power limit in a 700 Hz bandwidth and the wideband power density limit in a 1 MHz bandwidth.

NOTE 2 – Because the antenna in some RNSS receiver applications could potentially be pointed in almost any direction, the maximum antenna gain in the lower hemisphere could (under worst-case conditions) be equal to that for the upper hemisphere.

TABLE 7

Characteristics and protection criteria of QZSS feeder-link receiving earth stations operating in the band 5 010-5 030 MHz

Parameter	Parameter value
Antenna pattern	Rec. ITU-R S.465-5
Maximum antenna gain (dBi)	49.0
Necessary bandwidth (kHz)	400
Noise temperature (K)	150

TABLE 8

Characteristics of QZSS feeder-link transmitting space stations operating in the band 5 010-5 030 MHz

Parameter	Parameter value
Antenna pattern	Global beam
Polarization	RHCP
Transmit e.i.r.p. (dBW)	23.3/9.8
Modulation	PCM-PSK/PM

2.3 AMS(R)S characteristics in the band 5 030-5 091 MHz

The 5 030-5 091 MHz band is proposed for beyond LoS CNPC of future UAS. System parameters used for the analysis are shown in Tables 9 and 10 (extracted from Report ITU-R M.2205).

TABLE 9

AMS(R)S return link parameters for compatibility analysis

Parameter	AMS(R)S
UA e.i.r.p. (dBW)	17
Uplink propagation loss (around 39 000 km)	–198.5
Satellite Rx antenna gain (dBi)	45.1
Satellite Rx feeder loss (dB)	0.5
Satellite *G*/*T* (dB/°K)	18.7
Satellite repeater e.i.r.p (dBW)	17
Downlink propagation loss (around 37 000 km)	–198
UACS *G*/*T* (dB/°K)	18.8
UACS Rx antenna diameter (m)	3.8
UACS Rx antenna gain (dBi)	44.1
UACS Rx feeder loss (dB)	1

TABLE 10

AMS(R)S forward link parameters for compatibility analysis

Parameter	**AMS(R)S**
UACS e.i.r.p. (dBW)	49.6
Uplink propagation loss (around 37 000 km)	–198
Satellite Rx antenna gain (dBi)	45.1
Satellite Rx feeder loss (dB)	0.5
Satellite G/T (dB/°K)	18.7
Satellite repeater e.i.r.p (dBW)	47.7
Downlink propagation loss (around 39 000 km)	–198.5
UA G/T (dB/°K)	–23
UA Rx antenna gain (dBi)	3
UA Rx feeder loss (dB)	2

2.4 MLS characteristics in the band 5 030-5 150 MHz

Table 11 below gives the MLS characteristics taken into account in this study.

TABLE 11

MLS characteristics

Frequency range (MHz) for non-DME functions	5 030-5 091
Frequency range (MHz) for DME functions	960-1 215
Power (dBm)	43 (all signals)
Preamble and data (DPSK) antenna gain (dBi)	2 to 8; 0 outside coverage region
Guidance azimuth and elevation (CW) antenna gain (dBi)	Up to 23; 0 outside coverage region
Radiation patterns for clearance / out-of-coverage indication (OCI) and DPSK data over 360° (dBi)	Up to 18 for CW, 11 for data over 360°
Airborne antenna gain (dBi) toward MLS ground station	0
Azimuth antenna beamwidth (degrees)	Less than 4
Azimuth scan limits (degrees)	–40 to +40 (typical), –62 to 62 (max)
Azimuth scan duration (ms)	15.9
Elevation antenna beamwidth (degrees)	Less than 2.5
Elevation scan limits (degrees)	0.9 to 15 (typical), 0.9 to 29.5 (max)
Elevation scan duration (ms)	5.6
Polarization	Vertical
Longest continuous DPSK data sequence (ms)	9.3 – 15
Duty factor	25% (DPSK)
DPSK data modulation rate (kHz)	15.625
Interference threshold for the protection of MLS against emissions from other systems (dBm)	–130
Receiver bandwidth (kHz)	150
Receiver sensitivity (dBm)	–112

3 Compatibility analysis

3.1 In-band sharing studies

3.1.1 Methodology 1

This methodology assesses the possibility of AM(R)S sharing of the 5 030-5 091 MHz band without harmful interference to or from MLS and future AMS(R)S systems in the band.

3.1.1.1 Sharing analysis of the 5 030-5 091 MHz band

3.1.1.1.1 Potential AM(R)S architecture

A possible AM(R)S system architecture for providing UAS CNPC in the 5 030-5 091 MHz band is described below. In the following discussion this band will often be referred to as "5 GHz-band" in accordance with widespread practice.

3.1.1.1.1.1 Preliminary design considerations

It will be assumed that 5 GHz data links can be used by all sizes of UA. However the smaller UA types have very strict size, weight and power (SWAP) constraints, may not carry video cameras devoted to flying the UA, and certainly would not carry weather radar. Since video constitutes the largest CNPC throughput requirement and weather radar the second largest, this means that the maximum throughput required by an individual small or medium UA could be quite small.

Second, due to the limited size of UA, particularly the smaller types, there will be limited isolation between transmit and receive antennas for the various systems on board the UA. Thus, co-site issues will be very important if the UA carries any other systems that include airborne receivers operating in the same band. A possible answer is to limit the duty factor of the airborne CNPC transmitter. Unfortunately, this approach may be infeasible because of repetition-rate requirements discussed below.

Third, because of the limited isolation discussed in the previous paragraph, it may be difficult to implement a CNPC system that has a frequency division duplex (FDD) architecture requiring simultaneous transmission and reception.

It is possible that the ground users of the system (UA pilots) in a given area will be linked together in such a way that they can share ground radio assets. In other words, they can be multiplexed together. This may (1) provide a "trunking gain" in throughput performance and (2) allow a pilot to control a UA BLoS by allowing switching between connected ground radios. On the other hand, for certain UA with a limited range, this capability may be unnecessary and/or undesirable. In such cases, the pilots could be connected directly with their UA via individual dedicated radios. Such pilot/UA pairs can be accommodated through the use of fixed, prearranged time-slot assignments. In any case, an important parameter in the analysis will be the number of UA/pilot pairs that can be assumed to share a single radio site. This ratio could be as low as 1 (absolutely no networking via a common ground infrastructure; this is also the degenerate condition for a UA and pilot relying on their own deployed resources, even if they share spectrum and channel resources within a larger community). However, in the description given below the ratio can be as large as 20 (as a typical example).

Based on these considerations, a representative 5 GHz-band design will be described in the following sections. The design is not necessarily meant to be a candidate for the future system. Instead, it is meant to represent a design with just enough detail to allow the determination of various performance measures.

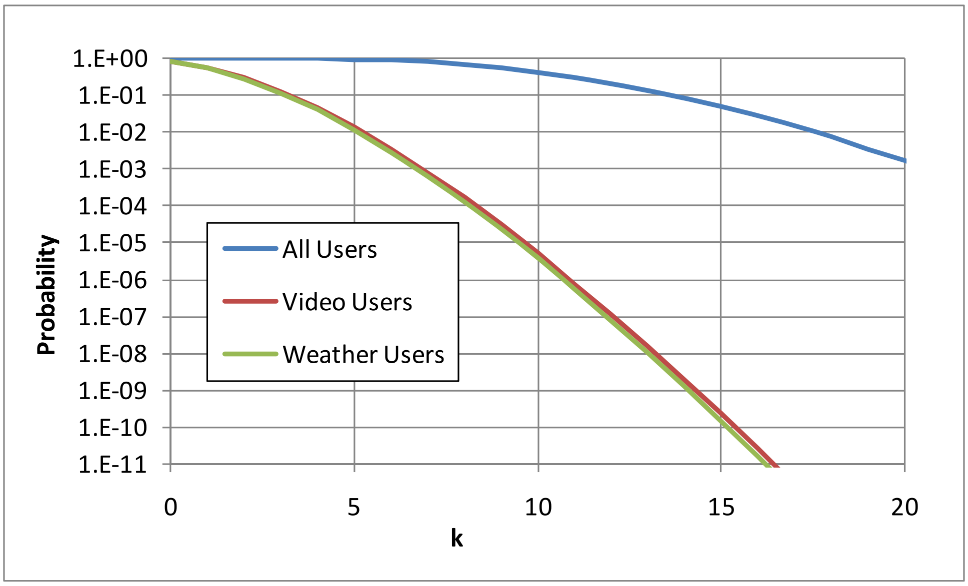
3.1.1.1.1.2 Statistical considerations

Using the given UAS densities from the tables in Report ITU-R M.2171, we can determine that a hexagonal sector with radius 127 km (about 69 nmi) will have an average of 1.84 large UAS and 8.17 medium UAS (for an average total of 10.01 medium and large UAS combined). (Cell radius is defined as the radius of the circle circumscribing a perfect hexagonal cell.) It is further assumed that only 19% of the medium and large UAS utilize video at any given time, so that the average number of video users is 1.90. Finally, since it is assumed that all large UAS and no medium UAS have weather radar data, the average number of weather data users is 1.84.

We can also assume that the actual number of users (n) of any type in any given cell follows a Poisson distribution. (We are assuming that the long-time distribution across CONUS is constant and that the fluctuations are purely statistical. This is clearly only an approximation.) The Poisson equation is $P(n) = e^{-N} (N^n / n!)$, with N being the average number. Figure 5 is a graph of the probability of the number of users in a cell exceeding the number on the horizontal axis.

FIGURE 5

Probability that a cell 127 km (69 nmi) in radius contains more than *k* medium and large UAS users



The probability of the total number of cell occupants exceeding 20 is 0.0016. This means that if the "basic" (non-video, non-weather-radar) resources allocated to the cell provide for up to 20 users, there could be blockage in 0.16% of the cells (or in a single cell 0.16% of the time). The other two curves relate to allocations for video and weather radar data. If we provide for up to 4 video users at a given time, the likelihood that there is blockage is 4.4%. Similarly, if we provide for just 4 weather radar channels, there will be blockage 4.0% of the time.

The reason that the blocking percentages are higher for video and weather is related to the fact that the standard deviation (σ) of the Poisson distribution is $\sqrt{N}$, and so $\sigma/N = 1/\sqrt{N}$. In other words, the fractional deviation gets smaller as the average number of users gets larger. It follows that if we want to make the probability of blockage for video and weather comparable to the basic information that all users must employ we would need to increase the video and weather allocation. Otherwise, we need to accept blocking at a frequency of about 4%.

The above analysis assumes that all users in a cell (or sector) use their designated capabilities constantly. In other words, a large UAS with basic data, weather data and video will need to be able to transmit all the time. This may not be true in a networked situation, but as a worst case we can assume there is *no* networking and that each pilot/UA pair has designated, permanent resources.

3.1.1.1.1.3 Detailed designs

In this section we investigate the feasibility of providing terrestrial LoS control communications for UAS in the 5 030-5 091 MHz band. The purpose of the investigation is to assess whether or not it is possible to meet the preliminary system requirements found in Report ITU-R M.2171 and, if so, how much spectrum is required. Prior work on estimating frequency requirements has already been done, but this effort attempts to provide another level of detail by postulating a particular system architecture. This allows for a somewhat more detailed assessment of system overhead requirements. The proposed design should be considered as an existence proof, and there is no implied claim that the solution is optimal.

For all UAS types and for both frequency bands there is a requirement to support a channel access rate (or "repetition rate") of at least 20 Hz. This rapid rate is necessary to support operations involving manual, real-time control. The bandwidth requirements are abstracted from the *loading* requirements found in Report ITU-R M.2171 Table 13. The Report ITU-R M.2171 *throughput* requirements (which include allowances for overheads) are not used here, since the analysis below attempts to estimate the overheads more accurately, on the basis of a specific example. The requirements vary based on the size of the UAS, on the phase of flight and on whether the channel is uplink or downlink. In Table 12 below, the worst-case phase-of-flight requirements are listed. (Note that the worst case is typically the "terminal arrival" phase, while the aircraft is landing.) The medium and large UAS downlink requirements are very large because they can include 13.6 kbps for control, ATC voice relay, etc.; 20.6 kbps for downlinked airborne-weather radar data; and 200 kbps for non-payload video. Uplink and small UAS requirements are much smaller.

TABLE 12

Assumed loading requirements

UA Type	Up (kbps)	Down (kbps)
Medium/Large	7	234.2
Small	2.5	4.0

3.1.1.1.1.3.1 Medium and large UA system design

This section describes a possible time division duplex (TDD) architecture for a terrestrial CNPC system operating in the 5 GHz band from 5 030 to 5 091 MHz to support medium and large UAS. The following capabilities are provided:

– Every UA is assigned downlink time slots supporting an information data rate of 20.8 kbps. (Requirement = 13.6 kbps).

– Every UA is assigned uplink time slots supporting an information data rate of 10.45 kbps. (Requirement = 7 kbps).

– The maximum access time for each UA is 40 ms, i.e., the repetition rate is 25 Hz. (Requirement = 20 Hz).

– The system also supports up to 4 UA simultaneously transmitting video at a rate of 204 kbps (in a given sector). (Requirement = 200 kbps).

– The system also supports up to 4 UA simultaneously transmitting weather radar data at a rate of 21.6 kbps (in a given sector). (Requirement = 20.6 kbps).

As mentioned previously, it is assumed that the sectors are sized so that there are, on average, 10 UA in any individual sector. This corresponds to a cell radius of about 127 km (69 nmi). To allow for fluctuations in the number of UAS in a cell, the architecture provides enough bandwidth to service 20 UAS basic control channels. The architecture conserves bandwidth by allowing the UA/controller pairs in a single sector to share resources so that the system needs to provide for only 4 video channels at any given time. In the architecture each UAS gets the use of a 37.5-kHz-wide "basic" control channel, but each user must arrange with a central authority to get access to one of four 300-kHz "wideband" channels when video is needed. The weather radar channels in each sector are assumed to be assigned to up to 4 large UA that have the appropriate radar equipment.

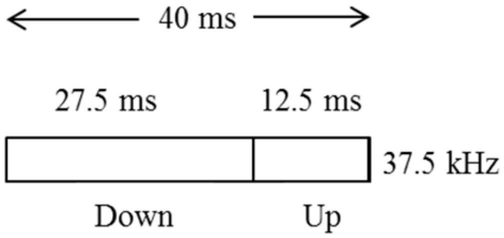
Finally, it is assumed that the physical location of the control station antenna for each UA can be anywhere within its operational sector. This does not preclude scenarios in which pilots are connected to their UA via a centralized radio antenna, but that is not required. This means it is ***not*** necessary to have a centralized antenna high enough to provide coverage down to the ground at every point in the cell where UA might be landing or taking off. Instead, individual ground antennas can, when necessary, be placed close enough to particular airports or airstrips to allow those antennas to be placed at reasonable heights (say, 30 m (100 feet) or less).

3.1.1.1.1.3.1.1 Link layer description

The "basic" medium and large UAS channels (for carrying everything except video and downlinked airborne weather-radar data) are arranged as shown in Fig. 6:

FIGURE 6

Basic medium and large UAS channel

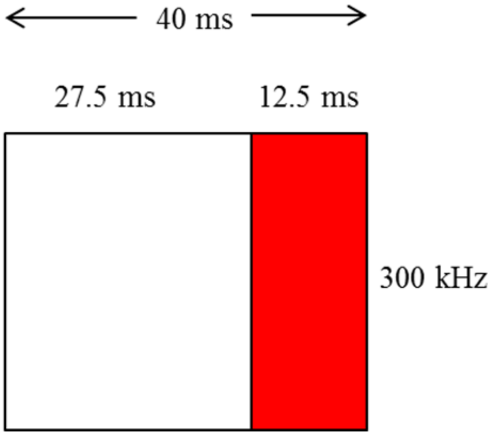


In a 40-ms cycle, each user on a frequency channel has access to a 27.5 ms downlink time slot and a 12.5 ms uplink time slot. After accounting for overhead due to synchronization, header, and guard time, the resulting downlink information rate is 20.8 kbps and the uplink information rate is 10.45 kbps. This presumes that the signalling rate is 37.5 kbaud, the modulation is differential quadrature phase-shift keying (DQPSK) and the error correction code rate is 4/9 for the downlink and 5/9 for the uplink. Note that the access rate, or "rep rate," of this scheme is 25 Hz.

The timing of a wideband downlink channel capable of carrying video and airborne weather-radar data as well as basic data is similar, as indicated in Fig. 7:

FIGURE 7

Wideband downlink channel

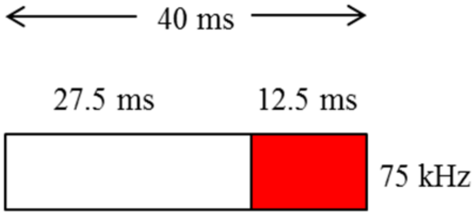


Note that the bandwidth of each wideband channel is increased from 37.5 kHz to 300 kHz. A user who is assigned a video channel has access to all the unshaded time slots until the temporary reservation is denied or ceded back to the central authority. The shaded times are not available because transmission of video could interfere with the reception of uplink control messages by co-site receivers or receivers on nearby UAS. If the error correction code rate for video is changed to 17/25, then the video rate is 204 kbps. (Since the video has inherent redundancy, it is expected that this reduction in robustness vis-à-vis channel errors is acceptable.)

The timing of an ”intermediate” downlink channel capable of carrying basic data and airborne weather-radar data (but not video) is illustrated in Fig. 8:

FIGURE 8

Intermediate downlink channel



In this case, each user can transmit during one 27.5 ms time slot per 40 ms period. The UA cannot transmit during the shaded intervals for the same reasons as discussed for the wideband downlinks. Since the bandwidth of these channels is 75 kHz, this allocation can support up to 42.4 kbps, which exceeds the 34.2 kbps combined requirement for basic and weather-radar data.

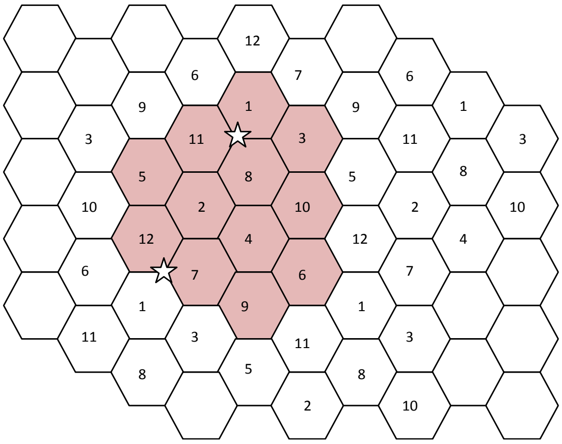
3.1.1.1.1.3.1.2 Spectrum requirements

The spectrum requirements are based on at least two factors: the amount of bandwidth needed in a single sector, and the separation required between sectors to allow frequency reuse. The separation needed is related to the co-channel interference tolerance of the system’s signal-in-space. This is usually expressed in terms of the waveform’s minimum desired-to-undesired (D/U) power ratio. One way to ensure a high D/U ratio is to assign frequencies so they are reused only in sectors that are over-the-horizon with respect to one another. This is the method used below. The allowable patterns will depend on the radii and maximum altitudes of the sectors. In general, tall and slender sectors require many frequency groups (a high K-factor), while short and wide sectors require lower K-factors. (This phenomenon explains why the K-factors for aeronautical applications may be larger than they are for typical land-based cellular telephone applications.) The bandwidth requirements for a single cell are discussed in the next paragraph. The necessary K-factor is then discussed in the subsequent paragraph.

The amount of spectrum needed to support 20 users in a region is 20 × 37.5 kHz for the basic channels, 4 × 225 kHz for the on-demand video channels and 4 × 37.5 kHz for weather radar downlinks, for a total of 1.8 MHz. Nevertheless, to simplify the multiple-access design, it is assumed that there are actually 12 basic channels (37.5 kHz each), 4 intermediate basic/weather channels (75 kHz each), and 4 wideband basic/weather/video channels (300 kHz each), for a total of 1.95 MHz. If the channels spacing was equal to the channel bandwidths (37.5, 75, or 300 kHz), there could be considerable adjacent channel interference. This leads to a requirement that adjacent frequency channels not be assigned to neighbouring sectors. The smallest cell pattern for which this is possible is $K = 12$ (Fig. 9 shows an example showing no adjacent, consecutive numbers). For a $K = 12$ pattern, the grand total bandwidth requirement is 12 × 1.95 = 23.4 MHz.

FIGURE 9

***K*=12 pattern with adjacent-channel protection**



The $K = 12$ pattern also provides ample frequency reuse protection, since the minimum reuse distance is 4 × 127 = 508 km (274 nmi) (the distance between the stars in Fig. 9), which corresponds to the maximum line-of-sight range for a UA at 14 000 m (46 000 feet) and a ground antenna atop a 30 m (100-foot) tower. (A $K = 9$ pattern whose minimum reuse distance is 443 km (239 nmi) might also suffice if the maximum UA altitude were 10 400 m (34 000 feet). Unfortunately, a $K = 9$ pattern could not allow for assigning adjacent frequencies only in non-neighbouring cells. In that case we would need to provide extra guard bands between channels, which would probably negate the possible efficiency improvement achieved by using $K = 9$.)

3.1.1.1.1.3.2 Small UAS system design

This section presents a design for a terrestrial CNPC system operating from 5 030 to 5 091 MHz to support small UAS. The following capabilities could be provided:

- Every UA is assigned downlink time slots supporting an information data rate of 7.9 kbps. (Requirement = 4 kbps).

- Every UA is assigned uplink time slots supporting an information data rate of 2.5 kbps. (Requirement = 2.5 kbps).
- The maximum access time for each UA is 40 ms, i.e., the “rep rate” is 25 Hz. (Requirement = 20 Hz).

It is assumed that the sectors are sized so that there are, on average, 10 participating UAS in any individual sector. Based on the assumed densities of small UAS and the assumption that only half of them will participate (see Tables 35 and 36 of Report ITU-R M.2171), this corresponds to a cell radius of about 98 km (53 nmi). In the architecture, each UAS gets the use of a 12.5 kHz wide control channel. According to Table 36 of Report ITU-R M.2171, small UAS do not require video or weather radar channels.

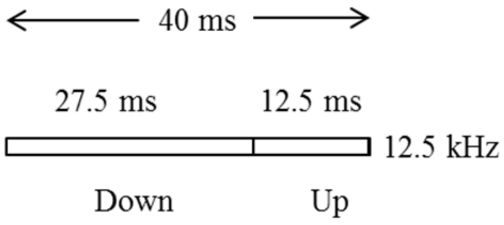
Again, it is assumed that the physical location of the control station antenna for each UA can be anywhere within its operational sector. This does not preclude scenarios in which pilots are connected to their UA via a centralized radio antenna, but that is not required.

3.1.1.1.1.3.2.1 Link layer description

A small UAS channel timing diagram appears in Fig. 10. With less traffic to carry than its medium or large UAS counterpart, the small UAS frequency channel occupies only 12.5 instead of 37.5 kHz. In a 40-ms cycle, each user on a channel has access to a 27.5 ms downlink time slot and a 12.5 ms uplink time slot. After accounting for overhead due to synchronization, header, and guard time, the resulting downlink information rate is 7.9 kbps and the uplink information rate is 2.5 kbps. This presumes that the signalling rate is 12.5 kbaud, the modulation is DQPSK, and the error correction code rate is 29/51 for the downlink and 11/20 for the uplink. It would take 20 of these 12.5 kHz channels to support 20 UA. The access (repetition) rate of this scheme is 25 Hz.

FIGURE 10

Small UAS channel



3.1.1.1.1.3.2.2 Spectrum requirements

The amount of spectrum needed to support 20 small UAS users in a region is 20 × 12.5 kHz for a total of 250 kHz. If we assume that the channels are 12.5 kHz wide and that the channel spacing is 12.5 kHz, then there can be considerable adjacent-channel interference. This would lead to a requirement that adjacent frequency channels not be assigned to neighbouring sectors. The smallest cell pattern for which this is possible is K = 12. For such a pattern, the grand total bandwidth requirement would be 12 × 250 kHz = 3.0 MHz. This is a large amount of bandwidth compared to the actual loading requirements.

For small UAS a better approach would be to use a K = 4 pattern. For this pattern the minimum reuse distance is 170 km (92 nmi), which corresponds to the LoS distance for a UA at 1 300 m (4 200 feet) and a ground antenna mounted on a 30 m (100-foot) tower. Note that a K = 3 pattern is also a possibility; however, its minimum reuse distance is only 98 km (53 nmi), corresponding to a UA altitude of only 335 m (1 100 feet) (with a 30 m (100-foot) ground antenna tower). For either

$K = 3$ or $K = 4$, in order to provide adjacent channel protection, there would need to be guard bands between channels. If we assume that the channel spacing is 17.5 kHz, then the required bandwidth using a $K = 4$ pattern would be 4 × 20 × 17.5 kHz = 1.4 MHz.

It follows that the total bandwidth requirement in the 5-GHz band is 1.4 MHz + 23.4 MHz = 24.8 MHz if a link for small UAS is included, or just 23.4 MHz if the small UAS backup link is not needed in the 5-GHz band.

3.1.1.1.2 Link budget

Table 13 shows a budget for one kind of CNPC link, using a medium and large UAS basic channel, at a range equal to the 127 km (69 nmi) cell radius. A UA at 5 500 m (18 000 feet) above ground level and a ground station with its antenna at the top of a 30 m (100 foot) tower are assumed in the budget. It should be borne in mind that the Orthogonal Frequency-Division Multiplexing (OFDM) waveform requires a relatively linear transceiver system, which often results the need to reduce amplifier efficiency by "backing-off" the amplifier gain. For instance, the assumed 10 watts of transmitter power might need to be generated by a transmitter amplifier rated at about 4 dB higher, i.e., 25 watts. This can have an impact on SWAP and heat dissipation, which is important for the downlink.

The ground antenna gain is assumed to be rather high, 28 dBi. This high gain implies that there is a directional antenna with a diameter of at least 0.64 m pointing at each medium or large UAS. This could complicate the design of centralized ground stations using the OFDM method described previously; but, as noted earlier, the ground stations do not have to be centralized.

TABLE 13

Link budget for basic medium and large UAS channel at 127 km (69 nmi) range

Parameter	Uplink	Downlink
Transmitter power (dBm) (10 watts)	40	40
Transmitting antenna gain (dBi)	28	5
Transmitter cable loss (dB)	1	2
Equivalent isotropically radiated power (e.i.r.p.) (dBm)	67	43
Free-space path loss (5 GHz, 127 km (69 nmi)) (dB)	149	149
Receiving antenna gain (dBi)	5	28
Receiver cable loss (dB)	2	1[a)]
Received signal power (dBm)	–79	–79
Thermal noise at 290 K (dBm/Hz)	–174	–174
Receiver noise figure (dB)	2	2
Receiver bandwidth (dBHz) (37.5 kHz)	46	46
Receiver noise power (dBm)	–126	–126
Signal-to-noise ratio (SNR) (dB)	47	47
Theoretical SNR (dB) for message error rate = 10^{-4}	6	6
Implementation loss margin (dB)	2	2
Required SNR (dB)	8	8
Aviation safety margin (dB)	6	6
Margin (dB)[c)]	33	33

a) Low-noise amplifier assumed to be located near top of ground antenna tower.

b) DQPSK with Reed-Solomon coding (rate = 4/9 on downlink and 5/9 on uplink).

c) The link margin is needed for additional losses caused by multipath propagation, airframe shadowing, and/or destructively interfering airframe reflections that will occasionally result from temporarily unfavourable orientations of the UA with respect to the ground station.

Maximum link ranges are smaller for medium and large UAS wideband downlinks, which can carry video and weather-radar data as well as basic information, because their bandwidths are much larger (300 instead of 37.5 kHz). Ranges are also smaller for small UAS links because their stringent SWAP requirements generally limit their transmitter power levels to one watt (30 dBm) or less, and also because they generally fly much lower than 5 500 m (18 000 feet) and thus tend to be limited by much closer radio horizons than their medium and large UAS counterparts.

3.1.1.2 Compatibility with ARNS

3.1.1.2.1 MLS characteristics

MLS is a precision approach and landing guidance system that provides position information and various ground-to-air data from ground transmitters to airborne receivers at altitudes up to 6 000 m (20 000 feet) and ranges out to 42 km (22.5 nmi). The system's functions may be divided as follows: approach azimuth, back azimuth (missed approach and departure), approach elevation, range, and data communications. All the functions except ranging use the 5 030-5 091 MHz band.

Azimuth guidance equipment is normally located at each end of the runway. The azimuth antenna facing the approaching aircraft is configured as the approach azimuth transmitting antenna, while the opposite antenna becomes the back azimuth transmitting antenna. The approach azimuth transmitter is used to guide the aircraft during an instrument (non-visual) approach to the runway. The azimuth coverage extends to 62 degrees (normally 40 degrees) on either side of the runway.

As viewed by the pilot of an aircraft on final approach to the runway, the azimuth beam is swept from the rightmost coverage angle to the leftmost in the “to” scan and is then returned to the rightmost coverage angle in the “fro” scan after a specified delay at the leftmost limit. The time difference between receptions of the signals during the to and fro scans is determined. Information derived from the data words transmitted to the aircraft by the MLS gives the aircraft MLS receiver specific information with regard to site geometry. This information is used along with beam timing to determine accurately the azimuth angle of the aircraft.

The elevation station transmits signals on the same frequency as the azimuth station. The elevation beam originates at an angle near horizontal (minimum elevation angle), scans to the upper elevation angle limit of 29.5 degrees (normally 15 degrees) in an upward direction (the to scan), and then returns (the fro scan). The time interval between the to and fro scans is measured in the receiver and based on the data transmitted from the ground (concerning site geometry and configuration) the elevation angle of the aircraft is determined.

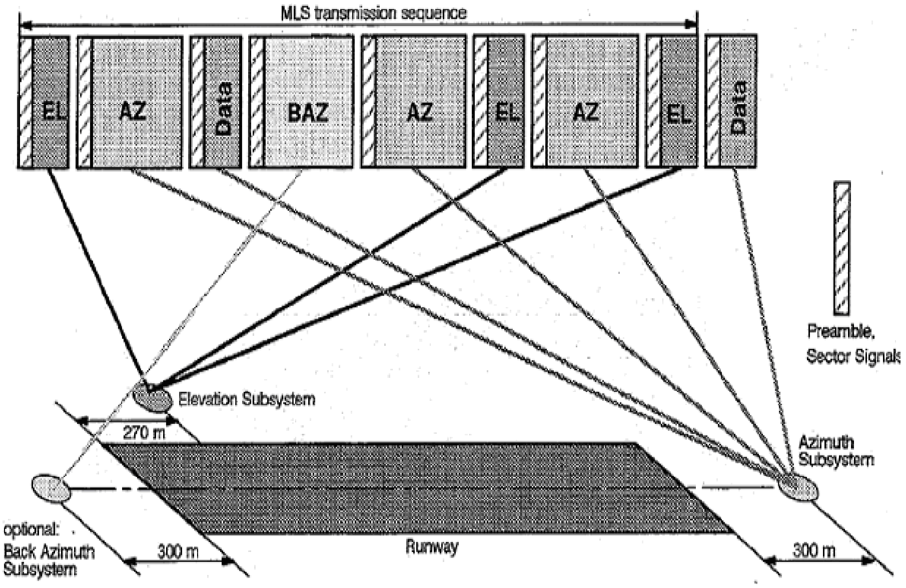
The range signal is produced by the DME, which operates in the 960-1 215 MHz band. The DME is the MLS ranging element, and is responsible for providing the aircraft's slant range to a specified ground position. Precision DME (DME/P) provides for two modes of operation for approaching aircraft. The initial approach (IA) mode is active in the region from 13 km (7 nmi) to 42 km (22.5 nmi) from the DME/P transponder. The final approach (FA) region is from the transponder to a range of 13 km (7 nmi). The FA mode has enhanced precision and tolerances when compared to the IA mode. The narrow-spectrum DME (DME/N) is compatible with the IA mode. DME transponders operate on assigned frequencies that are paired with specific frequencies of the MLS angle transmitters.

MLS data communications include station identification and location, DME channel and status, waypoint coordinates, runway conditions, and weather.

A preamble is transmitted using DPSK modulation. It is followed by angle guidance in azimuth, elevation, and back azimuth transmitted as unmodulated continuous wave (CW) signals. The MLS transmission sequence as depicted in Fig. 11 may include clearance and out-of-coverage indications (OCI), which are emitted as CW and/or pulsed CW. Finally, it may include additional DPSK data radiated over wide angular sectors. Different radiation patterns are obtained by successively reconfiguring the transmission arrays both in the distinct azimuth and elevation stations to achieve: (1) narrow scanning beamwidth of few degrees with high gain (> 20 dBi), (2) intermediate gains for clearance indication (>14 dBi), and (3) wide beamwidth for both the DPSK preamble and additional data transmissions, the latter over the OCI antenna(s), with gains in the 14 to 8 dBi range, particularly if data is required over 360°.

FIGURE 11

MLS transmission sequence



The MLS angle and data functions operate on any one of the 200 channels that are spaced 300 kHz apart between 5 031 and 5 090.7 MHz. (The expansion band up to 5 150 MHz is not currently used.) Each MLS channel is paired with a DME channel. Forty MLS channels paired with DME X and DME W operate between 5 031 and 5 042.7 MHz. One hundred sixty MLS channels paired with DME Y and DME Z operate between 5 043 and 5 090.7 MHz. MLS channels paired with DME W and DME Z are currently not used.

The distance between co-channel MLS stations must be at least 380 km (205 nmi), and the desired/undesired (D/U) received-signal ratios must be at least 26.5 dB. The ground stations operating on the first and second adjacent channels are sited beyond the radio horizon distance from the coverage volume to avoid ground/air intra-MLS interference. Essential MLS parameters are summarized in Table 14.

TABLE 14

MLS characteristics

Frequency range (MHz) for non-DME functions	5 030-5 091
Frequency range (MHz) for DME functions	960-1 215
Power (dBm)	43 (all signals)
Preamble and data (DPSK) antenna gain (dBi)	2 to 8; 0 outside coverage region
Guidance azimuth and elevation (CW) antenna gain (dBi)	Up to 23; 0 outside coverage region
Antenna gains for clearance/out-of-coverage indication (OCI) and DPSK data over 360° (dBi)	Up to 18 for CW, 11 for data over 360°
Airborne antenna gain (dBi) toward MLS ground station	0
Azimuth antenna beamwidth (degrees)	Less than 4
Azimuth scan limits (degrees)	–40 to +40 (typical), –62 to 62 (max)
Azimuth scan duration (ms)	15.9
Elevation antenna beamwidth (degrees)	Less than 2.5
Elevation scan limits (degrees)	0.9 to 15 (typical), 0.9 to 29.5 (max)
Elevation scan duration (ms)	5.6
Polarization	Vertical
Longest continuous DPSK data sequence (ms)	9.3 - 15
Duty factor	25% (DPSK)
DPSK data modulation rate (kHz)	15.625
Maximum tolerable power flux-density (pfd) of unwanted emissions (dBW/m²)	–124.5*
Receiver bandwidth (kHz)	150

* International Civil Aviation Organization, Annex 10, *Aeronautical Telecommunications, Volume 1: Radio Navigation Aids, International Standards and Recommended Practices*, Sixth Edition, July 2006, Attachment G, Paragraph 7.2.4.1. This is equivalent to the –160 dBW threshold referenced in Recommendations ITU-R S.1342 and ITU-R M.1582 (footnote to Table 1).

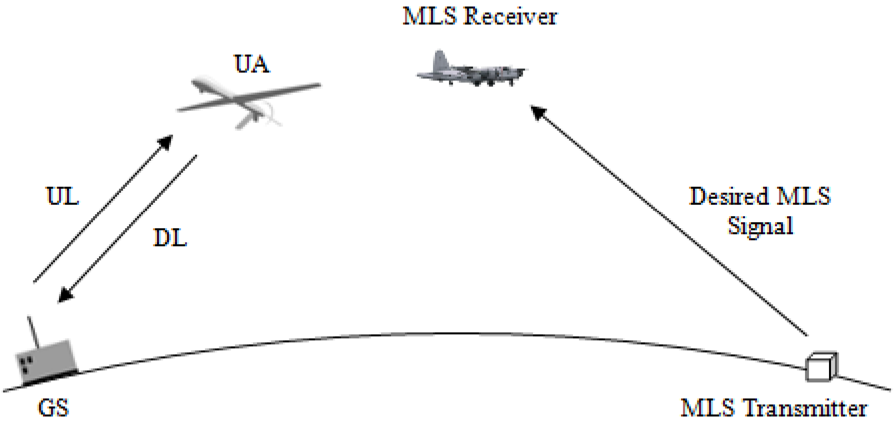
3.1.1.2.2 Compatibility analysis of AM(R)S and MLS

3.1.1.2.2.1 Single interferer analysis

Figure 12 depicts a situation where mutual interference might occur between MLS and a UAS terrestrial CNPC system whose uplink (UL) and downlink (DL) operate in the 5 030-5 091 MHz band, connecting the UAS ground station (GS) and the UA. It will be assumed throughout this analysis that the UL and DL signals are both vertically polarized, like the MLS signal, and that consequently neither system will be protected by polarization isolation against interference from the other system.

FIGURE 12

Coexistence of MLS and terrestrial UAS CNPC links



Four potential interference cases exist between MLS and the terrestrial UAS CNPC system:

1) UAS uplink CNPC transmitter to MLS receiver;

2) MLS transmitter to UAS uplink CNPC receiver;

3) UAS downlink CNPC transmitter to MLS receiver;

4) MLS transmitter to UAS downlink CNPC receiver.

Those four cases are analysed below. A crucial variable in each case is the distance *d* (in nautical miles) between the potentially interfering transmitter and the receiver potentially affected by interference. An important intermediate parameter in determining d_{min}, the minimum value of *d* that suffices to prevent interference, is the frequency-dependent rejection (FDR). That parameter can be calculated as follows:

$$FDR(\Delta f) = 10log_{10}\left[\frac{\int_{-\infty}^{\infty} S(f)df}{\int_{-\infty}^{\infty} S(f)R(f+\Delta f)df}\right] \tag{1-1}$$

where:

$S(f)$: transmitter power spectral density;

$R(f)$: squared magnitude of the frequency-dependent receiver response;

Δf: difference between tuned transmitter and receiver frequencies.

The masks in Figs 13 through 15 show assumed values of $S(f)$ and $R(f)$ for three types of terrestrial CNPC links:

1) a small UAS link carrying only control data, in a 12.5-kHz channel;

2) a "basic" medium and large UAS link carrying all classes of CNPC traffic, *except* video and airborne weather-radar data, in a 37.5-kHz channel;

3) a "wideband" medium and large UAS downlink capable of carrying all classes of CNPC traffic, *including* video and airborne weather-radar data, in a 300-kHz channel;

4) "intermediate" medium and large UAS downlinks (which carry basic and weather-radar data in 75-kHz channels) are not explicitly analysed here, but interference results for them would fall between those to be shown later for basic and wideband channels.

For each type of link, the transmitter and receiver masks are assumed to have identical shapes, so a single graph suffices to depict the transmitter mask and receiver mask for each link type. (The values are shown in decibels, although the integrals will be evaluated in absolute power terms in calculating FDR.)

FIGURE 13

Assumed small UAS transmitter and receiver masks (12.5-kHz channel width)

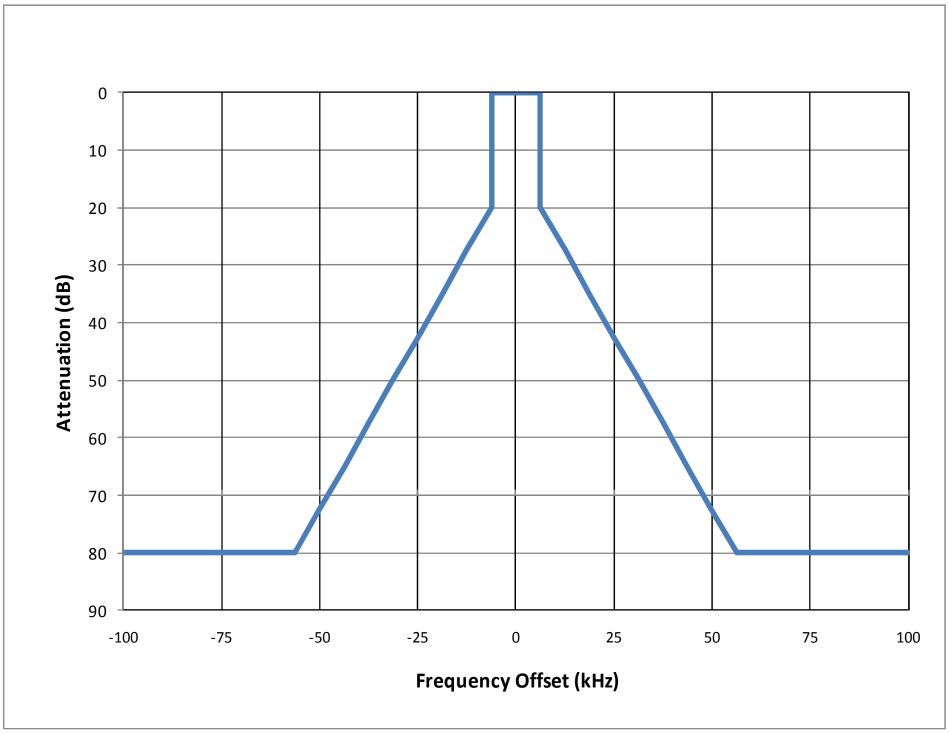


FIGURE 14

Assumed medium and large UAS transmitter and receiver masks for 37.5-kHz basic channel

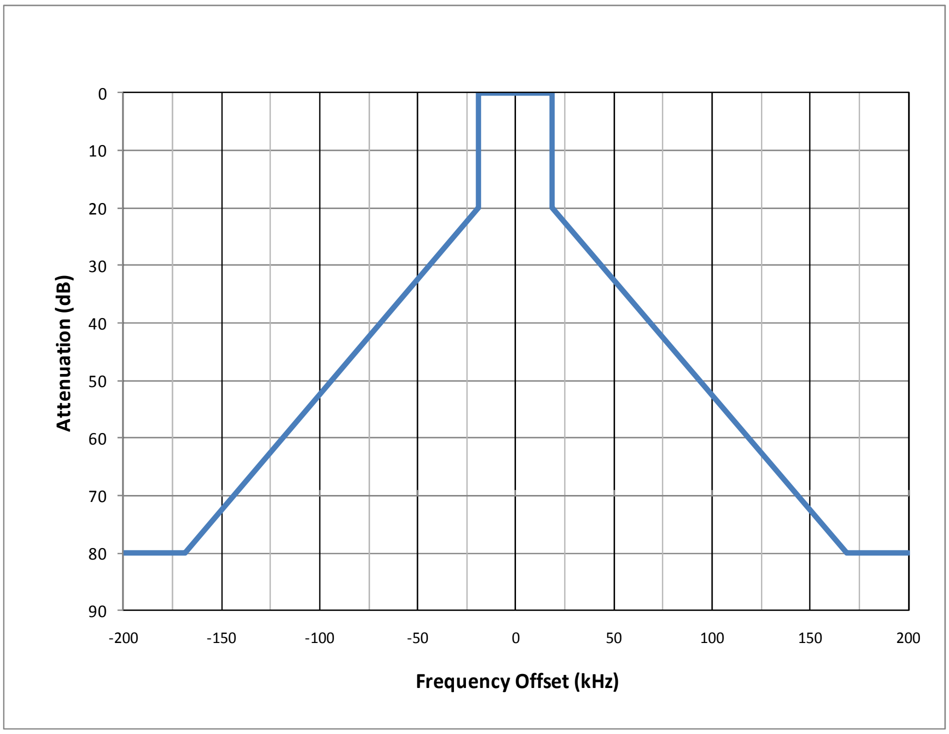


FIGURE 15

Assumed medium and large UAS transmitter and receiver masks for 300-kHz wideband channel

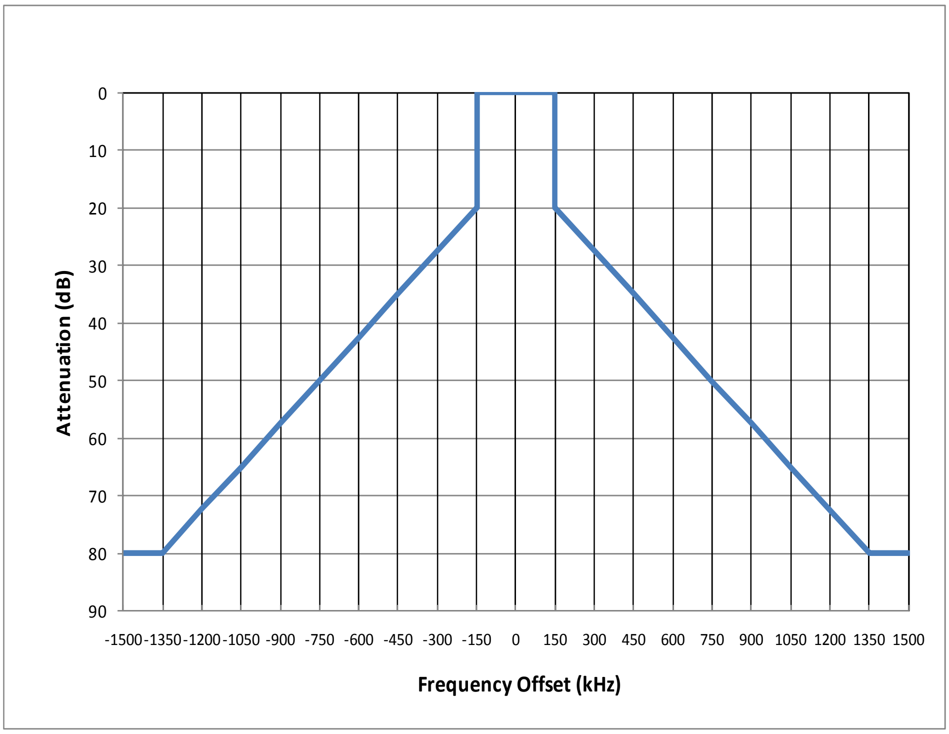


Figure 16 presents an MLS transmitter mask showing the emission attenuation, in decibels, of a DPSK-modulated MLS transmitter. For frequency offsets that are 75 kHz or more from the centre frequency, the curve can be expressed[3] as:

$$10 \log(2\pi^2 f_o^{\,2}/Bf_d)$$

where:

f_d: modulation rate = 15.625 kHz;

B: bandwidth = 150 kHz;

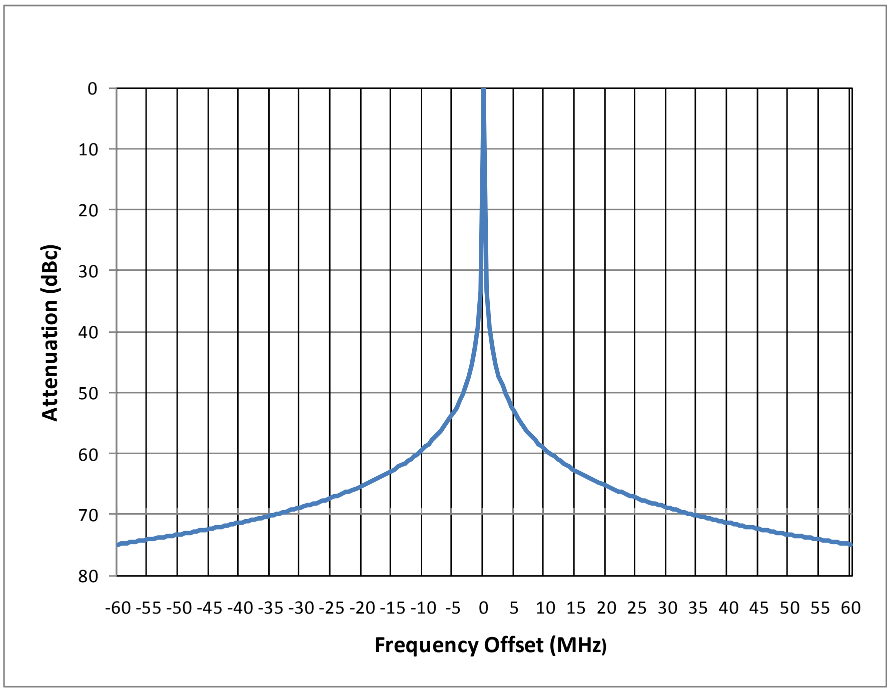
f_o: frequency offset (kHz).

For $|f_o| < 75$ kHz, attenuation is assumed to be 0 dB.

An assumed MLS receiver mask appears in Fig. 16.

FIGURE 16

MLS/DPSK transmitter mask



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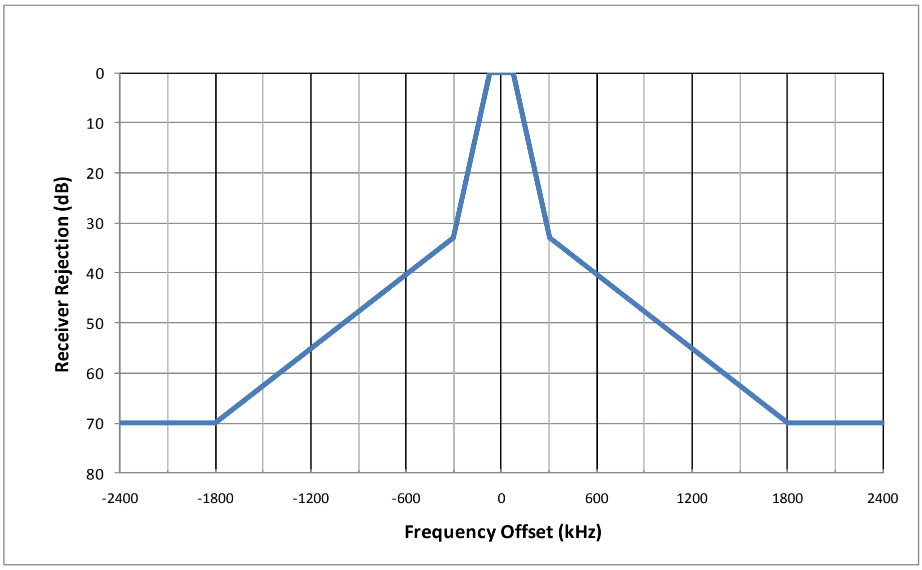
[3] International Civil Aviation Organization, Aeronautical Communications Panel, *MLS DPSK Unwanted Emissions Modelling*, ACP-WGF21/WP10, December 2009.

FIGURE 17

Assumed MLS receiver mask



3.1.1.2.2.1.1 Potential interference from UAS terrestrial uplink transmitter to MLS receiver

In order to avoid causing harmful interference, the pfd of the interfering uplink signal in the vicinity of the MLS receiving antenna should not exceed the MLS interference threshold. This can be expressed as the following PFD equation:

$$P_{eu} - 30 - 10 \log (4\pi) - 20 \log (1\,000 d_{min}) - FDR = T_{MLS} \qquad (1\text{-}2)$$

where:

P_{eu}: e.i.r.p. of undesired transmitter (dBm);

d_{min}: minimum required distance separation (km);

FDR: frequency-dependent rejection (dB);

T_{MLS}: MLS interference threshold = −124.5 dBW/m².

It follows that

$$d_{min} = \text{antilog}\,((P_{eu} - 101 - T_{MLS}) / 20) \times 10^{-FDR/20} \qquad (1\text{-}3)$$

For a medium or large UAS uplink whose e.i.r.p. is 67 dBm, this expression reduces to $d_{min} = 33\,497 \times 10^{-FDR/20}$. Together with the FDR values calculated using the basic medium and large UAS transmitter mask of Fig. 14, the MLS receiver mask of Fig. 17, and equation (1-1), the resulting minimum allowable distance separation values are displayed in Table 15. (The wideband medium and large UAS mask is not considered here, because it applies only to downlinks.)

TABLE 15

Minimum distance between medium and large UAS terrestrial uplink transmitter and MLS receiver

Δf (kHz)	**0**	**300**	**600**	**1 200**	**1 800**	**2 400**	**2 700**	**≥ 3 000**
FDR (dB)	0	32.3	40.3	54.8	65.8	68.0	68.0	68.1
d_{min} (km)	**342**[1]	**342**[1]	324	61	17.1	13.3	13.3	13.2
d_{min} (nmi)	**185**	**185**	**175**	**32.9**	**9.3**	**7.2**	**7.2**	**7.1**

[1] Based on equation 1-3, the separation distances are 33 497 km and 813 km respectively when $\Delta f = 0$ kHz and $\Delta f = 300$ kHz, which are far beyond LoS. The actual separation distance requirements 342 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS service volume (6 000 m) and H_2 is the height of UACS transmitter antenna (30 m).

For a small UAS uplink with an e.i.r.p. of only 57 dBm (10 dB lower), the expression becomes $d_{min} = 10\ 593 \times 10^{-FDR/20}$. The changed FDR and distance-separation values appear in Table 16.

TABLE 16

Minimum distance between small UAS terrestrial uplink transmitter and MLS receiver

Δf (kHz)	**0**	**300**	**600**	**1 200**	**1 800**	**2 400**	**2 700**	**≥ 3 000**
FDR (dB)	0	32.8	40.3	54.7	64.3	65.8	65.8	65.8
d_{min} (km)	**342**[1]	243	102.3	19.5	6.5	5.4	5.4	5.4
d_{min} (nmi)	**185**	**131**	**55.3**	**10.5**	**3.5**	**2.9**	**2.9**	**2.9**

[1] Based on equation 1-3, the separation distances is 10 593 km when $\Delta f = 0$ kHz, which is far beyond LoS. The actual separation distance requirement 342 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the maximum height of MLS service volume (6 000 m) and H_2 is the height of UACS transmitter antenna (30 m).

The results of Tables 15 and 16 suggest that UAS terrestrial uplink transmitters should not point their main beams directly at nearby aircraft that are actively using MLS receivers unless mitigation techniques such as power control are used.

3.1.1.2.2.1.2 Potential interference from MLS to UA receiver

A potential worst-case situation for MLS interference to the UAS uplink would seem to arise when the UA is within the coverage angle of the unmodulated MLS azimuth and elevation transmissions that have antenna gains of up to 23 dBi. However, those high-gain antennas scan continuously throughout the coverage volume and so will appear as brief pulses (≤ 0.5 ms) with repetition intervals of 5.6-15.9 ms to any UA receivers they illuminate; the average received power would be 10-15 dB less, affording protection to UA receivers with sufficiently long integration times. Moreover, the emission spectrum of the unmodulated signal is much narrower and falls to –70 dB referred to the carrier (dBc) much faster than the MLS/DPSK emission mask shown in Fig. 16. Accordingly, this analysis instead considers the DPSK-modulated signal, whose antenna gain can be as high as 11 dBi, as the actual worst-case interferer.

Using the above assumptions, the minimum allowance distance d_{min} is calculated as the *largest* distance at which the undesired MLS signal entering the receiver could be equal to the noise level of the UAS uplink receiver:

$$P_{tu} + G_{tu} - 20\log(fd_{min}) - 32.5 - FDR + G_{ru} - L_r = N \qquad (1\text{-}4)$$

where:

P_{tu}: MLS transmitter power = 43 dBm;

G_{tu}: MLS transmitter antenna gain = 11 dBi;

f: frequency = 5 060 MHz;

FDR: is calculated from the MLS transmitter mask and the UAS receiver mask;

G_{ru}: UAS receiving antenna gain (dBi) toward MLS transmitter = 5 dBi;

L_r: UA receiver cable loss = 2 dB;

N: UA receiver noise level in dBm.

It follows that

$$d_{min} = \text{antilog}\ ((-49.6 - \text{N})/20) \times 10^{-FDR/20} \qquad (1\text{-}5)$$

Since $N = -126$ dBm for the basic medium and large UAS receiver of the link budget in Table 13, $d_{min} = 6\,607 \times 10^{-FDR/20}$ for the medium and large UAS case. The calculated FDR and d_{min} values are given in Table 17 below.

TABLE 17

Minimum distance between MLS transmitter and medium or large UA receiver

Δf (kHz)	**0**	**300**	**600**	**900**	**1 500**	**3 000**	**6 000**	**15 000**
FDR (dB)	6.1	34.9	40.9	44.5	48.9	54.9	60.9	68.6
d_{min} (km)	**425**[1]	118.9	59.6	39.4	23.7	11.9	6.0	2.5
d_{min} (nmi)	**229**	**64.2**	**32.2**	**21.3**	**12.8**	**6.4**	**3.2**	**1.3**

[1] Based on equation 1-3, the separation distances is 3 273 km when $\Delta f = 0$ kHz, which is far beyond LoS. The actual separation distance requirement 425 km can be calculated via standard equation $4.12\times(\sqrt{H_1}+\sqrt{H_2})$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the UA height (10 000 m).

For the case where the interference victim is a small UAS uplink, the channel width is only 12.5 kHz (one-third that of the basic medium or large UAS uplink) and so $N = -131$ dBm. Consequently, for the MLS-to-small-UAS-uplink case, $d_{min} = 11\,749 \times 10^{-FDR/20}$. The calculated FDR and d_{min} values for that case appear in Table 18.

TABLE 18

Minimum distance between MLS transmitter and small UA receiver

Δf (kHz)	**0**	**300**	**600**	**900**	**1 500**	**3 000**	**6 000**	**15 000**
FDR (dB)	10.7	39.5	45.5	50.0	53.4	59.4	65.3	72.6
d_{min} (km)	**425**[1]	124.5	62.4	37,2	25.1	12.6	6.4	2.8
d_{min} (nmi)	**229**	**67.2**	**33.7**	**20.1**	**13.6**	**6.8**	**3.4**	**1.5**

[1] Based on equation 1-3, the separation distances is 3 428 km when $\Delta f = 0$ kHz, which is far beyond LoS. The actual separation distance requirement 425 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the UA height (10 000 m).

It follows from Tables 17 and 18 that if a UA using a 5 GHz-band terrestrial CNPC uplink needs to operate less than about 2.8 km (1.5 nmi) from an active MLS transmitter, the CNPC ground station should be closer to the UA than the maximum link ranges assumed in the earlier discussion of CNPC link budgets. A shorter link range would provide the CNPC uplink with additional margin for avoiding interference from MLS.

3.1.1.2.2.1.3 Potential interference from UA transmitter to MLS receiver

Equation (1-3), derived earlier for the uplink-to-MLS interference analysis, applies to this case as well. Three different sets of results will be derived, for the cases in which the potentially interfering downlink is medium and large UAS wideband, medium and large UAS basic, and small UAS, respectively.

For the medium and large UAS downlinks, P_{eu} = 43 dBm and equation (1-3) reduces to $d_{min} = 2\,113 \times 10^{-FDR/20}$.

For the small UAS link budget, the transmitter power and thus P_{eu} are assumed to be 10 dB lower than for medium and large UAS, so the small UAS value of P_{eu} will be 33 dBm and equation (1-3) becomes $d_{min} = 668 \times 10^{-FDR/20}$.

For each of the three cases, a different transmitter mask is used in computing FDR. The calculated FDR and d_{min} values for the three cases are presented in Tables 19 through 21 below.

TABLE 19

Minimum distance between wideband medium and large UA transmitter and MLS receiver

Δf (kHz)	**0**	**300**	**600**	**1 200**	**1 800**	**2 400**	**2 700**	**≥ 3 000**
FDR (dB)	1.7	20.2	37.6	54.2	66.4	69.5	69.7	69.7
d_{min} (km)	**732**[1]	206.5	27.9	4.1	1.0	0.7	0.7	0.7
d_{min} (nmi)	**395**	**111.5**	**15.0**	**2.2**	**0.5**	**0.4**	**0.4**	**0.4**

[1] Based on equation 1-3, the separation distances is 1 737 km when $\Delta f = 0$ kHz, which is far beyond LoS. The actual separation distance requirement 732 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the maximum height of MLS service volume (6 000 m) and H_2 is the UA height (10 000 m).

TABLE 20

Minimum distance between basic medium and large UA transmitter and MLS receiver

Δf (kHz)	**0**	**300**	**600**	**1 200**	**1 800**	**2 400**	**2 700**	**≥ 3 000**
FDR (dB)	0	32.3	40.3	54.8	65.8	68.0	68.0	68.1
d_{min} (km)	**732**[1]	51.3	20.4	3.8	1.1	0.8	0.8	0.8
d_{min} (nmi)	**395**	**27.7**	**11.0**	**2.1**	**0.6**	**0.5**	**0.5**	**0.4**

[1] Based on equation 1-3, the separation distances is 2 113 km when $\Delta f = 0$ kHz, which is far beyond LoS. The actual separation distance requirement 732 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the maximum height of MLS service volume (6 000 m) and H_2 is the UA height (10 000 m).

TABLE 21

Minimum distance between small UACS transmitter and MLS receiver

Δf (kHz)	**0**	**300**	**600**	**1 200**	**1 800**	**2 400**	**2 700**	**≥ 3 000**
FDR (dB)	0	32.8	40.3	54.7	64.3	65.8	65.8	65.8
d_{min} (km)	**668**	15.3	6.5	1.2	0.41	0.34	0.34	0.34
d_{min} (nmi)	**361**	**8.3**	**3.5**	**0.7**	**0.22**	**0.18**	**0.18**	**0.18**

In all three of these downlink-to-MLS interference cases, d_{min} exceeds 300 m (1 000 feet) even for the largest possible values of Δf. In order for the UA to fly as close as 300 m (1 000 feet) from an MLS-equipped aircraft, the power of its downlink transmitter would need to be reduced somewhat from the values assumed here: by about 7 dB for the wideband medium and large UAS downlink, 9 dB for the basic medium and large UAS downlink, and 1 dB in the case of the small UAS downlink. These reductions in downlink power levels would be necessary only when the UA approached within 0.9 km (0.5 nmi) of an MLS service volume (i.e. within 42.6 km (23 nmi) of the MLS transmitter at the centre of the service volume, whose radius is 42 km (22.5 nmi)).

3.1.1.2.2.1.4 Potential interference from MLS to UACS receiver

Equation (1-4), derived in § 3.1.1.2.2.1.2 for the MLS-to-uplink interference analysis, also applies here. Although the downlink receiving antenna's main-beam gain is 28 dBi, we will assume here that the antenna beam is pointed sufficiently far away (at least 15 degrees in azimuth and/or elevation) from the MLS transmitter that G_{ru} will be a side lobe gain value not exceeding 5 dBi. Cable loss L_r is only 1 dB for the downlink receiver. P_{tu}, G_{tu}, and f have the same values as in § 3.1.1.2.2.1.2. Three cases must be considered because there are three different downlink receiver masks (medium and large UAS wideband, medium and large UAS basic, and small UAS). Each of the three downlink receiver types has a different noise level. For the basic receiver considered in the link budget, the bandwidth is 37.5 kHz and $N = -126$ dBm. For the wideband receiver, whose bandwidth is 300 kHz (eight times as large), the noise level is 9 dB higher: $N = -117$ dBm. The small UAS receiver has a 12.5-kHz bandwidth and hence a noise level of –131 dBm.

For the wideband medium and large UAS case, solving the equation yields $d_{min} = 2\,630 \times 10^{-FDR/20}$ and the results are as shown in Table 22.

TABLE 22

Minimum distance between MLS transmitter and wideband medium or large UACS receiver

Δf (kHz)	**0**	**300**	**600**	**900**	**1 500**	**3 000**	**6 000**	**15 000**
FDR (dB)	**0**	22.6	31.2	35.2	39.8	45.8	51.8	59.8
d_{min} (km)	**35.6**[1]	**35.6**[1]	35.6[2]	35.6[2]	27.0	13.5	6.8	2.7
d_{min} (nmi)	**19.2**	19.2	**19.2**	**19.2**	**15.0**	**7.3**	**3.7**	**1.5**

[1] Based on equation 1-3, the separation distances are 2 630 km and 195 km respectively when Δf = 0 kHz and Δf = 300 kHz, which are far beyond LoS. The actual separation distance requirements 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the height of UAS terrestrial receiver antenna (30 m).

[2] The separation distances are 72 km and 46 km respectively when Δf = 600 kHz and Δf = 900 kHz, which are beyond LoS. The actual separation distance requirements 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the height of UACS receiver antenna (30 m).

For the basic case, the equation yields $d_{min} = 7\,413 \times 10^{-FDR/20}$. The results appear in Table 23.

TABLE 23

Minimum distance between MLS transmitter and basic medium or large UACS receiver

Δf (kHz)	**0**	**300**	**600**	**900**	**1 500**	**3 000**	**6 000**	**15 000**
FDR (dB)	6.1	34.9	40.9	44.5	48.9	54.9	60.9	68.6
d_{min} (km)	**35.6**[1]	**35.6**[1]	35.6[2]	35.6[2]	27	13.3	6.7	2.8
d_{min} (nmi)	**19.2**	**19.2**	**19.2**	**19.2**	**15**	**7.2**	**3.6**	**1.5**

[1] Based on equation 1-3, the separation distances are 3 673 km and 133 km respectively when Δf = 0 kHz and Δf = 300 kHz, which are far beyond LoS. The actual separation distance requirements 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the height of UAS terrestrial receiver antenna (30 m).

[2] The separation distances are 67 km and 44 km respectively when Δf = 600 kHz and Δf = 900 kHz, which are beyond LoS. The actual separation distance requirements 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the height of UACS receiver antenna (30 m).

For the small UAS case, the equation yields $d_{min} = 13\,183 \times 10^{-FDR/20}$. The results appear in Table 24.

TABLE 24

Minimum distance between MLS transmitter and small UAS terrestrial downlink receiver

Δf (kHz)	**0**	**300**	**600**	**900**	**1 500**	**3 000**	**6 000**	**15 000**
FDR (dB)	10.7	39.5	45.5	50.0	53.4	59.4	65.3	72.6
d_{min} (km)	**35.6**[1]	**35.6**[1]	35.6[2]	35.6[2]	28	14.1	7.2	3.1
d_{min} (nmi)	**19.2**	**19.2**	**19.2**	**19.2**	**15**	**7.6**	**3.9**	**1.7**

[1] Based on equation 1-3, the separation distances are 3 846 km and 140 km respectively when $\Delta f = 0$ kHz and $\Delta f = 300$ kHz, which are far beyond LoS. The actual separation distance requirements 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the height of UAS terrestrial receiver antenna (30 m).

[2] The separation distances are 70 km and 42 km respectively when $\Delta f = 600$ kHz and $\Delta f = 900$ kHz, which are beyond LoS. The actual separation distance requirements 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the height of UACS receiver antenna (30 m).

It follows from Tables 22, 23, and 24 that 5 GHz-band UAS CNPC downlink receiving stations should not be placed within about 3 km (1.6 nmi) of MLS transmitters. The CNPC downlink receiving antenna should not be aimed within 15 degrees (in azimuth or elevation) of any MLS transmitter to which it has a direct LoS, unless larger distance separations than those shown in Tables 22, 23, and 24 are maintained.

3.1.1.2.2.2 Aggregate interference analysis

The compatibility analysis of the preceding subsection considered single-interferer cases in which the victim receiver was exposed only to the undesired signal of a single potentially interfering transmitter. It is also possible for multiple interfering signals to be present, but in most situations involving terrestrial radios (airborne or ground-based) a single undesired signal is much stronger than all other undesired signals combined. A major reason for this is the squared distance dependency of free-space propagation loss. For example, an undesired signal entering an MLS receiver from a single UA downlink transmitter 300 m away would be 10 dB stronger than the combined signals from 10 identical UA that were each 3 km away. Many of those UA would almost certainly be oriented in such a way that their maximum e.i.r.p.s in the direction of the victim MLS receiver would be less than the worst-case values assumed in the single-interferer analysis. Higher UA densities might increase aggregate power levels but would tend to violate air traffic control separation rules. For these reasons, observance of the single-interferer rules derived above will suffice to protect MLS and CNPC from mutual interference under realistic operational conditions.

3.1.1.2.2.3 Conclusion of the study between AM(R)S and ARNS

The foregoing analysis of terrestrial 5 GHz-band UAS CNPC compatibility with MLS has shown that all cases of potential interference between the terrestrial CNPC system and MLS could be prevented through appropriate combinations of frequency separation, proper placement of CNPC ground sites, and (when necessary) additional mitigation measures such as power control.

In case of operation of UAS in the same occupied bandwidth (150 kHz) with MLS in the band 5 030-5 091 MHz, it would be difficult to achieve compatibility between these two systems.

In order to avoid interference from UAS terrestrial CNPC links to MLS system operating in the same occupied bandwidth, the minimum separation distance requirements can be drawn from the study results in the minimum distance tables. The separation distance from UAS terrestrial uplink transmitter to MLS receiver should not be less than 432 km, and the separation distance from UAS terrestrial downlink transmitter to MLS receiver should not be less than 732 km.

3.1.1.2.3 Compatibility with AMS(R)S

3.1.1.2.3.1 Proposed AMS(R)S system characteristics

A satellite communications (SATCOM) system that would use the existing AMS(R)S allocation in the 5 030-5 091 MHz band has been proposed for use by UAS CNPC links. It would employ several geostationary satellites, each creating numerous spot beams within its coverage area, to support a forward link (FL) and a return link (RL) between each participating ground earth station (GES) and airborne Earth station (AES). Each SATCOM link includes an Earth-to-space (E/S) and a space-to-Earth (S/E) path. Table 25 summarizes the salient RF characteristics of the proposed system.

TABLE 25

AMS(R)S system characteristics

Link	**Forward**		**Return**	
Direction	Earth-to-space	Space-to-Earth	Earth-to-space	Space-to-Earth
Abbreviation	FL (E/S)	FL (S/E)	RL (E/S)	RL (S/E)
Frequency range (MHz)	5 071-5 091	5 030-5 050	5 071-5 091	5 030-5 050
Channel width (kHz)	37.5	37.5	150	150
Polarization	Circular	Circular	Circular	Circular
Transmitting station	GES	Satellite	AES	Satellite
Transmitting antenna gain (dBi)	44.1	45.1	3.0	45.1
Transmitter e.i.r.p. per carrier (dBm)	79.6	77.7	47.0	47.1
Total path loss (dB)	198.0	198.5	198.5	198.0
Receiving station	Satellite	AES	Satellite	GES
Receiving antenna gain (dBi)	45.1	3.0	45.1	44.1
Receiving station G/T (dB/K)	18.7	–23.0	18.7	18.8

3.1.1.2.3.2 Compatibility analysis of potential AM(R)S and AMS(R)S systems

Shared operation within the 5 030-5 091 MHz band of separate AM(R)S and AMS(R)S systems for UAS CNPC creates the possibility of mutual interference between the two systems. Figure 18 illustrates the potentially interfering links. The terrestrial system provides an uplink (UL) and downlink (DL) between a ground station (GS) and a UA. Table 26 identifies the potential interference cases to be studied.

FIGURE 18

Coexistence of AM(R)S and AMS(R)S CNPC links

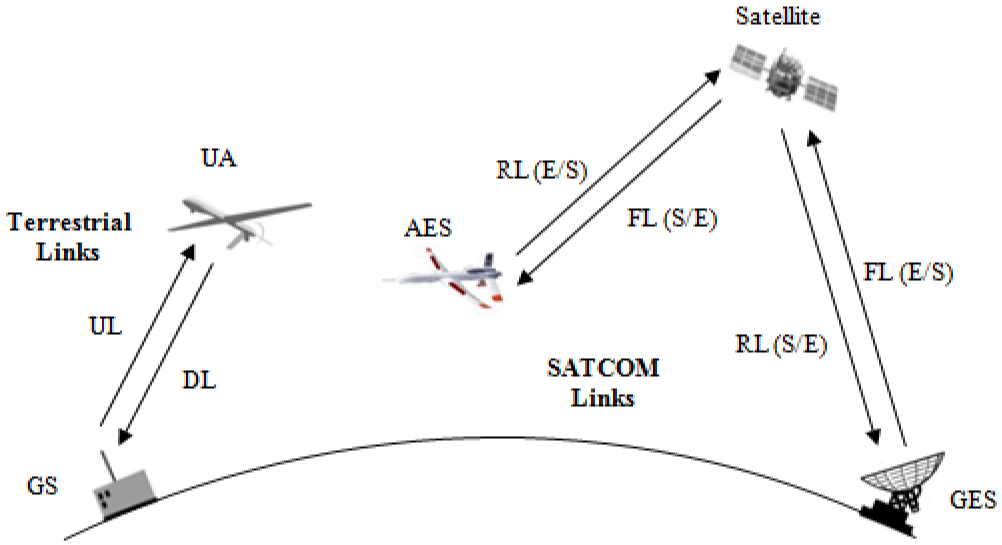


TABLE 26

Potential interference cases between AM(R)S and AMS(R)S CNPC links

Case	Interference source link	Interference victim link
1.1	UL	FL (E/S)
1.2	UL	RL (E/S)
1.3	FL (E/S)	UL
1.4	RL (E/S)	UL
2.1	UL	FL (S/E)
2.2	UL	RL (S/E)
2.3	FL (S/E)	UL
2.4	RL (S/E)	UL
3.1	DL	FL (E/S)
3.2	DL	RL (E/S)
3.3	FL (E/S)	DL
3.4	RL (E/S)	DL
4.1	DL	FL (S/E)
4.2	DL	RL (S/E)
4.3	FL (S/E)	DL
4.4	RL (S/E)	DL

Assumed values of satellite spot isolation are shown in Table 27. An undesired signal approaching or leaving the satellite via a spot beam adjacent to that of the desired signal is said to have a "spot separation" of 1 and is attenuated at least 3 dB by the beam's off-axis pattern characteristics. When the spot separation is 2 or greater, the undesired signal passes through the antenna side lobes, which attenuate it by at least 25 dB.

TABLE 27

Spot isolation

Spot separation	Resultant spot isolation (dB)
0	0
1	3
≥ 2	25

The transmitter masks and receiver selectivity curves assumed in this analysis for SATCOM forward and return links are shown in Figs 19 and 20.

FIGURE 19

Assumed transmitter and receiver masks for AMS(R)S forward links

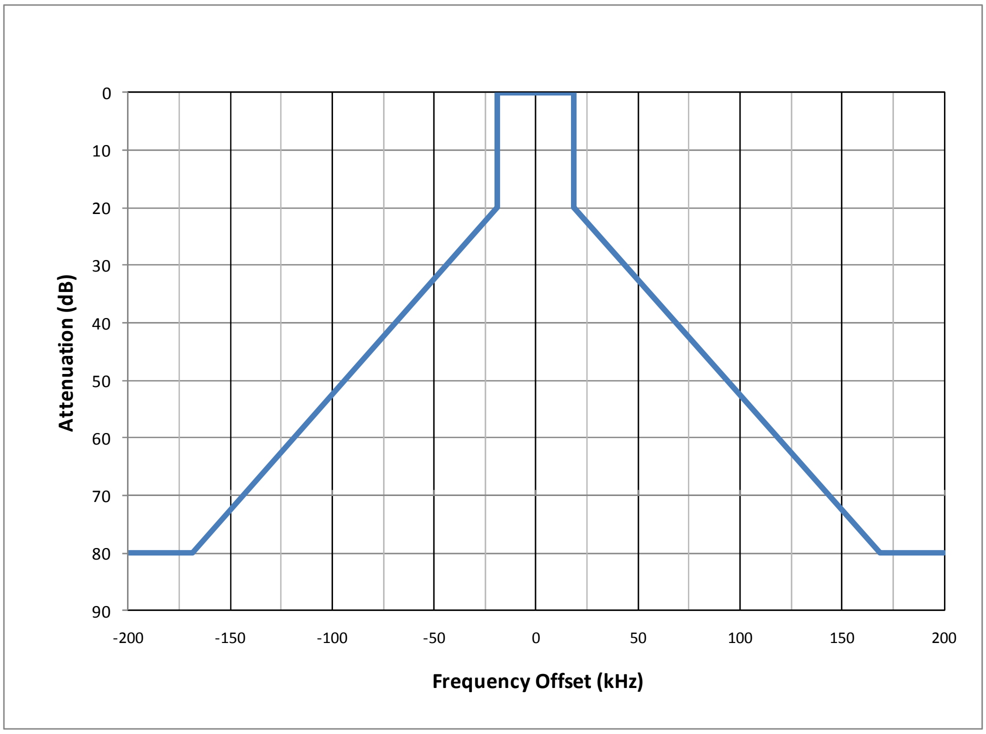


FIGURE 20

Assumed transmitter and receiver masks for AMS(R)S return links

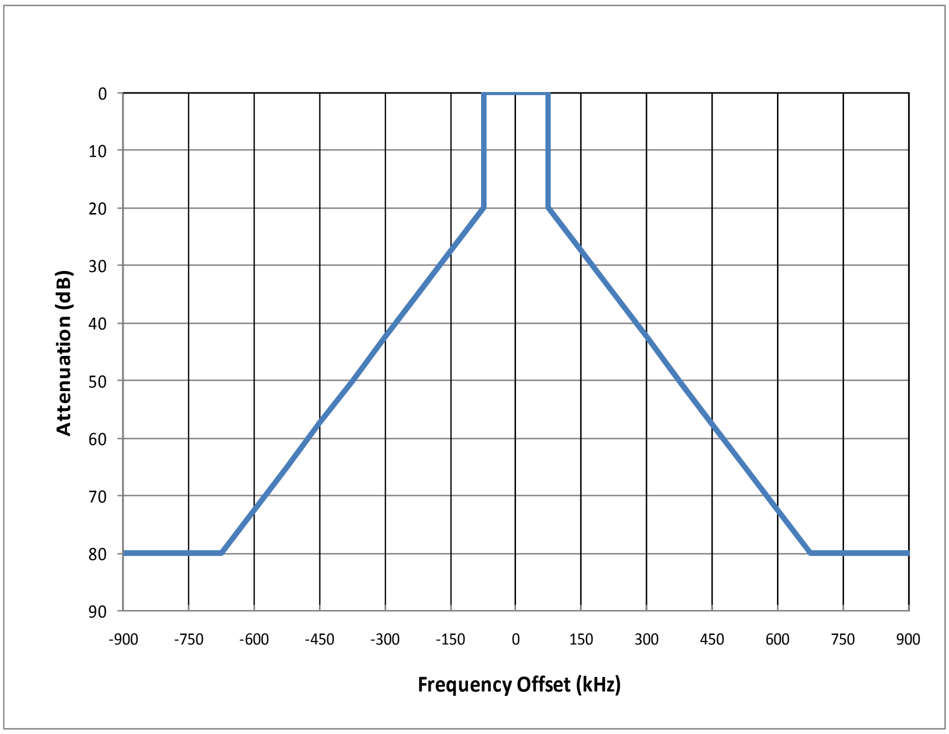


Table 28 summarizes the relevant parameters associated with each of the 16 cases of potential interference between the terrestrial and SATCOM CNPC links. In every case, the terrestrial link is assumed to be a medium or large UAS link (discussed in § 3.1.2.1.3). This is a worst-case assumption, since medium and large UAS terrestrial links will have much larger e.i.r.p.s and bandwidths than small UAS links, making them more prone to becoming sources or victims of interference with SATCOM links in any given situation. Since medium and large UAS terrestrial downlinks can operate either in a "basic" mode with a 37.5-kHz bandwidth, an "intermediate" mode with a 75-kHz bandwidth, or a wideband mode with a 300-kHz bandwidth, we make the additional conservative assumption that each terrestrial DL is in the basic (narrowband) mode when considered as a source of interference but in the wideband mode when considered as a victim; for large frequency separations this maximizes the potential interference in each case. (All medium and large UAS uplinks operate in the basic mode, so wideband operation is never considered for them.)

TABLE 28

Interference parameters

Case	Interference source link	Interference victim link	Locations of terminals [a]				Source transmitter		Propagation loss (dB) of undesired signal[c] at 5 060 MHz (*d* in km)	Victim receiver			
			Source link		Victim link		Undesired e.i.r.p. (dBm)	Band-width (kHz)[b]		Undesired antenna gain (dBi)	Cable/ Feeder loss (dB)	Band-width (kHz)[b]	Noise power (dBm)[d]
			Tx	Rx	Tx	Rx							
1.1	UL	FL (E/S)	GS	UA	GES	Sat.	67.0	37.5	198.0	45.1	0.5	37.5	–126.5
1.2	UL	RL (E/S)	GS	UA	AES	Sat.	67.0	37.5	198.0	45.1	0.5	150.0	–120.4
1.3	FL (E/S)	UL	GES	Sat.	GS	UA	79.6	37.5	106.5 + 20 log *d*	5.0	2.0	37.5	–126.2
1.4	RL (E/S)	UL	AES	Sat.	GS	UA	47.0	150.0	106.5 + 20 log *d*	5.0	2.0	37.5	–126.2
2.1	UL	FL (S/E)	GS	UA	Sat.	AES	67.0	37.5	106.5 + 20 log *d*	3.0	2.0	37.5	–126.9
2.2	UL	RL (S/E)	GS	UA	Sat.	GES	67.0	37.5	106.5 + 20 log *d*	0.0 [e]	1.0	150.0	–121.5
2.3	FL (S/E)	UL	Sat.	AES	GS	UA	77.7	37.5	198.0	5.0	2.0	37.5	–126.2
2.4	RL (S/E)	UL	Sat.	GES	GS	UA	47.1	37.5	198.0	5.0	2.0	37.5	–126.2
3.1	DL	FL (E/S)	UA	GS	GES	Sat.	43.0	37.5	198.0	45.1	0.5	37.5	–126.5
3.2	DL	RL (E/S)	UA	GS	AES	Sat.	43.0	37.5	198.0	45.1	0.5	150.0	–120.4
3.3	FL (E/S)	DL	GES	Sat.	UA	GS	35.5 [e]	37.5	106.5 + 20 log *d*	28.0	1.0	300.0	–117.2
3.4	RL (E/S)	DL	AES	Sat.	UA	GS	47.0	150.0	106.5 + 20 log *d*	28.0	1.0	300.0	–117.2
4.1	DL	FL (S/E)	UA	GS	Sat.	AES	43.0	37.5	106.5 + 20 log *d*	3.0	2.0	37.5	–126.9
4.2	DL	RL (S/E)	UA	GS	Sat	GES	43.0	37.5	106.5 + 20 log *d*	44.1	1.0	150.0	–121.5
4.3	FL (S/E)	DL	Sat.	AES	UA	GS	77.7	37.5	198.0	28.0	1.0	300.0	–117.2
4.4	RL (S/E)	DL	Sat	GES	UA	GS	47.1	37.5	198.0	28.0	1.0	300.0	–117.2

a Terminal identifiers: UA denotes aircraft carrying terrestrial (AM(R)S) radio. AES is aircraft carrying SATCOM (AMS(R)S) radio. GS is terrestrial ground station. GES is SATCOM ground earth station.

b Terrestrial downlink (DL) is assumed to be in basic mode (37.5-kHz bandwidth) when considered as interference source, but in wideband mode (300-kHz bandwidth) when considered as interference victim.

c 198.0-dB path loss is conservatively assumed for all undesired E/S and S/E signals.

d Noise figure of 2 dB is assumed for each terrestrial receiver. SATCOM receiver noise values were calculated from antenna gains, *G*/*T* values and channel widths listed in Table 25.

e GES antenna is assumed to have 0-dBi side lobe gain in direction of GS.

The SATCOM receiver noise values in Table 28 were calculated as $N = kTB = kBG/(G/T)$, where k is Boltzmann's constant, B is channel width, G is antenna gain, and G and G/T are expressed non-logarithmically. In logarithmic terms, this becomes $N\,(\text{dBm}) = -168.6 + 10 \log B\,(\text{kHz}) + G\,(\text{dBi}) - (G/T)\,(\text{dB}/K)$.

Since the SATCOM links are circularly polarized and the terrestrial links are vertically polarized, their mutual cross-polarization loss will be assumed equal to 3 dB throughout this analysis.

Case 1.1: Potential interference from terrestrial uplink to forward Earth-to-space link

The interference-prevention criterion used in this analysis is an interference-to-noise ratio (INR) below a specified threshold value T in decibels. This can be expressed as

$$INR = P_{eu} - L_p - L_x - FDR - R_s + G_{ru} - L_r - N \leq T \tag{1-6}$$

where:

P_{eu}: source e.i.r.p. (dBm);

L_p: path loss (dB);

L_x: cross-polarization loss = 3 dB for all cases studied here;

FDR: frequency-dependent rejection (dB);

R_s: spot isolation (dB) as shown in Table 27;

G_{ru}: receiving antenna gain (dBi);

L_r: receiver cable or feeder loss (dB);

N: receiver noise power (dBm);

T: maximum allowable INR;

T: –6 dB when the victim link is Earth-to-space or space-to-Earth;

T: 0 dB when the victim link is terrestrial.

The resultant INR values for various frequency differences and spot separations are shown in Table 29 below. There is little potential for interference in this case, even when the GS and GES are in the same spot, except when their frequency separations are quite small.

TABLE 29

INR caused by terrestrial uplink in forward Earth-to-space link satellite receiver

Δf (kHz)		0	30	60	90	120	150	210	≥ 240
FDR (dB)		0	7.1	31.5	43.5	55.4	66.9	76.8	77.0
INR (dB) when GES and GS are:	In same spot	37.1	30.0	5.6	–6.4	–18.3	–29.8	–39.7	–39.9
	In adjacent spots	34.1	27.0	2.6	–9.4	–21.3	–32.8	–42.7	–42.9
	Farther apart	12.1	5.0	–19.4	–31.4	–43.3	–54.8	–64.7	–64.9

Expression (1-6) will also be used below for the analysis of cases 1.2, 2.3, 2.4, 3.1, 3.2, 4.3, and 4.4.

Case 1.2: Potential interference from terrestrial uplink to return Earth-to-space link

Evaluating (1-6) in this case yields the results of Table 30. Frequency separations of 240 kHz or more will suffice to avoid any risk of interference in this case.

TABLE 30

INR caused by terrestrial uplink in return Earth-to-space link satellite receiver

Δf (kHz)		0	120	240	360	480	540	600	≥ 900
FDR (dB)		0	24.1	36.4	48.3	60.1	65.5	69.7	73.0
INR (dB) when AES and GS are:	In same spot	31.0	6.9	–5.4	–17.3	–29.1	–34.5	–38.7	–42.0
	In adjacent spots	28.0	3.9	–8.4	–20.3	–32.1	–37.5	–41.7	–45.0
	Farther apart	6.0	–18.1	–30.4	–42.3	–54.1	–59.5	–63.7	–67.0

Case 1.3: Potential interference from forward Earth-to-space link to terrestrial uplink

The minimum distance separation d_{min} (km) that will suffice to prevent interference from the source transmitter to the victim receiver can be computed as follows:

$$P_{eu} - (106.5 + 20 \log d_{min}) - L_x - FDR + G_{ru} - L_r - N = T$$

Solving for minimum allowable distance:

$$d_{min} = \text{antilog}\,((P_{eu} - 109.5 + G_{ru} - L_r - N - T)/20) \times 10^{-FDR/20} \qquad (1\text{-}7)$$

Using the values applicable to this case yields $d_{min} = 92\ 257 \times 10^{-FDR/20}$.

The results are shown in Table 31 below. They indicate that a UA using the terrestrial system should not fly through the main beam of a SATCOM GES, regardless of frequency separation, unless the UA and GES are at least 13 km (7 nmi) apart.

TABLE 31

Minimum distance between GES and UA

Δf (kHz)	0	30	60	90	120	150	210	≥ 240
FDR (dB)	0	7.1	31.5	43.5	55.4	66.9	76.8	77
d_{min} (km) between GES and UA	BLoS	BLoS	BLoS	616.6	156.7	41.7	13.3	13.0
d_{min} (nmi) between GES and UA	BLoS	BLoS	BLoS	332.9	84.6	22.5	7.2	7.0

Expression (1-7) will also be used below in the analysis of cases 1.4, 2.1, 2.2, 3.3, 3.4, 4.1, and 4.2.

Case 1.4: Potential interference from return Earth-to-space link to terrestrial uplink

In this case, expression (1-7) reduces to $d_{min} = 2\ 162 \times 10^{-FDR/20}$, yielding the results in Table 32. These results, together with those to be presented later for Case 4.1, demonstrate that the terrestrial (AM(R)S) and SATCOM (AMS(R)S) CNPC systems can operate simultaneously on separate aircraft (the AES and UA of Fig. 18) that are less than 300 m (1 000 feet) apart without mutual interference when their tuned frequencies differ by 900 kHz or more.

TABLE 32

Minimum distance between AES and UA

Δf (kHz)	0	120	240	360	480	540	600	≥ 900
FDR (dB)	6.1	30.1	42.4	54.4	66.2	71.6	75.7	79
d_{min} (km) between AES and UA	BLoS	67.6	16.4	4.1	1.06	0.57	0.35	0.24
d_{min} (nmi) between AES and UA	BLoS	36.5	8.9	2.2	0.57	0.31	0.19	0.13

Case 2.1: Potential interference from terrestrial uplink to forward space-to-Earth link

In this case d_{min} = 37 154 × $10^{-FDR/20}$. The results appear in Table 33 below.

TABLE 33

Minimum distance between GS and AES

Δf (kHz)	0	30	60	90	120	150	210	≥ 240
FDR (dB)	0	7.1	31.5	43.5	55.4	66.9	76.8	77
d_{min} (km) between GS and AES	BLoS	BLoS	BLoS	248	63.1	16.8	5.4	5.2
d_{min} (nmi) between GS and AES	BLoS	BLoS	BLoS	134	34.1	9.1	2.9	2.8

Case 2.2: Potential interference from terrestrial uplink to return space-to-Earth link

For this case, d_{min} = 15 850 × $10^{-FDR/20}$, yielding the following results shown in Table 34. These results, together with those to be presented below for case 3.3, indicate that ground sites of the terrestrial and SATCOM systems should be kept at least 3.5 km (1.9 nmi) apart.

TABLE 34

Minimum distance between GS and GES

Δf (kHz)	0	120	240	360	480	540	600	≥ 900
FDR (dB)	0	24.1	36.4	48.3	60.1	65.5	69.7	73
d_{min} (km) between GS and GES	BLoS	BLoS	240	61	15.7	8.4	5.2	3.5
d_{min} (nmi) between GS and GES	BLoS	BLoS	130	33	8.5	4.5	2.8	1.9

Case 2.3: Potential interference from forward space-to-Earth link to terrestrial uplink

Expression (1-6) yields the results presented in Table 35 below. There is little interference potential here except when the frequency separation is extremely small.

TABLE 35

INR caused by forward space-to-Earth link in UA receiver

Δ*f* (kHz)		0	30	60	90	120	150	210	≥ 240
FDR (dB)		0	7.1	31.5	43.5	55.4	66.9	76.8	77.0
INR (dB) when UA and AES are:	In same spot	5.9	–1.2	–25.6	–37.6	–49.5	–61.0	–70.9	–71.1
	In adjacent spots	2.9	–4.2	–28.6	–40.6	–52.5	–64.0	–73.9	–74.1
	Farther apart	–19.1	–26.2	–50.6	–62.6	–74.5	–86.0	–95.9	–96.1

Case 2.4: Potential interference from return space-to-Earth link to terrestrial uplink

The results for this case appear in Table 36 below. There is essentially no chance of interference in this case.

TABLE 36

INR caused by return space-to-Earth link in UA receiver

Δ*f* (kHz)		0	120	240	360	480	540	600	≥ 900
FDR (dB)		6.1	30.1	42.4	54.4	66.2	71.6	75.7	79.0
INR (dB) when UA and GES are:	In same spot	–30.8	–54.8	–67.1	–79.1	–90.9	–96.3	–100.4	–103.7
	In adjacent spots	–33.8	–57.8	–70.1	–82.1	–93.9	–99.3	–103.4	–106.7
	Farther apart	–55.8	–79.8	–92.1	–104.1	–115.9	–121.3	–125.4	–128.7

Case 3.1: Potential interference from terrestrial downlink to forward Earth-to-space link

The results for this case appear in Table 37 below. Here, interference is possible only at frequency separations lower than 60 kHz.

TABLE 37

INR caused by terrestrial downlink in forward Earth-to-space link satellite receiver

Δ*f* (kHz)		0	30	60	90	120	150	210	≥ 240
FDR (dB)		0	7.1	31.5	43.5	55.4	66.9	76.8	77.0
INR (dB) when GES and UA are:	In same spot	13.1	6.0	–18.4	–30.4	–42.3	–53.8	–63.7	–63.9
	In adjacent spots	10.1	3.0	–21.4	–33.4	–45.3	–56.8	–66.7	–66.9
	Farther apart	–11.9	–19.0	–43.4	–55.4	–67.3	–78.8	–88.7	–88.9

Case 3.2: Potential interference from terrestrial downlink to return Earth-to-space link

The results for this case appear in Table 38 below. Interference cannot occur unless the frequency separation is lower than 120 kHz.

TABLE 38

INR caused by terrestrial downlink in return Earth-to-space link satellite receiver

Δf (kHz)		0	120	240	360	480	540	600	≥ 900
FDR (dB)		0	24.1	36.4	48.3	60.1	65.5	69.7	73.0
INR (dB) when AES and UA are:	In same spot	7.0	–17.1	–29.4	–41.3	–53.1	–58.5	–62.7	–66.0
	In adjacent spots	4.0	–20.1	–32.4	–44.3	–56.1	–61.5	–65.7	–69.0
	Farther apart	–18.0	–42.1	–54.4	–66.3	–78.1	–83.5	–87.7	–91.0

Case 3.3: Potential interference from forward Earth-to-space link to terrestrial downlink

For this case, expression (1-7) yields $d_{min} = 3\,236 \times 10^{-FDR/20}$.

The results are given in Table 39 below.

TABLE 39

Minimum distance between GES and GS

Δf (kHz)	0	200	400	600	900	1 200	1 500	≥ 1 700
FDR (dB)	0	22.3	32.5	42.5	57.3	68.3	70.3	70.4
d_{min} (km) between GES and GS	BLoS	248	76.7	24.3	4.4	1.2	1.0	1.0
d_{min} (nmi) between GES and GS	BLoS	134	41.4	13.1	2.4	0.7	0.5	0.5

Case 3.4: Potential interference from return Earth-to-space link to terrestrial downlink

In this case expression (1-7) becomes $d_{min} = 12\,161 \times 10^{-FDR/20}$. The results appear in Table 40 below.

TABLE 40

Minimum distance between AES and GS

Δf (kHz)	0	200	400	600	900	1 200	1 500	≥ 1 700
FDR (dB)	0	7.8	31.6	41.9	56.9	70.3	74.9	75.2
d_{min} (km) between AES and GS	BLoS	BLoS	320	97.7	17.4	3.7	2.2	2.1
d_{min} (nmi) between AES and GS	BLoS	BLoS	173	52.8	9.4	2.0	1.2	1.1

Case 4.1: Potential interference from terrestrial downlink to forward space-to-Earth link

Here, $d_{min} = 2\,344 \times 10^{-FDR/20}$, yielding the results that are presented in Table 41 below.

TABLE 41

Minimum distance between UA and AES

Δf (kHz)	0	30	60	90	120	150	210	≥ 240
FDR (dB)	0	7.1	31.5	43.5	55.4	66.9	76.8	77
d_{min} (km) between UA and AES	BLoS	BLoS	62.4	15.7	4.0	1.06	0.34	0.33
d_{min} (nmi) between UA and AES	BLoS	BLoS	33.7	8.5	2.1	0.57	0.18	0.18

Case 4.2: Potential interference from terrestrial downlink to return space-to-Earth link

For this case, $d_{min} = 160\,327 \times 10^{-FDR/20}$, and the results appear in Table 42. They indicate that a UA using the terrestrial CNPC system should avoid flying through the main beam of a nearby SATCOM GES, regardless of frequency separation. (If the UA were exposed only to the GES side lobes, the minimum distances would be much smaller than those indicated in the table.)

TABLE 42

Minimum distance between UA and GES

Δf (kHz)	0	120	240	360	480	540	600	≥ 900
FDR (dB)	0	24.1	36.4	48.3	60.1	65.5	69.7	73
d_{min} (km) between UA and GES	BLoS	BLoS	BLoS	617	158	85	52	36
d_{min} (nmi) between UA and GES	BLoS	BLoS	BLoS	333	86	46	28	19

Case 4.3: Potential interference from forward space-to-Earth link to terrestrial downlink

The results for this case appear in Table 43 below. Interference cannot occur except during co-channel operation.

TABLE 43

INR caused by forward space-to-Earth link in GS receiver

Δf (kHz)		0	200	400	600	900	1 200	1 500	≥ 1 700
FDR (dB)		0	22.3	32.5	42.5	57.3	68.3	70.3	70.4
INR (dB) when GS and AES are:	In same spot	20.9	–1.4	–11.6	–21.6	–36.4	–47.4	–49.4	–49.5
	In adjacent spots	17.9	–4.4	–14.6	–24.6	–39.4	–50.4	–52.4	–52.5
	Farther apart	–4.1	–26.4	–36.6	–46.6	–61.4	–72.4	–74.4	–74.5

Case 4.4: Potential interference from return space-to-Earth link to terrestrial downlink

The results for this case appear in Table 44 below. There is essentially no potential for interference in this case.

TABLE 44

INR caused by return space-to-Earth link in GS receiver

Δf (kHz)		0	200	400	600	900	1 200	1 500	≥ 1 700
FDR (dB)		0	7.8	31.6	41.9	56.9	70.3	74.9	75.2
INR (dB) when GS and GES are:	In same spot	–9.7	–17.5	–41.3	–51.6	–66.6	–80.0	–84.6	–84.9
	In adjacent spots	–12.7	–20.5	–44.3	–54.6	–69.6	–83.0	–87.6	–87.9
	Farther apart	–34.7	–42.5	–66.3	–76.6	–91.6	–105.0	–109.6	–109.9

3.1.1.2.3.3 Aggregate interference analysis

The compatibility analysis of the preceding subsection considered single-interferer cases in which the victim receiver was exposed only to the undesired signals of a single potentially interfering transmitter. In terrestrial analyses this is realistic, because in typical situations one undesired signal entering a receiver is stronger than all the other undesired signals combined. However, for the four cases (1.1, 1.2, 3.1, and 3.2) that involve satellite receivers exposed to potential interference from more than one-third of the Earth's surface, it is also necessary to consider the possibility of multiple undesired signals entering the receiver at comparable power levels.

As a worst case, consider the Report ITU-R M.2171 scenario in which 1 856 medium and large UAS simultaneously operate in an area of 7 800 000 square kilometres. (The scenario also stipulates 6 257 small UAS, half of which would be using terrestrial CNPC links, but those links would be low-power and can be omitted from this analysis without much effect on the results.) If that area happens to be near the limb of the Earth as viewed from the satellite, the elongated footprint of a spot beam directed at that area could conceivably encompass a few hundred of those medium and large UAS. Adjacent spot beams could cover several hundred more, although undesired signals entering via those adjacent spots would be attenuated by at least 3 dB. In the worst case, the effective number of same-spot interferers could be in the range 500-1 000. If the effective number were 1 000, then the resultant INR levels could be 30 dB higher than the values shown in the tables.

However, there are mitigating factors. In cases 1.1 and 1.2, the interferers are terrestrial uplinks with highly directive antennas, most of which would be pointing away from the satellite at any given time, so the INR increase would be limited to 20 dB or less. In cases 3.1 and 3.2 the interferers are terrestrial downlinks whose transmitting antennas will ordinarily be radiating most of their energy downwards towards their terrestrial ground receivers, so their e.i.r.p.s in the direction of the satellite will usually be lower than the 43 dBm assumed in the single-interferer analysis. And in all the cases, proper frequency planning would ensure that all (or nearly all) of the interferers would be widely separated in frequency from the potential victim link. Then it would be necessary only to consider the effect on the INR values in the columns on the right side of the relevant tables. For instance, in Table 29 (for case 1.1), the single-interferer INR value of –39.9 dB shown for Δf = 240 kHz and a spot separation of zero might increase by 20 dB, to an aggregate INR of about −20-dB still far below the level needed to cause harmful interference. And in Table 37 (for case 3.1) the single-interferer value of –63.9 dB shown for the same Δf and spot-separation values, if increased by 30 dB, would still rise only to an aggregate INR value of about –34 dB.

A similar aggregate-interference analysis could be performed for the four cases (2.3, 2.4, 4.3, and 4.4) that involve satellite transmitters potentially interfering with terrestrial CNPC receivers. Undesired signals emanating from the satellite via adjacent spot beams can augment the interference arriving via the beam actually illuminating the victim receiver. But there is no danger in any of those cases that harmful interference would result from any conceivable aggregation of those signals, at least not if reasonable frequency separations are maintained between the SATCOM and terrestrial CNPC systems. Adequate terrestrial/SATCOM frequency separations can be assured by placing the terrestrial CNPC system in the 5 050-5 071 MHz sub-band that will not be used by the SATCOM system.

3.1.1.2.3.4 Summary of the study between AM(R)S and AMS(R)S

This compatibility analysis of terrestrial (AM(R)S) and SATCOM (AMS(R)S) CNPC systems sharing the 5 030-5 091 MHz band has demonstrated that, based on the detailed and numerous assumptions made, all cases of potential interference can be prevented by appropriate use of frequency and spot separations, together with proper placement of terrestrial ground stations and satellite Earth stations. By placing the terrestrial system in the 5 050-5 071 MHz sub-band, which the SATCOM system under consideration would not use, adequate frequency separations between the two systems can easily be achieved in all cases.

3.1.1.3 Conclusion for the band 5 030-5 091 MHz

Nearly all of the 24.8 MHz needed by the terrestrial CNPC system within the 5 030-5 091 MHz segment can be found in the 5 050-5 071 MHz sub-band, which is not anticipated for use by the AMS(R)S CNPC system that is also being proposed for 5 030-5 091 MHz.

All cases of potential interference between terrestrial and AMS(R)S systems in the 5 030-5 091 MHz band can be prevented by appropriate use of frequency and spot separations, together with proper placement of terrestrial ground stations and satellite Earth stations. All cases of potential interference between the terrestrial CNPC system and MLS can be prevented through appropriate combinations of frequency separation, proper placement of CNPC ground sites, and (when necessary) additional measures of mitigation such as power control.

In case of operation of UAS in the same occupied bandwidth (150 kHz) with MLS in the band 5 030-5 091 MHz, it would be difficult to achieve compatibility between these two systems.

3.1.2 Methodology 2

This methodology assesses the feasibility of AM(R)S sharing of the 5 030-5 091 MHz band without harmful interference to or from MLS and future AMS(R)S systems in the band.

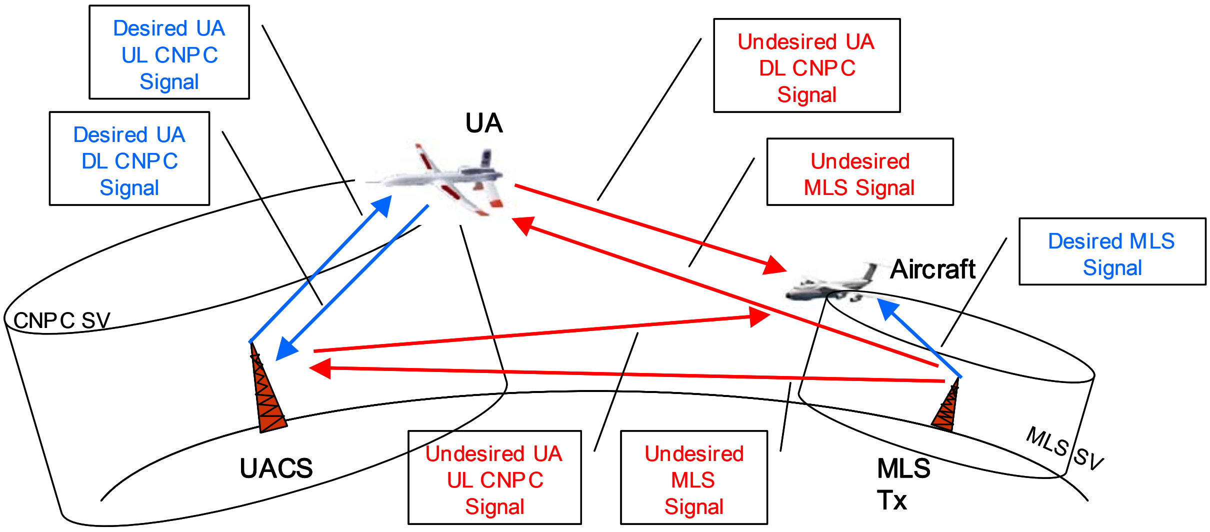
3.1.2.1 Interference analysis between UAS CNPC terrestrial links and MLS

The study hereafter aims at analysing the sharing between UAS CNPC and the MLS to enable the future UA system to operate successfully in the band without harmful interference to MLS or to itself. A CNPC system can be implemented without constraining the concurrent use of the band by MLS.

The figure hereunder shows all potential mutual interferences between a MLS and a UAS CNPC terrestrial link (uplink and downlink) operating in the 5 030-5 091 MHz frequency range. The UAS CNPC links and the MLS operate in different type of service volume.

FIGURE 21

Interference scenarios between UAS CNPC terrestrial links and MLS



Four potential interference cases exist:

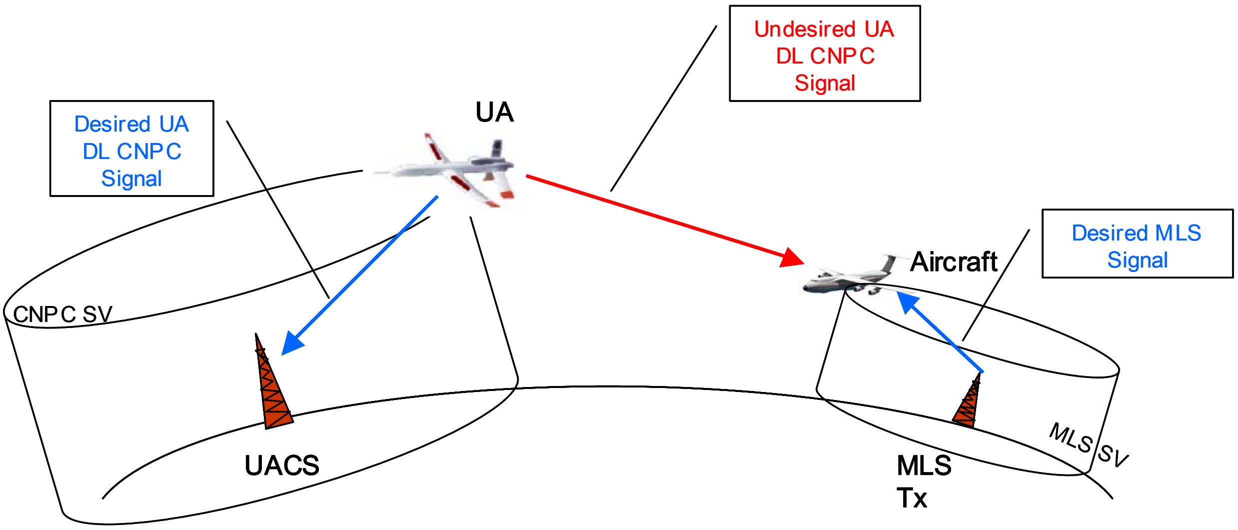
- Case 1: UAS downlink CNPC transmitter to MLS receiver;
- Case 2: MLS transmitter to UAS uplink CNPC receiver;
- Case 3: UAS uplink CNPC transmitter to MLS receiver;
- Case 4: MLS transmitter to UAS downlink CNPC receiver.

3.1.2.1.1 Case 1: Analysis of radio interference from UA transmitter to MLS receiver

That case 1 of potential interference is presented in Figure 22:

FIGURE 22

Interference from UA transmitter to MLS receiver



At MLS receiver antenna, the undesired UAS CNPC pfd shall not exceed the MLS interference threshold (MLS threshold = –124.5 dBW/m^2).

The relation to avoid harmful interference is:

$$EIRP_{UA} + G_{MLS} - 30 - 10.\log_{10}(4\pi) - 20.\log_{10}(1000.D_{\min}) - L_{CP} - FDR \leq MLS_{Threshold}$$

And then, to estimate the minimum separation distance:

$$D_{MIN} = 10^{\left(\frac{EIRP_{UA} + G_{MLS} - 90 - 10.\log_{10}(4\pi) - L_{CP} - MLS_{Threshold} - FDR}{20}\right)}$$

Where:

$EIRP_{ua}$: Maximum UA transmitter e.i.r.p. (dBm);

G_{MLS}: MLS antenna gain (0 dB);

L_{CP}: Cross polarization loss (dB = 10);

$MLS_{threshold}$: MLS pfd interference threshold (pfd max of –124.5 dBW/m^2);

FDR: Frequency dependent rejection (dB);

D_{min}: Minimum required distance separation (km).

FDR can be calculated as follows:

$$\text{FDR}(\Delta f) = 10\log_{10}\left[\frac{\int_{-\infty}^{\infty} S(f)df}{\int_{-\infty}^{\infty} S(f)R(f+\Delta f)df}\right] \qquad (1\text{-}8)$$

where:

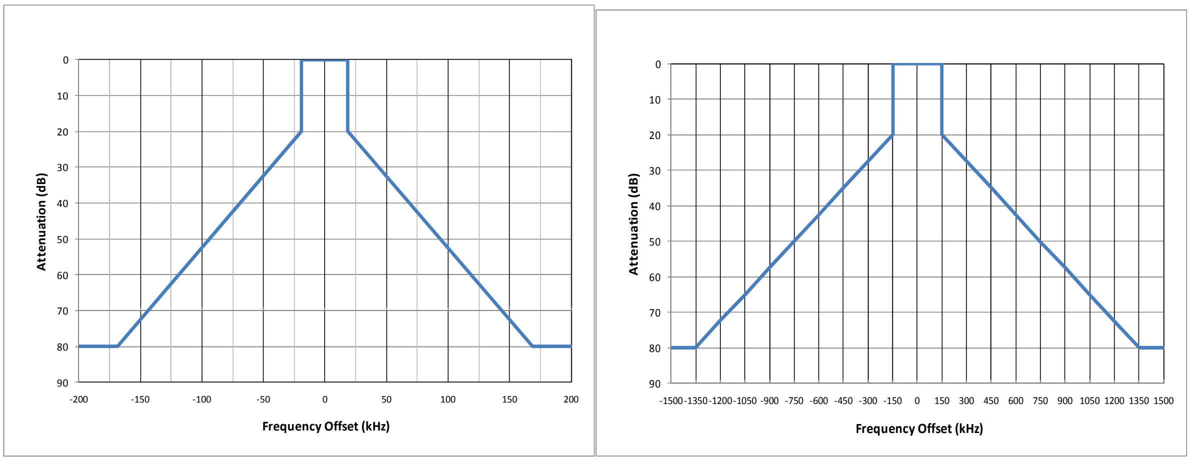
$S(f)$: transmitter power spectral density;

$R(f)$: squared magnitude of the frequency-dependent receiver response;

Δf: difference between tuned transmitter and receiver frequencies

FIGURE 23

Assumed medium and large UA transmitter and receiver masks for 37.5 and 300-kHz basic channel (S(f))



The formula for the masks above is the following:

Attenuation equals 0 dB	$0 \leq$ offset $<$ bw/2
Attenuation from 20 to 80 dB	bw/2 $\leq$ offset $<$ 9/2 bw
Attenuation equals 80 dB	9/2 bw $\leq$ offset
With bw:	UAS bandwidth

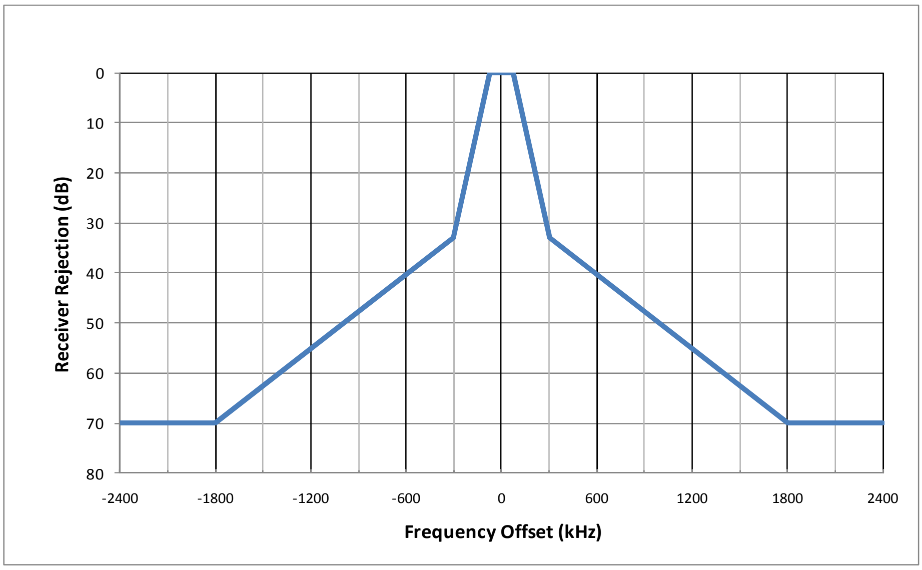
A postulated MLS receiver mask appears in the following figure.

The generic form is as follows:

Attenuation equals 0 dB	$0 \leq$ offset $<$ 75 kHz
Attenuation from 0 to 33 dB	75 kHz $\leq$ offset $<$ 300 kHz
Attenuation from 33 to 70 dB	300 kHz $\leq$ offset $<$ 1 800 kHz
Attenuation equals 70 dB	1 800 kHz $\leq$ offset

FIGURE 24

Postulated MLS receiver mask (*R*(*f*))



Based on the UAS CNPC link assumptions, the table hereunder summarize the compatibility issue depending on frequency offset.

TABLE 45

Minimum distance between an UA transmitter without video (37.5 kHz) and a MLS receiver

Δ channels	0	1	2	3	4	5	6
Δ*f* (kHz)	0	300	600	900	1 200	1 500	1 800
UA e.i.r.p. max (dBm)	41	41	41	41	41	41	41
CP_{loss} (dB)	10	10	10	10	10	10	10
FDR (dB)	0	32.3	40.4	47.8	55.1	62.2	68
D_{min} (km) Worst case	530	12.9	5.1	2.2	0.93	0.41	<0.3

TABLE 46

Minimum distance between an UA transmitter with video (300 kHz) and a MLS receiver

Δ channels	0	1	2	3	4	5	6
Δ*f* (kHz)	0	300	600	900	1 200	1 500	1 800
UA e.i.r.p. max (dBm)	41	41	41	41	41	41	41
CP_{loss} (dB)	10	10	10	10	10	10	10
FDR (dB)	1.7	20.3	38.1	46.9	54.6	62	68.6
D_{min} (km) Worst case	437	51.4	6.6	2.4	0.99	0.42	<0.3

Assuming air traffic rules of separation between air vehicles, we have a minimum separation between aircraft of 3.7 km (2 nmi) or 330 m (1000 ft). In this second case (vertical separation), the relative antenna gains are reduced due to the fuselage attenuation (in the range of 17 to 22 dB according to the parameter values from § 2.1). Therefore, the fourth MLS channel could be used for UAS CNPC link in the MLS service volume.

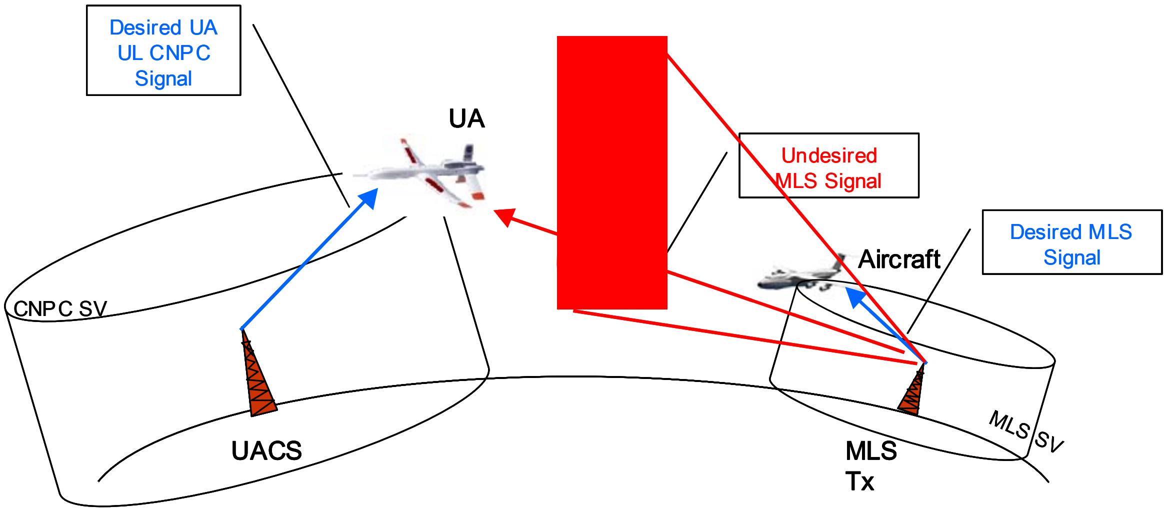
Use of closest frequencies is subject to geographical coordination.

3.1.2.1.2 Case 2: Analysis of the radio interference from MLS transmitter to UA receiver

The case 2 of potential interference is presented in Figure 25:

FIGURE 25

Interference from MLS transmitter to UAS uplink CNPC receiver



The worst case interference is achieved in the following configuration: An UA located in the coverage angle of the MLS transmitter and receiving the undesired MLS signal (U) in addition to the desired uplink CNPC signal (D).

At UA receiver input, a minimum $S/(N+I)$ ratio of 12 dB should be granted to avoid interference. That 12 dB interference free ($S/(N+I)$) value is a typical protection value for an UAS CNPC link.

The relation to avoid harmful interference is:

$$S = EIRP_{MLS} + G_{Rx\_UA} - 20 \log (\lambda / 4 \pi d_{min}) - CP_{loss} - FDR + S/(N+I)$$

With

S: UAS CNPC received power at the receiver input $EIRP_{MLS}$: Maximum MLS transmitter e.i.r.p.;

G_{Rx_UA}: UA antenna gain;

d_{min}: minimum distance separation between the UA and the MLS ground transmitter;

CP_{loss}: Cross polarization loss (10 dB);

FDR: Frequency dependent rejection (dB);

$S/(N+I)$: Protection at the UA receiver input to avoid harmful interference;

D_{min}: minimum required distance separation.

FDR can be calculated as above. The MLS emission mask is calculated below:

The emission attenuation in decibels of a DPSK-modulated MLS transmitter is described by:

$$PSD(f) = \frac{P}{f_d} \cdot \left[\frac{\sin\left(\pi \cdot \frac{f}{f_d}\right)}{\pi \cdot \frac{f}{f_d}} \right]^2 ,$$

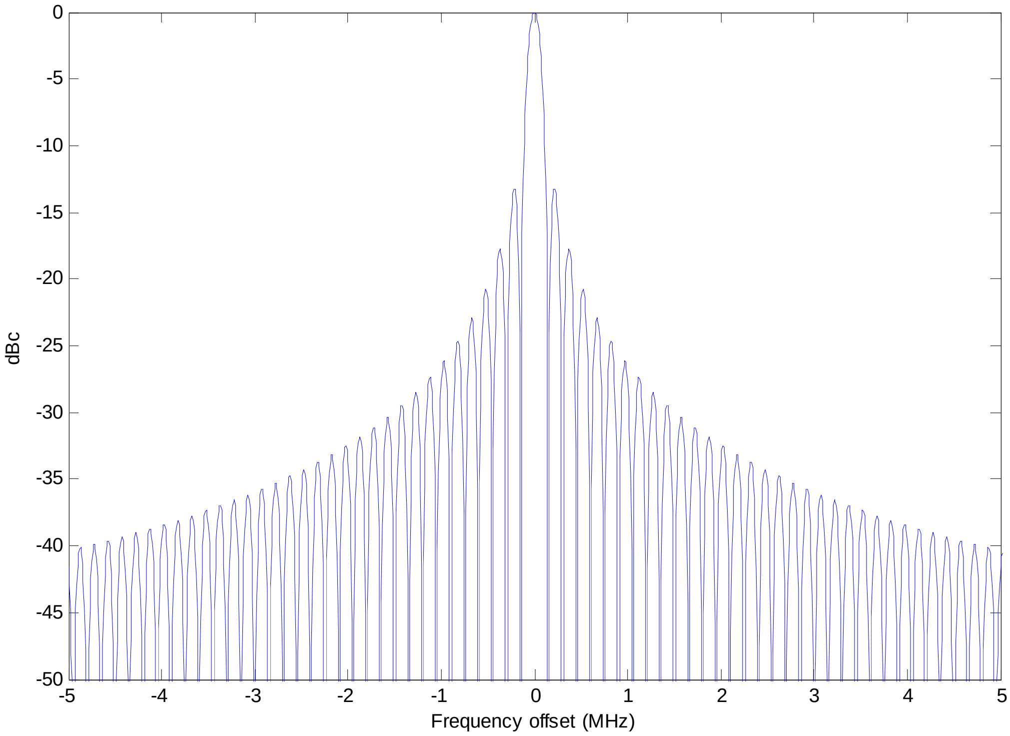
where:

f_d: modulation rate = 15.625 kHz;

f: frequency offset (kHz).

FIGURE 26

DPSK signal



Based on the UAS CNPC link assumptions and the MLS characteristics, Table 47 summarizes the compatibility issue depending on frequency offset.

TABLE 47

Minimum distance between a MLS ground transmitter and an UACS

Δ channels	0	1	2	3	4	5	6
Δf (kHz)	0	300	600	900	1200	1500	1800
MLS e.i.r.p. (dBm)	66	66	66	66	66	66	66
S (dBm)	–99.6	–99.6	–99.6	–99.6	–99.6	–99.6	–99.6
N (dBm)	–126.26	–126.26	–126.26	–126.26	–126.26	–126.26	–126.26
$S/(N+I)$	12	12	12	12	12	12	12
I_{max} (dBm)	–111.75	–111.75	–111.75	–111.75	–111.75	–111.75	–111.75
CP_{loss} (dB)	10	10	10	10	10	10	10
FDR (dB)	0.4	35	40.4	44	47.1	49.4	50.6
D_{min} (km) Worst case	425[1]	23	12	8.2	5.7	4.4	3.8

[1] Based on equation 1-3, the separation distances when Δf = 0 kHz, are far beyond LoS. The actual separation distance requirement 425 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the UA height (10 000 m).

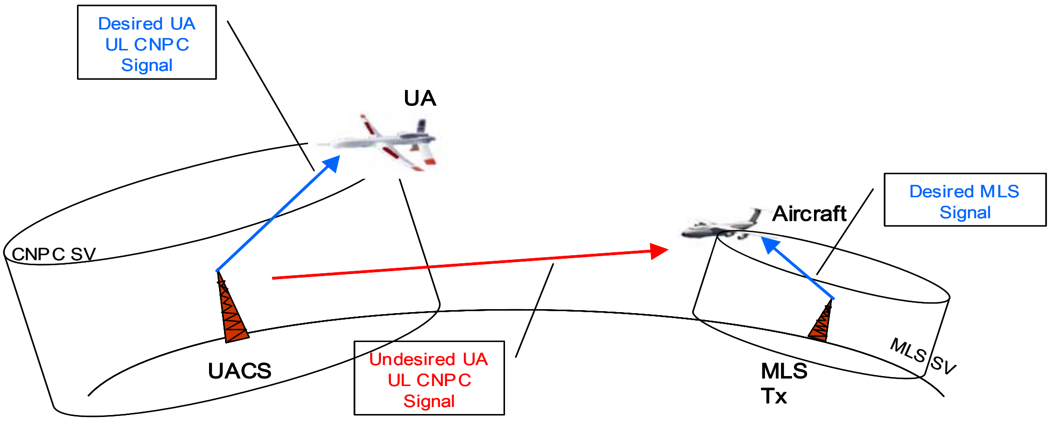
The computation leads to the conclusion that the UACS CNPC link can share frequency bandwidth with MLS based on geographical coordination with the MLS ground stations. Indeed, the required distance separation has been calculated considering the minimum desired signal at the UA. If the UACS desired signal is higher thanks to appropriate geographical coordination with the MLS ground station, the UA could operate at very close distances from the MLS ground station.

3.1.2.1.3 Case 3: Analysis of the radio interference from UACS transmitter to MLS receiver

The case 3 of potential interference is presented in Figure 27:

FIGURE 27

Interference from UACS transmitter to MLS receiver



This case is similar to the case 1.

The same equation as in case 1 applies to estimate the minimum separation distance:

$$D_{MIN} = 10^{\left(\frac{EIRP_{UACS} + G_{MLS} - 90 - 10.\log_{10}(4\pi) - L_{CP} - MLS_{Threshold} - FDR}{20}\right)}$$

where

$EIRP_{ua}$: Maximum UA transmitter e.i.r.p. (dBm);

G_{MLS}: MLS antenna gain (0 dB);

L_{CP}: Cross polarization loss (dB = 10);

$MLS_{threshold}$: MLS pfd interference threshold (pfd max of –124.5 dBW/m^2);

FDR: Frequency dependent rejection (dB);

D_{min}: Minimum required distance separation (km).

Based on the UACS link assumptions, Table 48 summarizes the compatibility issue depending on frequency offset.

TABLE 48

Minimum distance between an UACS transmitter and a MLS receiver

Δ channels	0	1	2	3	4	5	6
Δ*f* (kHz)	0	300	600	900	1 200	1 500	1 800
UACS e.i.r.p. max (dBm)	52	52	52	52	52	52	52
CP_{loss}	10	10	10	10	10	10	10
FDR (dB)	0	32.3	40.4	47.8	55.1	62.2	68
D_{min} (km) Worst case	342[1]	45.7	18	7.7	3.3	1.5	0.75

[1] Based on equation 1-3, the separation distances when Δ*f* = 0 kHz, are far beyond LoS. The actual separation distance requirement 343 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the maximum height of MLS service volume (6 000 m) and H_2 is the height of UACS transmitter antenna (30 m).

Assuming standard sectoral antenna pattern for ground antennas, the fourth MLS channel could be used for UACS CNPC link in the MLS service volume.

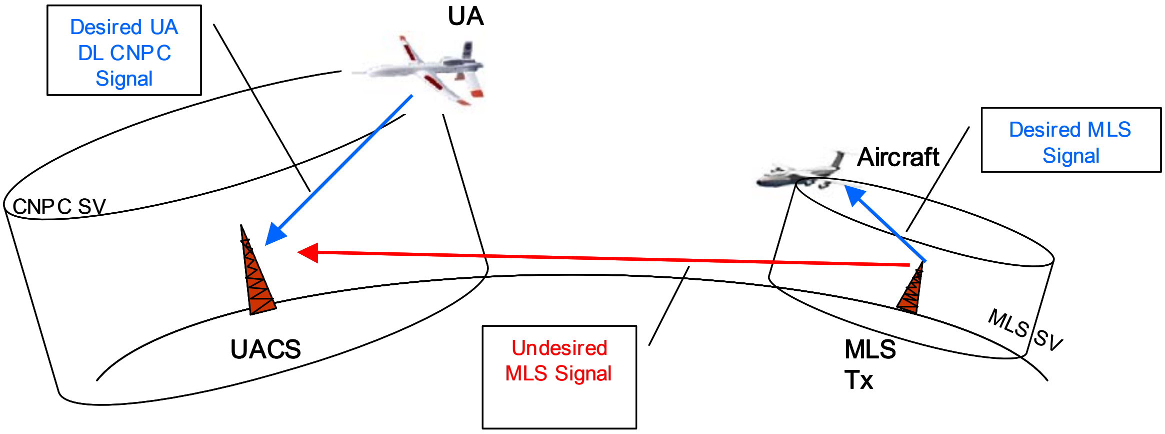
Use of closest frequencies or tracking antennas is subject to geographical coordination.

3.1.2.1.4 Case 4: Analysis of the radio interference from MLS transmitter to UACS receiver

The case 4 of potential interference is presented in Figure 28:

FIGURE 28

Interference from MLS transmitter to UACS receiver



The worst case interference is achieved in the following configuration: An UACS located in the coverage angle of the MLS transmitter and receiving the undesired MLS signal (U) in addition to the desired uplink CNPC signal (D).

At UA receiver input, a minimum $S/(N+I)$ ratio of 12 dB should be granted to avoid interference. That 12 dB interference free ($S/(N+I)$) value is a typical protection value for an UACS CNPC link.

The relation to avoid harmful interference is:

$$S = EIRP_{MLS} + G_{Rx\_UACS} - 20 \log (\lambda / 4 \pi d_{min}) - CP_{loss} - FDR + S/(N+I)$$

with

S: UACS received power at the receiver input;

$EIRP_{MLS}$: MLS transmitter maximum e.i.r.p.;

G_{Rx_UA}: UACS antenna gain;

d_{min}: Minimum distance separation between the UA and the MLS ground transmitter;

CP_{loss}: Cross polarization loss (10 dB);

FDR: Frequency dependent rejection (dB);

$S/(N+I)$: Protection at the UACS receiver input to avoid harmful interference;

D_{min}: Minimum required distance separation.

For FDR computation, see § 3.1.2.1.

Based on the UACS link assumptions and the MLS characteristics, Table 49 summarize the compatibility issue depending on frequency offset.

TABLE 49

Minimum distance between a MLS ground transmitter and an UACS receiver using sectoral antennas and 37.5 kHz bandwidth

Δ channels	0	1	2	3	4
Δf (kHz)	0	300	600	900	1200
MLS e.i.r.p. (dBm)	66	66	66	66	66
S (dBm)	–102.6	–102.6	-102.6	–102.6	-102.6
N (dBm)	–126.26	–126.26	–126.26	–126.26	–126.26
$S/(N+I)$	12	12	12	12	12
I_{max} (dBm)	–114.91	–114.91	–114.91	–114.91	–114.91
CP_{loss} (dB)	10	10	10	10	10
FDR (dB)	0.4	35	40.4	44	47.1
D_{min} (km) Worst case	35.6[1]	35.6	35.6	30	21

[1] Based on equation 1-3, the separation distances when Δf = 0 kHz, 300 kHz and 600 kHz, are far beyond LoS. The actual separation distance requirement 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the UACS receiver antenna height (30 m).

TABLE 50

Minimum distance between a MLS ground transmitter and an UACS receiver using tracking antennas and 37.5 kHz bandwidth

Δ channels	0	1	2	3	4
Δf (kHz)	0	300	600	900	1200
MLS e.i.r.p. (dBm)	66	66	66	66	66
S (dBm)	–88.6	–88.6	–88.6	–88.6	–88.6
N (dBm)	–126.26	–126.26	–126.26	–126.26	–126.26
$S/(N+I)$	12	12	12	12	12
I_{max} (dBm)	–100.61	–100.61	–100.61	–100.61	–100.61
CP_{loss} (dB)	10	10	10	10	10
FDR (dB)	0.4	35	40.4	44	47.1
D_{min} (km) Worst case	35.6[1]	35.6[1]	35.6[1]	29	20

[1] Based on equation 1-3, the separation distances when Δf = 0 kHz, 300 kHz and 600 kHz, are far beyond LoS. The actual separation distance requirement 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the UACS receiver antenna height (30 m).

TABLE 51

Minimum distance between a MLS ground transmitter and an UACS receiver using sectoral antennas and 300 kHz bandwidth

Δ channels	0	1	2	3	4
Δf (kHz)	0	300	600	900	1200
MLS e.i.r.p. (dBm)	66	66	66	66	66
S (dBm)	–102.6	–102.6	–102.6	–102.6	–102.6
N (dBm)	–117.23	–117.23	–117.23	–117.23	–117.23
$S/(N+I)$	12	12	12	12	12
I_{max} (dBm)	–118.03	–118.03	–118.03	–118.03	–118.03
CP_{loss} (dB)	10	10	10	10	10
FDR (dB)	0.04	22.8	31.2	35.2	37.7
D_{min} (km) Worst case	35.6[1]	35.6[1]	22	14	10

[1] Based on equation 1-3, the separation distances when Δf = 0 kHz and 300 kHz, are far beyond LoS. The actual separation distance requirement 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the UACS receiver antenna height (30 m).

TABLE 52

Minimum distance between a MLS ground transmitter and an UACS receiver using tracking antennas and 300 kHz bandwidth

Δ channels	0	1	2	3	4
Δf (kHz)	0	300	600	900	1 200
MLS e.i.r.p. (dBm)	66	66	66	66	66
S (dBm)	–88.6	–88.6	–88.6	–88.6	–88.6
N (dBm)	–117.23	–117.23	–117.23	–117.23	–117.23
$S/(N+I)$	12	12	12	12	12
I_{max} (dBm)	–100.70	–100.70	–100.70	–100.70	–100.70
CP_{loss}(dB)	10	10	10	10	10
FDR (dB)	0.04	22.8	31.2	35.2	37.7
D_{min} (km) Worst case	35.6[1]	35.6[1]	22	14	10

[1] Based on equation 1-3, the separation distances when Δf = 0 kHz and 300 kHz, are far beyond LoS. The actual separation distance requirement 35.6 km can be calculated via standard equation $4.12\times\left(\sqrt{H_1}+\sqrt{H_2}\right)$, where H_1 is the height of MLS transmitter antenna (10 m) and H_2 is the UACS receiver antenna height (30 m).

The computation leads to the conclusion that the UACS CNPC link can share frequency bandwidth with MLS based on geographical coordination with the MLS ground stations.

3.1.2.1.5 Conclusion for the sharing between UAS CNPC link and ARNS in the band 5 030-5 091 MHz

All cases of potential interference between the terrestrial CNPC system and MLS can be prevented through appropriate combinations of frequency separation, proper placement of CNPC ground sites, and (when necessary) additional measures of mitigation such as power control.

In case of operation of UAS in the same occupied bandwidth (150 kHz) with MLS in the band 5 030-5 091 MHz, it would be difficult to achieve compatibility between these two systems.

3.1.2.2 Interference analysis between UAS CNPC terrestrial link and AMS(R)S

The study hereafter aims at analysing the sharing between terrestrial UAS CNPC and the satellite UAS CNPC to enable the future UA system to operate successfully in the band without harmful interference to AMS(R)S or to itself. A CNPC system can be implemented without constraining the concurrent use of the band by a system operating under the AMS(R)S allocation.

It is proposed to adapt the terrestrial links depending on the way of the satellite links to facilitate the sharing between the AM(R)S and the AMS(R)S services. Therefore, if there is an Earth-to-space link in a given frequency band, it is proposed to study only the introduction of an air-to-ground link for the terrestrial LoS communication. On the contrary, if there is a space-to-Earth link in a given frequency band, it is proposed to study only the introduction of a ground-to-air link for the terrestrial LoS communication.

Finally, it is considered that AM(R)S links and AMS(R)S links in the 5 030-5 091 MHz band will not operate on the same frequency bandwidth thanks to an appropriate frequency planning. It is assumed that the minimum coupling loss for the first adjacent channel will be at least 45 dB.

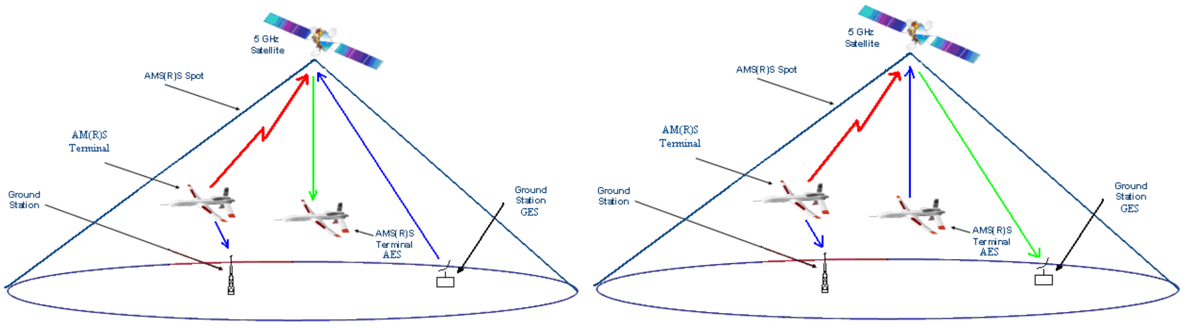
3.1.2.2.1 Interference analysis between UACS receiver and AMS(R)S Earth-to-space

The necessary studies are the following ones:

Impact of the terrestrial infrastructure on the satellite infrastructure: aircraft station of UAS terrestrial infrastructure → Satellite receiver of the UAS satellite infrastructure

FIGURE 29

Interference scenario with an aircraft station of UAS terrestrial infrastructure impacting a satellite receiver of the UAS satellite infrastructure

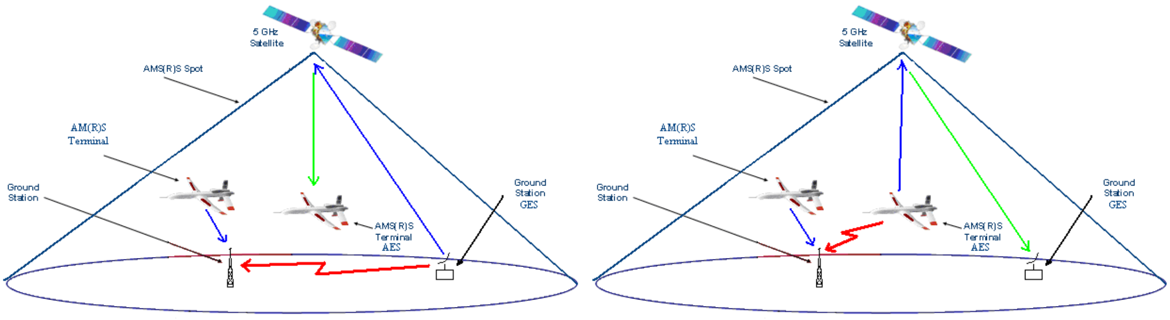


Impact of the satellite infrastructure on the terrestrial infrastructure:

- UACS of UAS satellite infrastructure → UACS of UAS terrestrial infrastructure.
- Airborne earth station (AES) of UAS satellite infrastructure → UACS of UAS terrestrial infrastructure.

FIGURE 30

Interference scenario with a transmitter of the UAS satellite infrastructure impacting a ground receiver of the UAS terrestrial infrastructure



3.1.2.2.1.1 Impact of aircraft stations of UAS terrestrial infrastructure on a satellite receiver of the UAS satellite infrastructure

TABLE 53

Temperature increase of a satellite receiver of the UAS satellite infrastructure due to aircraft stations of UAS terrestrial infrastructure

Parameters	Values for UA with 37.5 kHz bandwidth and at 300 kHz offset	Values for UA with 300 kHz bandwidth and at 300 kHz offset	Values for UA with 300 kHz bandwidth and at 600 kHz offset	Values for UA with 300 kHz bandwidth and at 900 kHz offset
Frequency (MHz)	5 050	5 050	5 050	5 050
Number of UA per spot[1] (including small aircrafts)	70	70	70	70
Number of UA per spot and per MHz[2] (including small aircrafts)	2	2	2	2
Maximum e.i.r.p per UA[3] (dBW)	11	11	11	11
UA relative antenna gain towards satellite (G_{max}/G_r)[3] (dB)	–13.21	–13.21	–13.21	–13.21
UA roll-off over the satellite 300 kHz Rx bandwidth (dBc)	–70.5	–25.5	–40.5	–55.5
Propagation loss (dB)	–198	–198	–198	–198
Satellite Rx antenna gain (dBi)	45.1	45.1	45.1	45.1
Satellite Rx feeder loss (dB)	0.5	0.5	0.5	0.5
Aggregated interference level (dBW)	–206.2	–206.2	–206.2	–206.2
Satellite G/T (dB/°K)	18.7	18.7	18.7	18.7
T (°K)	437	437	437	437
N (dBW/MHz)	–142.3	–142.3	–142.3	–142.3
$\Delta T/T$	<0.1%	11.5%	0.36%	<0.1%

NOTE 1 – Compliant with Report ITU-R M.2171.

NOTE 2 – The total spectrum need for the terrestrial component of the UAS CNPC infrastructure is 34 MHz (Report ITU-R M.2171).

NOTE 3 – The worst case of an elevation of 50° from the satellite is considered.

Conclusion: based on the hypothesis of this document, there would be no impact of aircraft stations of UAS terrestrial infrastructure on a satellite receiver of the UAS satellite infrastructure if UAS have low channel bandwidth (i.e. without video), and simple frequency or geographical coordination would be needed if UAS have larger bandwidth (i.e. with video).

3.1.2.2.1.2 Impact of UACS of UAS satellite infrastructure on UACS of UAS terrestrial infrastructure

TABLE 54

Minimum separation between a UACS transmitter of UAS satellite infrastructure and a UACS receiver of UAS terrestrial infrastructure

Parameters	Values for UACS Rx with 37.5 kHz bandwidth and tracking antenna	Values for UACS Rx with 300 kHz bandwidth and tracking antenna	Values for UACS Rx with 37.5 kHz bandwidth and sectoral antenna	Values for UACS Rx with 300 kHz bandwidth and sectoral antenna
Frequency (MHz)	5 050	5 050	5 050	5 050
Maximum UACS of the satellite infrastructure e.i.r.p (dBW/150 kHz)	49.6	49.6	49.6	49.6
Side lobe attenuation at 5° elevation[1] (dB)	29.5	29.5	29.5	29.5
UACS of the UAS terrestrial infrastructure Rx antenna gain (dBi)	24	24	10	10
UACS of the UAS terrestrial infrastructure Rx feeder loss (dB)	1	1	1	1
UACS of the UAS terrestrial infrastructure sensitivity (dBW)	–118.6	–103.5	–132.6	–117.5 32.6
$S/(N+I)$ protection criteria	12	12	12	12
At 300 kHz frequency offset				
UACS of the satellite infrastructure roll-off over the UACS of the UAS terrestrial infrastructure Rx bandwidth[2] (dBc)	–44.2	–35.2	–44.2	–35.2
Required attenuation (dB)	129.5	123.4	129.8	123.4
Required separation distance (km)	14	7	15	7
At 600 kHz frequency offset				
UACS of the satellite infrastructure roll-off over the UACS of the UAS terrestrial infrastructure Rx bandwidth[2] (dBc)	–73.2	–64.2	–73.2	–64.2
Required attenuation (dB)	100.5	94.4	100.8	94.4
Required separation distance (km)	0.5	0.2	0.5	0.2

NOTE 1 – A typical parabolic antenna pattern is considered.

NOTE 2 – The same roll-off is considered for UA and UACS (see Report ITU-R M.2205).

Conclusion: A coordination would be required since interference could occur up to distances of 40 km. This coordination should not be difficult especially if the number of GES is limited.

3.1.2.2.1.3 Impact of UA of UAS satellite infrastructure on UACS of UAS terrestrial infrastructure

TABLE 55

Minimum separation between a UAS transmitter of UAS satellite infrastructure and a UACS of UAS terrestrial infrastructure

Parameters	**Values for UACS Rx with 37.5 kHz bandwidth and tracking antenna**	**Values for UACS Rx with 300 kHz bandwidth and tracking antenna**	**Values for UACS Rx with 300 kHz bandwidth and sectoral antenna**	**Values for UACS Rx with 300 kHz bandwidth and sectoral antenna**
Frequency (MHz)	5 050	5 050	5 050	5 050
Maximum UA e.i.r.p (dBW/103.5 kHz)	17	17	17	17
UA G_r/G_{max} (dB)	–25	–25	–25	–25
UACS of the UAS terrestrial infrastructure Rx antenna gain (dBi)	24	24	10	10
UACS of the UAS terrestrial infrastructure Rx feeder loss (dB)	1	1	1	1
UACS of the UAS terrestrial infrastructure sensitivity (dBW)	–118.6	–103.5	–132.6	–117.5
$S/(N+I)$ protection criteria	12	12	12	12
At 300 kHz frequency offset				
UAS of the satellite infrastructure roll-off over the UACS of the UAS terrestrial infrastructure Rx bandwidth[1] (dBc)	–44.2	–35.2	–44.2	–35.2
Required attenuation (dB)	129.5	138.6	129.8	141.9
Required separation distance (km)	0.56	0.27	0.58	0.28
At 300 kHz frequency offset				
UACS of the satellite infrastructure roll-off over the UACS of the UAS terrestrial infrastructure Rx bandwidth[1] (dBc)	–73.2	–64.2	–73.2	–64.2
Required attenuation (dB)	100.5	109.6	100.8	112.9
Required separation distance (km)	< 0.03	< 0.03	< 0.03	< 0.03

NOTE 1 – The same roll-off is considered for UA and UACS (see Report ITU-R M.2205).

Conclusion: In order to avoid having UA communicating with a terrestrial infrastructure and a satellite infrastructure in a same area and in the same sub-band of the 5 030-5 091 MHz, frequency planning would be required since interference could occur from AES on ground station receiver of the UAS terrestrial infrastructure.

3.1.2.2.2 Interference analysis between UACS and AMS(R)S space-to-Earth

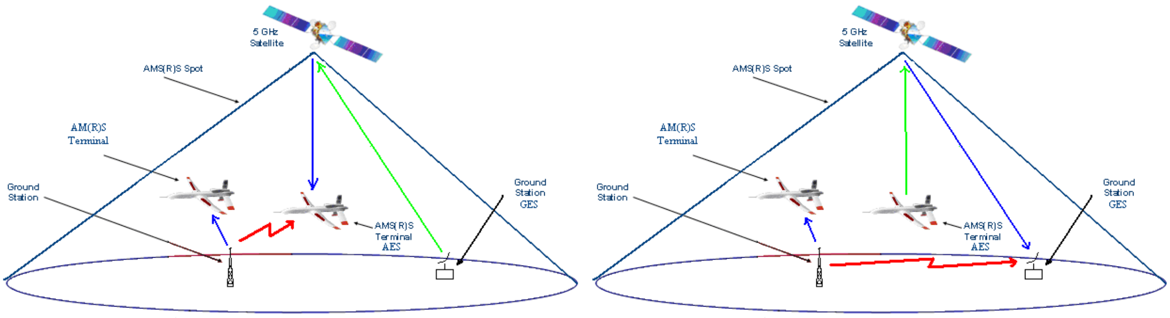
The necessary studies are the following ones:

Impact of the terrestrial infrastructure on the satellite infrastructure:

- UACS of UAS terrestrial infrastructure → Receiver onboard aircraft (AES) of the UAS satellite infrastructure.
- UACS of UAS terrestrial infrastructure → Receiver on the ground (UACS) of the UAS satellite infrastructure.

FIGURE 31

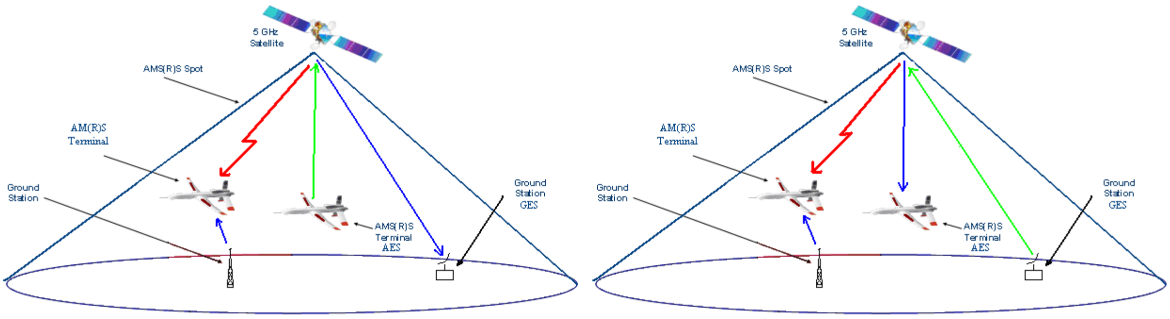
Interference scenario with a ground of the UAS terrestrial infrastructure impacting a receiver of the UAS satellite infrastructure



Impact of the satellite infrastructure on the terrestrial infrastructure: satellite station of UAS satellite infrastructure → Aircraft receiver of the UAS terrestrial infrastructure

FIGURE 32

Interference scenario with a satellite transmitter of the UAS satellite infrastructure impacting an aircraft receiver of the UAS terrestrial infrastructure



3.1.2.2.2.1 Impact of UACS of UAS terrestrial infrastructure on UA of the UAS satellite infrastructure

TABLE 56

Minimum separation between a UACS transmitter of UAS terrestrial infrastructure and a UA receiver of UAS satellite infrastructure

Parameters	Values
Frequency (MHz)	5 050
e.i.r.p (dBW/37.5 kHz)	22
UA G_r/G_{rmax} (dBc)	–25
UACS roll-off over the UA Rx bandwidth – First 300 kHz adjacent channel (dB)	–80
UA receiver maximum antenna gain G_{rmax}	3
UA Rx feeder loss (dB)	2
UA G/T (dB/°K)	–23
UA receiver T (°K)	398
UA receiver noise level (dBW/16.50 kHz)	–160.6
I/N (protection criteria) (dB)	–6
Ratio between UACS bandwidth (37.5 kHz) and UA bandwidth (16.5 kHz) (dB)	3.56
Required attenuation (dB)	81.0
Required separation distance (km)	0.05

Conclusion: In order to avoid having UA communicating with a terrestrial infrastructure and a satellite infrastructure in a same area and in the same sub-band of the 5 030-5 091 MHz, coordination would be required since interference could occur from ground stations of UAS terrestrial infrastructure on AES of the UAS satellite infrastructure.

3.1.2.2.2.2 Impact of UACS of UAS terrestrial infrastructure on UACS of the UAS satellite infrastructure

TABLE 57

Minimum separation between a UACS transmitter of UAS terrestrial infrastructure and a UACS receiver of UAS satellite infrastructure

Parameters	Values
Frequency (MHz)	5 050
UACS of the terrestrial infrastructure e.i.r.p. (dBW/37.5 kHz)	22
UACS of the terrestrial infrastructure roll-off over the UACS of the UAS satellite infrastructure Rx bandwidth – First 300 kHz adjacent channel (dB)	–80
UACS of the UAS satellite infrastructure Rx antenna gain (dB)	44.1
UACS of the UAS satellite infrastructure Rx feeder loss (dB)	1
Side lobe attenuation at 17° elevation (dB)	13
UACS of the UAS satellite infrastructure G/T (dB/°K)	18.8
UACS of the UAS satellite infrastructure receiver T (°K)	339
UACS of the UAS satellite infrastructure receiver noise level (dBW/103.5 kHz)	–153.2
I/N (protection criteria) (dB)	–6
Ratio between UACS of the terrestrial infrastructure bandwidth (37.5 KHz) and UACS of the UAS satellite infrastructure bandwidth (103.5 kHz) (dB)	–4.4
Required attenuation (dB)	135.8
Required separation distance (km)	29

Conclusion: Coordination is required since interference could occur up to 29 km. This coordination should not be difficult especially if the number of UACS is limited.

3.1.2.2.2.3 Impact of satellite transmitters of the satellite infrastructure on UA receivers of the UAS terrestrial infrastructure

TABLE 58

Protection margin between a satellite transmitter of UAS satellite infrastructure and a UA receiver of UAS terrestrial infrastructure

Parameters	Values
Frequency (MHz)	5 050
e.i.r.p. (dBW/16.5 kHz)	47.7
UA structure attenuation[1] (dB)	–13.21
Satellite transmitter roll-off over the UA of the UAS terrestrial infrastructure Rx bandwidth (i.e. 37.5 kHz) – First 300 kHz adjacent channel (dB)	–23
Propagation loss (dB)	–198.5
UA feeder losses (dB)	2
Interference level (dBW/37.5 kHz)	–189.0
UA received power (dBW/37.5 kHz)	–129.6
UA noise level (dBW/37.5 kHz)	–156.26
$S/(N+I)$ protection criteria (dB)	12
$S/(N+I)$ calculated (dB)	26.7
Margin (dB)	14.7

NOTE 1 – The worst case of an elevation of 50° from the satellite is considered.

Conclusion: Based on the hypothesis of this Report, there would be no impact of satellite transmitters on aircraft receivers of the UAS terrestrial infrastructure.

3.1.2.2.3 Conclusion on the interference analysis between UAS CNPC terrestrial link and AMS(R)S

The above sections show that the sharing between terrestrial UAS CNPC and the satellite UAS CNPC is possible in the 5 030-5 091 MHz band. Frequency planning would be needed to enable the future UA system to operate successfully in the band without harmful interference to AMS(R)S or to itself. A CNPC system in this band can be implemented without significantly constraining the concurrent use of the band by a system operating under the AMS(R)S allocation.

3.2 Adjacent band sharing studies

3.2.1 Introduction

This section examines the feasibility of AM(R)S compatibility of the 5 030-5 091 MHz band without harmful interference to RNSS systems operating in the adjacent 5 010-5 030 MHz band.

3.2.2 Adjacent band compatibility between RNSS feeder link in the 5 010-5 030 MHz band and proposed AM(R)S for UAS in the 5 030-5 091 MHz band

3.2.2.1 RNSS feeder links characteristics

Section 2.2 of this annex summarizes the receiving characteristics of the RNSS system in the band 5 010-5 030 MHz. As the protection criterion of the feeder-link earth stations of the RNSS systems in the 5 010-5 030 MHz band from the interference sources operating in the adjacent bands, a delta *T*/*T* allowance of 1% is assumed in this study.

No. 5.443B of the Radio Regulations requires that “in order not to cause harmful interference to the microwave landing system operating above 5 030 MHz, the aggregate pfd produced at the Earth’s surface in the band 5 030-5 150 MHz by all the space stations within any RNSS system (space-to-Earth) operating in the band 5 010-5 030 MHz shall not exceed –124.5 dB(W/m^2) in a 150 kHz band.” This RNSS system complies with this pfd requirement in the 5 030-5 150 MHz. Thus, this pfd level can be used for the study of the interference from RNSS systems in the 5 010-5 030 MHz band into the proposed AM(R)S system in the 5 030-5 091 MHz band. Currently, three RNSS systems are proposed for the band 5 010-5 030 MHz. Though more detailed assessment is required to find the maximum possible number of co-existing RNSS systems in the 5 010-5 030 MHz band, five RNSS systems are assumed in this study.

3.2.2.2 Compatibility analysis between RNSS feeder links and proposed systems

Shared operation within the 5 030-5 091 MHz band of separate AM(R)S and AMS(R)S systems for UAS CNPC creates the possibility of mutual interference between the two systems. Table 59 identifies the potential interference cases to be studied.

TABLE 59

Potential interference cases between RNSS feeder links and AM(R)S links

Case	Interference source link	Interference victim link
A.1	AM(R)S UL	RNSS FL (space-to-Earth)
A.2	AM(R)S DL	RNSS FL (space-to-Earth)
A.3	RNSS FL (space-to-Earth)	AM(R)S UL
A.4	RNSS FL (space-to-Earth)	AM(R)S DL

The AM(R)S characteristics for UAS in Table 2 in § 2.1 is used in this study. Because this table contains the UAS link budget for 37.5 kHz bandwidth signals, the compatibility analysis for other UAS link signals may need to be further studied.

Regarding the attenuation level of AM(R)S links in the 5 010-5 030 MHz band, –80 dBc is taken from Figs 14 to 17 in § 3.1.1.2.2.1, assuming AM(R)S links are enough separated from the lower edge of 5 030 MHz to keep the attenuation level of –80 dBc.

As the protection level of AM(R)S links, the interference power level equal to noise level (I/N of 0 dB) is assumed as used in the analyses in other sections.

Since the RNSS links are circularly polarized and the AM(R)S links for UAS are vertically polarized, their mutual cross-polarization loss will be assumed equal to 3 dB throughout this analysis.

In the interference analyses, the I/N is calculated using the following equation. Then, the calculated I/N values are compared with the protection criteria.

$I/N = P_{eu} - L_p - L_x - FDR + 10*\log10(B_{RNSS} / B_{UAS}) + G_{ru} - L_r - N$ for the AM(R)S link as the interfering link

$I/N = PFD + 10*\log10(\lambda^2/4\pi) + 10*\log10(N_{RNSS}) - L_x + G_{ru} - L_r - N$ for the RNSS link as the interfering link

where:

P_{eu}: source e.i.r.p. (dBW);

L_p: path loss (dB);

L_x: cross-polarization loss = 3 dB for all cases studied here;

B_{UAS}: bandwidth of AM(R)S link for UAS (kHz);

B_{RNSS}: bandwidth of RNSS link (kHz);

FDR: frequency-dependent rejection (dB), FDR of 80 dBc for the AM(R)S link as the interfering link;

PFD: aggregate pfd of a RNSS system = –124.5 (dBW/m^2/150 kHz);

λ: wavelength (μ);

N_{RNSS}: number of RNSS systems;

G_{ru}: receiving antenna gain (dBi);

L_r: receiver cable or feeder loss (dB);

N: receiver noise power (dBW);

Protection criteria for RNSS feeder link: $I/N < -20$ dB ($\Delta T/T < 1\%$);

Protection criteria for AM(R)S links for UAS: $I/N < 0$ dB.

Case A.1: Potential interference from AM(R)S uplink into RNSS feeder space-to-Earth link

A separation distance of 20 km is assumed as the LoS distance of maximum height of 30 m for the control station (see § 3.1.1.2.3.1) of AM(R)S links for UAS to check the possibility of geographical co-existence with RNSS systems.

However, because of the nature of this interference path, site-specific analysis is required before the actual implementation of AM(R)S links for UAS in order to check the impact of the interference into RNSS feeder links.

The interference analysis results are shown in Table 60 below.

TABLE 60

Potential interference from AM(R)S uplink into RNSS feeder space-to-Earth link

Parameter	Case 1	Case 2	Note
RNSS earth station receiving antenna gain (including feeder loss) (dBi)	49	0	NOTE 1
RNSS earth station thermal noise (150 K) (dBW/Hz)	–202.5	–202.5	
RNSS earth station receiver bandwidth (400 kHz) (dBW/Hz)	56	56	
RNSS earth station receiver noise power (dBW)	–146.5	–146.5	
Polarization loss (dB)	3	3	
UA control station e.i.r.p. (67 dBm/37.5 kHz) (dBW)	37	37	NOTE 2
Frequency (MHz)	5030	5030	
Assumed separation distance (km)	20	20	Edge of LoS
Free space loss (dB)	132.5	132.5	
Attenuation level (dBc)	80	80	
Received interference power at an RNSS earth station (400 kHz bandwidth) (dBW)	–119.2	–168.2	
Calculated *I*/*N* (dB)	27.3	–21.6	
I/*N* protection ratio (dB)	–20	–20	Δ*T*/*T* of 1%

Parameter	Case 1	Case 2	Note
Margin (dB)	–47.3	1.6	

NOTE 1 – As for the worst-case, the maximum receiving antenna gain of 49 dBi is assumed (Case 1). As one of the realistic case, the average gain of 0 dBi is assumed (Case 2).

NOTE 2 – This bandwidth is taken from Tables 1 and 2 in § 2.1. The compatibility analysis for other UAS link signals may need to be further studied.

As shown in Table 60, the interference from the AM(R)S uplink will not comply with the protection criterion of RNSS feeder space-to-Earth link, even in case that the RNSS receiving earth station is located at the edge of LoS of UACS. Therefore, it may not be suitable to locate the UACS within LoS of the earth stations of RNSS systems in the 5 010-5 030 MHz band.

Case A.2: Potential interference from AM(R)S downlink into RNSS feeder space-to-Earth link

Separation distance of 5.5 km (worst-case) and 265 km (LoS distance with height of 5.5 km) is assumed for the UA (see § 2.1 of this Annex) of AM(R)S links for UAS to check the possibility of geographical co-existence with RNSS systems.

The interference analysis results are shown in Tables 61 and 62 below:

TABLE 61

Potential interference from AM(R)S downlink into RNSS feeder space-to-Earth link (worst-case distance)

Parameter	Case 1.1	Case 1.2	Note
RNSS earth station receiving antenna gain (including feeder loss) (dBi)	49	0	NOTE 1
RNSS earth station thermal noise (150 K) (dBW/Hz)	–202.5	–202.5	
RNSS earth station receiver bandwidth (400 kHz) (dB/Hz)	56	56	
RNSS earth station receiver noise power (dBW)	–146.5	–146.5	
Polarization loss (dB)	3	3	
UA e.i.r.p. of 43 dBm/37.5 kHz (dBW)	13	13	NOTE 2
Frequency (MHz)	5030	5030	
Assumed separation distance (km)	5.5	5.5	Edge of LoS
Free space loss (dB)	121.2	121.2	
Attenuation level (dBc)	80	80	
Received interference power at an RNSS earth station (400 kHz bandwidth) (dBW)	–132.0	–181.0	
Calculated *I*/*N* (dB)	14.6	–34.4	
I/*N* protection ratio (dB)	–20	–20	Δ*T*/*T* of 1%
Margin (dB)	–34.6	14.4	

NOTE 1 – As for the worst-case, the maximum receiving antenna gain of 49 dBi is assumed (Case 1.1). As one of the realistic case, the average gain of 0 dBi is assumed (Case 1.2).

NOTE 2 – This bandwidth is taken from Tables 1 and 2 in § 2.1. The compatibility analysis for other UAS link signals may need to be further studied.

TABLE 62

Potential interference from AM(R)S downlink into RNSS feeder space-to-Earth link (edge of line-of-sight)

Parameter	Case 2.1	Case 2.2	Note
RNSS earth station receiving antenna gain (including feeder loss) (dBi)	49	0	NOTE 1
RNSS earth station thermal noise (150 K) (dBW/Hz)	–202.5	–202.5	
RNSS earth station receiver bandwidth (400 kHz) (dB/Hz)	56	56	
RNSS earth station receiver noise power (dBW)	–146.5	–146.5	
Polarization loss (dB)	3	3	
UA e.i.r.p. of 43 dBm/37.5 kHz (dBW)	13	13	NOTE 2
Frequency (MHz)	5030	5030	
Assumed separation distance (km)	265	265	Edge of LoS
Free space loss (dB)	155.0	155.0	
Attenuation level (dBc)	80	80	
Received interference power at an RNSS earth station (400 kHz) (dBW)	–165.6	–214.6	
Calculated *I*/*N* (dB)	–19.0	–68.0	
I/*N* protection ratio (dB)	–20	–20	Δ*T*/*T* of 1%
Margin (dB)	–1	48	

NOTE 1 – As for the worst-case, the maximum receiving antenna gain of 49 dBi is assumed (Case 2.1). As one of the realistic case, the average gain of 0 dBi is assumed (Case 2.2).

NOTE 2 – This bandwidth is taken from Tables 1 and 2 in § 2.1. The compatibility analysis for other UAS link signals may need to be further studied.

As shown in Tables 61 and 62, the interference from AM(R)S downlink may not comply with the protection criterion of RNSS feeder space-to-earth link. Therefore, it may not be suitable to locate the UA within the line-of-sight of the earth stations of RNSS systems in the 5 010-5 030 MHz band.

Case A.3: Potential interference from RNSS feeder space-to-Earth link into AM(R)S uplink

The UA (see § 2.1 of this annex) is the victim receiver in this case. The antenna maximum gain of the UA is supposed to be pointing towards the negative elevation angle. Because of the unavailability of the antenna pattern of the UA, the maximum gain of 5 dBi is used in this analysis for conservatism.

The interference analysis results are shown in Table 63 below:

TABLE 63

Potential interference from RNSS feeder space-to-Earth link into AM(R)S uplink

Parameter	Uplink	Note
UA receiving antenna gain (dBi)	5	NOTE 1
UA receiver cable loss (dB)	2	
UA thermal noise (290 K) (dBW/Hz)	–203.9	
UA receiver bandwidth (37.5 kHz) (dBHz)	45.7	NOTE 2
UA receiver noise power (dBW)	–158.2	
Polarization loss (dB)	3	
Aggregate pfd from one RNSS system (dBW/m^2/150 kHz)	–124.5	RR 5.443B
Frequency (MHz)	5030	
Aggregate power density at the surface of the Earth from one RNSS system (dBW/150 kHz)	–160.0	
Assumed number of RNSS systems	5	
Aggregate received interference power at an UA (37.5 kHz bandwidth) (dBW)	–159.0	
I/*N* (dB)	–0.78	
I/*N* protection ratio (dB)	0	
Margin (dB)	0.78	NOTE 3

NOTE 1 – This is conservative assumption. Because the maximum UA antenna gain is expected to be pointed towards the negative elevation angle and the interfering RNSS satellite power arrives from the positive elevation angle, the actual interference level is expected to be smaller than the one in this analysis.

NOTE 2 – This bandwidth is taken from Tables 1 and 2 in § 2.1. The compatibility analysis for other UAS link signals may need to be further studied.

NOTE 3 – Necessity of aeronautical safety margin of 6 dB may need to be discussed.

As shown in Table 63, there are possibilities that the interference from RNSS can comply with the protection criterion of AM(R)S link for UAS. The aggregate interference effect into AM(R)S link for UAS with other interference sources such as MLS and AMS(R)S may need to be studied further.

Case A.4: Potential interference from RNSS feeder space-to-Earth link into AM(R)S downlink

The UACS (see § 2.1 of this annex) is the victim receiver in this case. Because the interference assumption is given by the pfd level, the use of the averaged receiving antenna gain over all the possible pointing direction of the UA control station is appropriate. Because of the unavailability of the antenna pattern of the UACS, 5 dBi is assumed for this averaged gain in this analysis for the conservatism.

The interference analysis results are shown in Table 64 below.

TABLE 64

Potential interference from RNSS feeder space-to-Earth link into AM(R)S downlink

Parameter	**Downlink**	**Note**
Assumed UACS averaged receiving antenna gain (dBi)	5	NOTE 1
UACS receiver cable loss (dB)	2	
UACS thermal noise (290 K) (dBW/Hz)	–203.9	
UACS station receiver bandwidth (37.5 kHz) (dB/Hz)	45.7	NOTE 2
UACS receiver noise power (dBW)	–158.2	
Polarization loss (dB)	3	
Aggregate pfd from one RNSS system (dBW/m^2/150 kHz)	–124.5	RR 5.443B
Frequency (MHz)	5030	
Aggregate power density at the surface of the Earth from one RNSS system (dBW/150 kHz)	–160.0	
Assumed number of RNSS systems	5	
Aggregate received interference power at UACS (37.5 kHz) (dBW)	–159.0	
I/*N* (dB)	–0.78	
I/*N* protection ratio (dB)	0	
Margin (dB)	0.78	NOTE 3

NOTE 1 – The maximum receiving antenna gain of UACS is 28 dBi. Because the interference assumption is given by the pfd level, the use of the averaged receiving antenna gain over all the possible pointing direction of the UACS is appropriate. Because the antenna pattern of the UACS is not available, 5 dBi is assumed for conservatism.

NOTE 2 – This bandwidth is taken from Tables 1 and 2 in § 2.1. The compatibility analysis for other UAS link signals may need to be further studied.

NOTE 3 – Necessity of aeronautical safety margin of 6 dB may need to be discussed.

As shown in Table 64, the interference from RNSS will comply with the protection criterion of AM(R)S link for UAS. The aggregate interference effect into AM(R)S link for UAS with other interference sources such as MLS and AMS(R)S may need to be studied further.

3.2.3 Conclusion

The adjacent band interference from RNSS feeder downlinks in the 5 010-5 030 MHz band into proposed AM(R)S for UAS in the 5 030-5 091 MHz band can be acceptable.

To avoid adjacent band interference from the proposed AM(R)S applications for UAS in the 5 030-5 091 MHz into RNSS in the 5 010-5 030 MHz band, a certain separation distance is needed because the interference power level from even only one UAS interferer (either UACS or UA) could exceed the protection level of RNSS receiving earth stations. Due to the limited number of RNSS feeder link earth station in the band 5 010-5 030 MHz, local frequency management should control the necessary technical and operational restriction for such UAS systems. Potential interference from the terrestrial CNPC system into RNSS feeder links system in the band 5 010-5 030 MHz could be prevented only through proper placement of CNPC ground sites to avoid the line of sight within the earth stations of RNSS systems. Potential interference from the terrestrial CNPC system into RNSS service links in the band 5 010-5 030 MHz was not considered.

Appendix 1 to Annex 1

Assumptions on CNPC link budget used in methodology 2

Typical cell size is considered to be 200 km. Each link between the UA and the UACS would require bandwidth of 37.5 kHz. However, when considering approaches (distances up to 35 km), higher data rate might be needed and therefore, bandwidth of 300 kHz are considered (only the downlink case).

For small UA, distances up to 26 km can be considered.

Antenna gain on board is estimated at 3 dBi. On ground, at 5 GHz, the antenna gain is estimated at 10 dBi for sectoral antennas and 24 dBi for tracking antennas.

As the typical weight objective for an onboard communication equipment is 3 to 5 kg, the maximum transmitter power consumption shall be minimized in order to lower the impact on the UAV (autonomy and the thermal dissipation).

These budgets links are presented below.

TABLE I.1

Example of CNPC budget link

	5 000-5 010 MHz		**5 030-5 091 MHz**					
	UA --> UACS	**UA (video) --> UACS**	**UACS (tracking antenna) --> UA**	**UACS (sectoral antenna) --> UA**	**UA --> UACS (tracking antenna)**	**UA --> UACS (sectoral antenna)**	**UA (video) --> UACS (tracking antenna)**	**UA (video) --> UACS (sectoral antenna)**
Link budget	4QPSK	4QPSK	4QPSK	4QPSK	4QPSK	4QPSK	4QPSK	4QPSK
Frequency (MHz)	5091	5091	5091	5091	5091	5091	5091	5091
Wave length (m)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
UACS – UAV distance d (km)	26	26	200	200	200	200	35	35
UACS – UAV distance d (NM)	14	14	108	108	108	108	19	19
Free space losses (dB)	–134.88	–134.88	–152.6	–152.6	–152.6	–152.6	–137.5	–137.5
e.i.r.p. (dBm)	25.5	25.5	52	52	41	41	41	41
Transmitting antenna gain (dBi)	3	3	24	10	3	3	3	3
Emission losses (cables) (dB)	–2	–2	–1	–1	–2	–2	–2	–2
Received noise level (dBm)	–126.26	–117.23	–126.26	–126.26	–126.26	–126.26	–117.23	–117.23
Noise factor – dB	2	2	2	2	2	2	2	2
kT (dBm/Hz)	–174	–174	–174	–174	–174	–174	–174	–174
Symbol rate – kHz	37.5	300	37.5	37.5	37.5	37.5	300	300
Receiving antenna gain (dBi)	10	10	3	3	24	10	24	10
Receiver losses (cables) (dB)	–1	–1	–2	–2	–1	–1	–1	–1
Received power (dBm)	–100.38	–100.38	–99.6	–99.6	–88.6	–102.6	–73.5	–87.7
Received E_s/N_o – dB	25.88	16.85	26.66	26.66	37.66	23.66	43.77	29.77
Required min E_s/N_o – dB	6	6	6	6	6	6	6	6
CNPC link margin (dB)	19.88	10.85	20.66	20.66	31.66	17.66	37.77	23.77

The required E_s/N_0 does not include margins for interference. Therefore, the link margin is needed for additional losses caused by multipath propagation, airframe shadowing, and/or destructively interfering airframe reflections that will occasionally result from temporarily unfavourable orientations of the UA with respect to the ground station.

A balance between the two (feasibility/on board integration and spectrum efficiency/compatibility with existing system) should be found.

Annex 2

Glossary

ACP	Aeronautical Communications Panel
AES	Airborne earth station
AM(R)S	Aeronautical-mobile (route) service
AMS	Aeronautical-mobile service
AMS(R)S	Aeronautical-mobile satellite (route) service
AMSS	Aeronautical-mobile satellite service
AMT	Aeronautical mobile telemetry
ANLE	Airport Network and Location Equipment (a highly integrated, high-data-rate, wireless local-area network for airport surface areas)
ARNS	Aeronautical radionavigation service
ATC	Air traffic control
BER	Bit error ratio
BLoS	Beyond line-of-sight
CNPC	Control and non-payload communications
CP	Cross polarization
DL	Downlink
DME	Distance measuring equipment
DME/N	Narrow-spectrum distance measuring equipment
DME/P	Precision distance measuring equipment
DPSK	Differential phase-shift keying
DQPSK	Differential quadrature phase-shift keying
e.i.r.p.	Equivalent isotropically radiated power
E/S	Earth-to-space
FDD	Frequency-division duplex
FDR	Frequency-dependent rejection

FL	Forward link
FSS	Fixed-satellite service
GES	Ground earth station (for SATCOM CNPC system)
GPS	Global Positioning System
GS	Ground station (for terrestrial CNPC system)
G/T	Ratio of receiving-antenna gain to receiver thermal noise temperature (kelvins)
HIBLEO-4	A non-geostationary-orbit satellite network
ICAO	International Civil Aviation Organization
INR	Interference-to-noise ratio
LEO	Low Earth orbit (or a satellite in that orbit)
LoS	Line-of-sight
MLS	Microwave Landing System
MS	Mobile service
MSS	Mobile-satellite service
OFDM	Orthogonal frequency-division multiplexing
pfd	Power flux-density
PSK	Phase-shift keying
QPSK	Quadrature phase-shift keying
RF	Radio frequency
RL	Return link
RNSS	Radionavigation-satellite service
RR	Radio Regulations
Rx	Receiver
S&A	Sense and avoid
Sat.	Satellite
SATCOM	Satellite communications
S/E	Space-to-Earth
SNR	Signal-to-noise ratio
SWAP	Size, weight, and power
TDD	Time-division duplex
Tx	Transmitter
UA	Unmanned aircraft
UACS	UA control station
UAS	UA system(s)
UL	Uplink
WP	Working party
WRC	World Radiocommunication Conference
WRC-07	WRC 2007
WRC-12	WRC 2012