



Report ITU-R M.2238
(11/2011)

**Compatibility study to support line of sight
control and non-payload communications
links for unmanned aircraft systems
proposed in the frequency band
5 091–5 150 MHz**

M Series
**Mobile, radiodetermination, amateur
and related satellite services**

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Compatibility study to support line of sight control and non-payload communications links for unmanned aircraft systems proposed in the frequency band 5 091–5 150 MHz

(2011)

1 Introduction

Significant growth is forecast in the unmanned aircraft (UA) 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 frequency 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 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 unmanned aircraft 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.

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

2 Terminology

Unmanned aircraft: Designates all types of remotely controlled aircraft.

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

Sense and avoid: 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: Consists of the following subsystems:

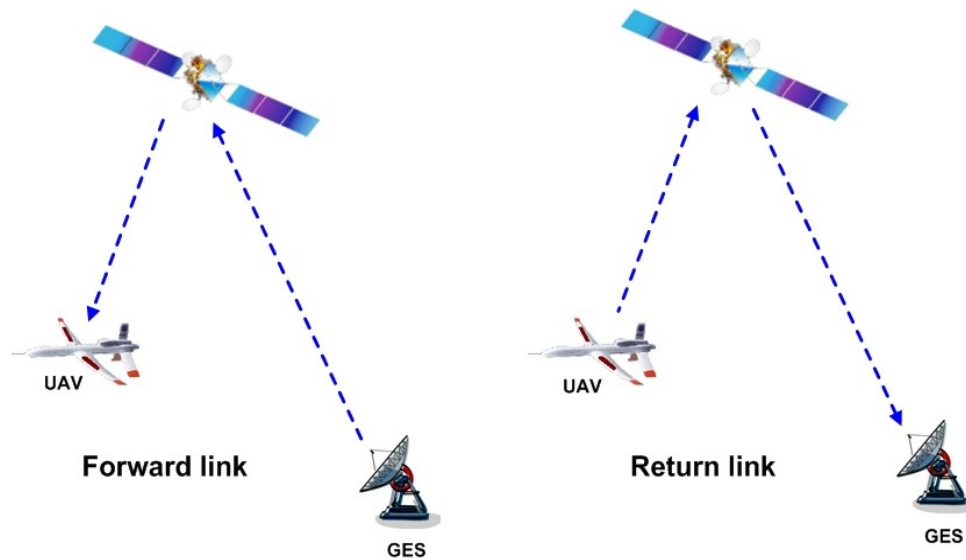
- UA subsystem (i.e. the aircraft itself);
- UACS subsystem;
- (ATC communication subsystem (not necessarily relayed through the UA));
- sense and avoid (S&A) subsystem; and
- payload subsystem (e.g. video camera ...)¹.

Control and non-payload communications: 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 Figure 1).

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.

Report ITU-R M.2171 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).

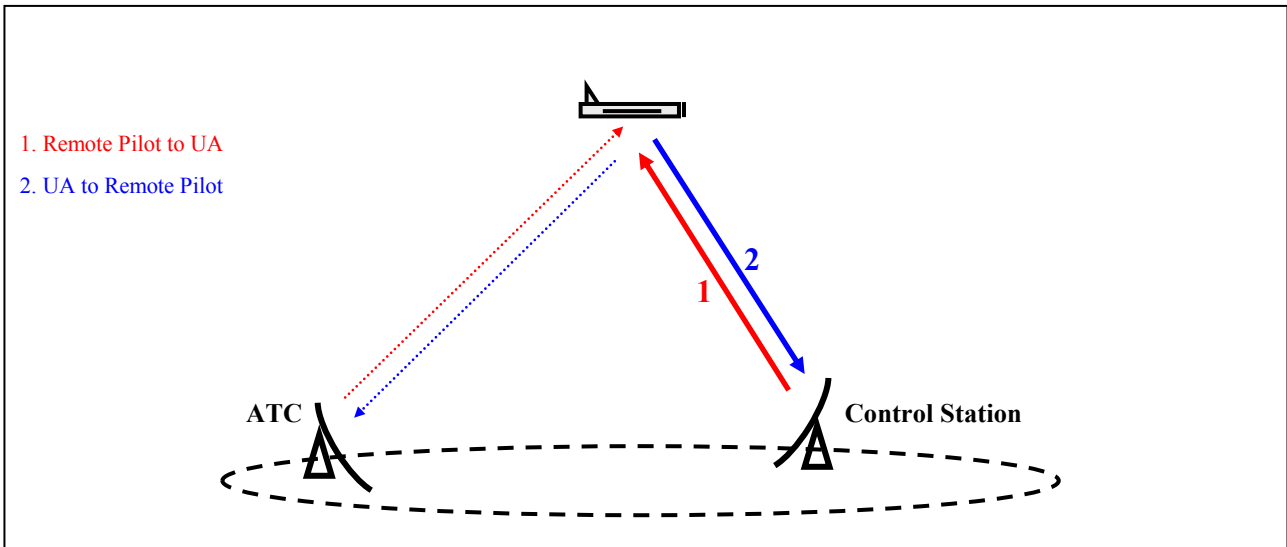
Report ITU-R M.2171 estimates the total spectrum requirements covering both terrestrial and satellite requirements in a separate manner. Deployment of UAS will require access to both terrestrial and satellite spectrum.

Report ITU-R M.2171 also 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 line-of-sight links in the system.

FIGURE 2
Links involved in line-of-sight communications



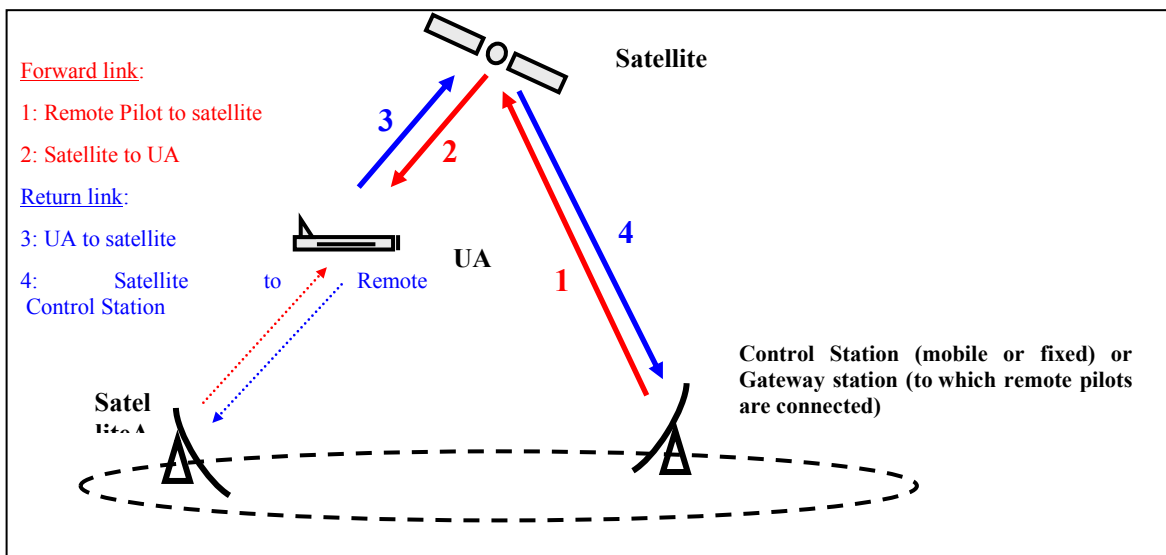
For LOS links:

- 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 aeronautical-mobile (route) service (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 beyond line-of-sight communications via satellite



Case 1: Mobile unmanned aircraft control station

- 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, fixed-satellite service (FSS) allocations can also be considered if sharing studies with other services allocated in the frequency bands, have been successfully completed which also require appropriate modifications of the Radio Regulations taking into account ICAO requirements.

Case 2: Fixed unmanned control stations

- 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 FSS could be considered taking also into account International Civil Aviation Organisation (ICAO) requirements. Additionally for links 2 and 3, FSS allocations can also be considered if sharing studies with other services allocated in the frequency 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 frequency 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.

International Civil Aviation Organization 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 frequency band whose incumbent radio-frequency 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 frequency 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 frequency 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 bands under consideration and regulatory aspects

In this Report, the frequency band 5 091-5 150 MHz is studied for the terrestrial component.

The existing allocations in the frequency band 5 091-5 150 MHz are listed in following Table 1 according to RR Article 5

TABLE 1

Frequency allocations in the frequency band 5 091–5 150 MHz

Region 1	Region 2	Region 3
5 091-5 150 MHz	AERONAUTICAL RADIONAVIGATION AERONAUTICAL MOBILE 5.444B 5.367 5.444 5.444A	

In accordance with the allocations and footnotes in Table 1, the 5 091-5 150 MHz frequency band is allocated to four primary services, i.e. ARNS, AMS, AMS(R)S and FSS (Earth-to-space):

- the ARNS is reserved as an expansion frequency band for microwave landing system (MLS) according to RR No. 5.444;
- the AMS is limited to three applications: the airport surface applications, the aeronautical flight telemetry, and the aeronautical security transmissions according to RR No. 5.444B; It has to be noted that the aeronautical security system was not taken into account in this report due to the absence of this system characteristics.
- the AMS(R)S, allocated through RR No. 5.367, has no systems currently operating in this frequency band;
- the FSS (Earth-to-space) is limited to feeder links of non-geostationary satellite systems in the mobile-satellite service according to RR No. 5.444A.

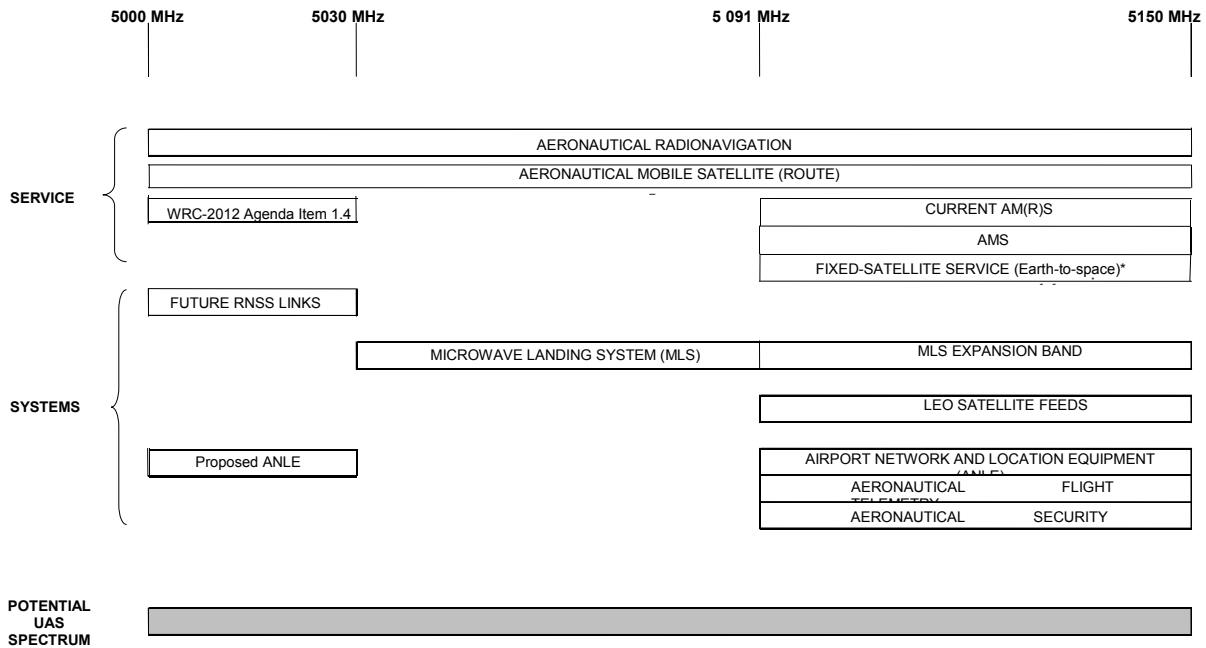
Figure 4 provides an overview of services in 5 000-5 150 MHz frequency band, with examples of systems using those services.

This Report analyses the compatibility between proposed AM(R)S systems for UAS terrestrial component (including UACS and UA transmitters and receivers) and existing services in the frequency band 5 091-5 150 MHz.

Characteristics of MLS which is not taken into account in this report can be found in Report ITU-R M.2237.

FIGURE 4

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



* This allocation is limited to MSS feeder links.

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

6 Systems characteristics

This section gives the systems characteristics taken into account for the compatibility studies computed in this report

6.1 Unmanned aircraft system characteristics

The main parameters of UAS terrestrial CNPC links for Medium/Large UA and small UA are listed in Tables 2 to 5.

Tables 2 and 3 correspond to the first set of parameters given in Annex 1 of Report ITU-R M.2233 and Tables 4 and 5 correspond to the second set of parameters given in that report.

TABLE 2
Unmanned aircraft system characteristics for the first type medium and large unmanned aircraft

Parameter	UACS Type 1	UA Type 1
Equivalent Isotropically Radiated Power (EIRP) (dbm)	67	43
Antenna Gain (dBi)	28	5
Antenna pattern	Recommendation ITU-R F.1245-1 ITU-R M.1459	Recommendation ITU-R M.1642 (see Table 6)
Cable Loss (dB)	1	2
Bandwidth (kHz)	37.5	37.5

TABLE 3

Unmanned aircraft system characteristics for the first type small unmanned aircraft

Parameter	UACS Type 1	UA Type 1
Equivalent Isotropically Radiated Power (EIRP) (dBm)	56	32
Antenna Gain (dBi)	28	5
Antenna pattern	Recommendation ITU-R F.1245-1 ITU-R M.1459	Recommendation ITU-R M.1642 (see Table 6)
Cable Loss (dB)	1	2
Bandwidth (kHz)	12.5	12.5

TABLE 4

Unmanned aircraft system characteristics for the second type medium and large unmanned aircraft

Parameter	UACS Type 2 (tracking antenna)	UACS Type 2 (sectoral antenna)	UA Type 2
Equivalent Isotropically Radiated Power (EIRP) (dBm)	52	52	40
Antenna Gain (dBi)	24	10	3
Antenna pattern	Recommendation ITU-R F.1245-1	Recommendation ITU-R F.1336-2	Recommendation ITU-R M.1642 (see Table 6)
Cable Loss (dB)	1	1	2
Bandwidth (kHz)	37.5	37.5	37.5

TABLE 5

Unmanned aircraft system characteristics for the second type small unmanned aircraft

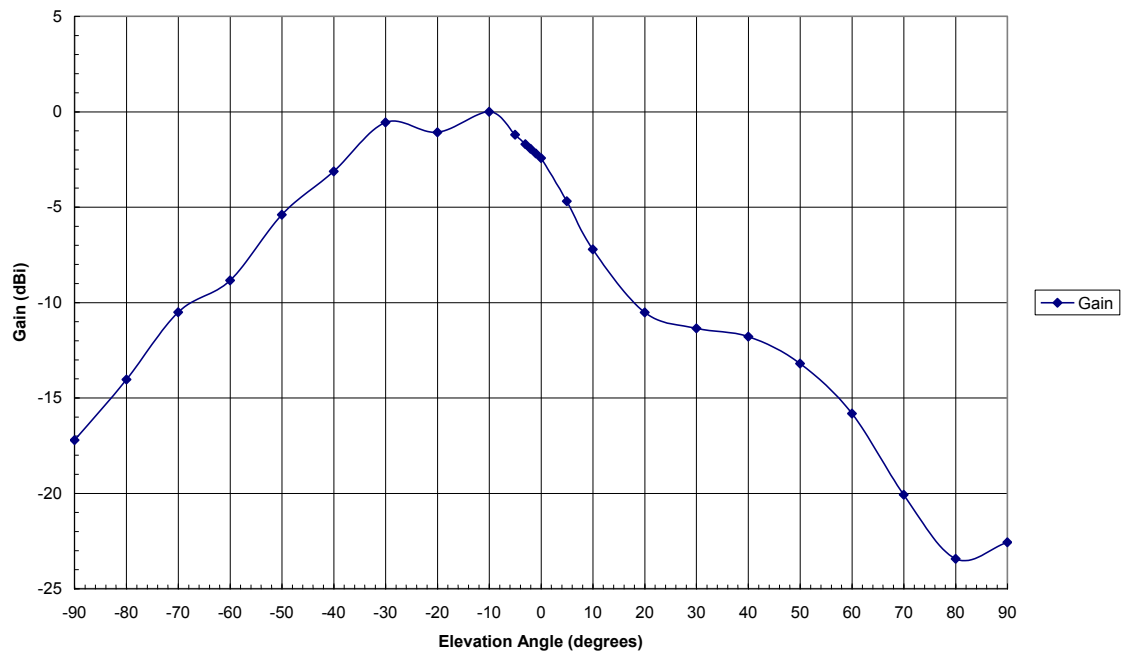
Parameter	UACS Type 2	UA Type 2
Equivalent Isotropically Radiated Power (EIRP) (dBm)	35.5	25.5
Antenna Gain (dBi)	10	3
Antenna pattern	Recommendation ITU-R F.1336-2	Recommendation ITU-R M.1642 (see Table 6)
Cable Loss (dB)	1	2
Bandwidth (kHz)	37.5	37.5

In this study it is considered to take an UA's antenna similar to the distance measuring equipment DME's antenna referred in Recommendation ITU-R M.1642. The table below gives the relevant UA's antenna gain for elevation angles between -90° and 90° .

TABLE 6
Medium and large unmanned aircraft antenna gain definition

	Extract from Rec. ITU-R M.1642	Elevation angle definition
Elevation angle (degrees)	Relative 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	
-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	-23.53	
90	-22.21	

FIGURE 5
Medium/large unmanned aircraft antenna gain



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 7.

TABLE 7
Small unmanned aircraft 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 omnidirectional (in azimuth) antenna used for the study is defined by Recommendation ITU-R F.1336-2, Sections 2.1 and 2.1.1 and is recalled below:

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

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

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).

The pattern of the UACS ground tracking antenna used for one study is defined by Recommendation ITU-R F.1245-1, Sections 2.2 and is recalled below:

$$G(\theta) = G_{\max} - 2.5 \times 10^{-3} \left(\frac{D}{\lambda} \theta \right)^2 \quad \text{for} \quad 0 \leq \theta < \theta_m$$

$$G(\theta) = 39 - 5 \log(D/\lambda) - 25 \log \theta \quad \text{for} \quad \theta_m \leq \theta < 48$$

$$G(\theta) = -3 - 5 \log(D/\lambda) \quad \text{for} \quad 48 \leq \theta \leq 180$$

where:

$G(\theta)$: UACS ground antenna gain (dBi);

θ : off-axis angle (degrees);

G_{\max} : maximum antenna gain (dBi), 24 dBi;

D : antenna diameter;

λ : wavelength;

θ_m : off-axis angle of the first side lobe (degrees);

$$\theta_m = \frac{20\lambda}{D} \sqrt{G_{\max} - G_1}$$

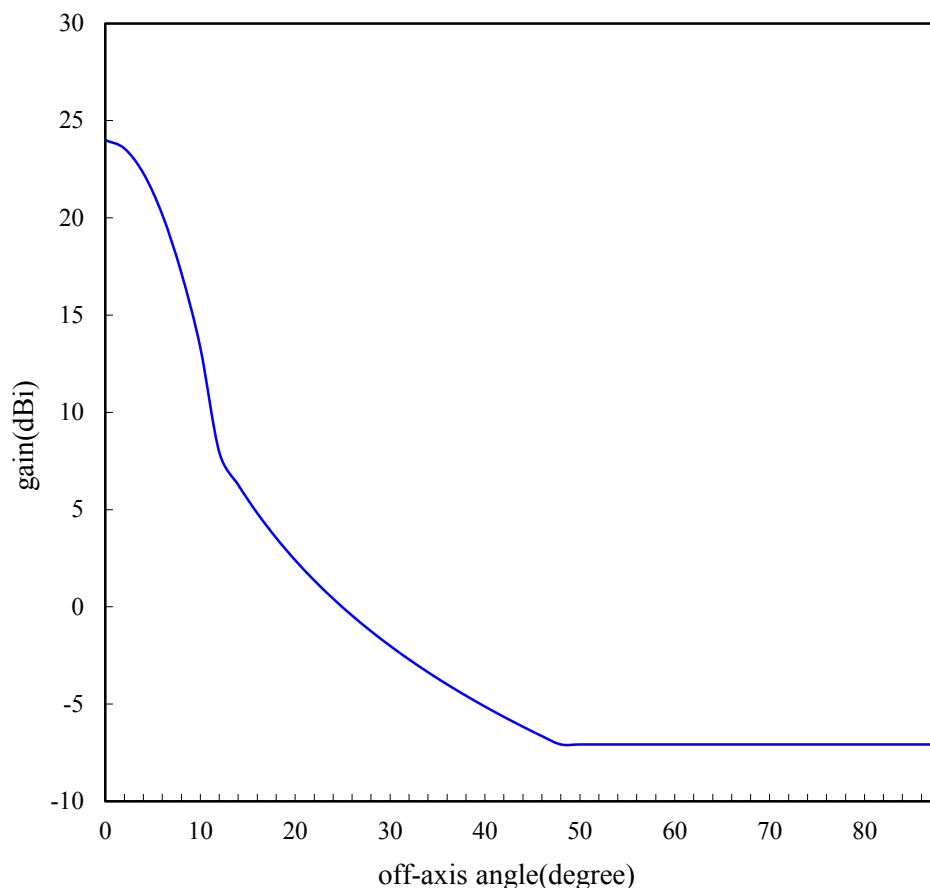
where:

G_1 : gain of the first side lobe (dBi)

$$G_1 = 2 + 15 \log(D/\lambda)$$

FIGURE 6

Pattern of unmanned aircraft control station ground antenna defined by Recommendation ITU-R F.1245-1



The pattern of the UACS ground tracking antenna used for one study is defined by Recommendation ITU-R M.1459, Sections 2.1 and is recalled below:

$$G(\theta) = 41.2 + 20 \log \left(\frac{\sin 1.952\theta}{1.952\theta} \right) \quad \text{dBi} \quad \text{for } 0^\circ \leq \theta \leq 0.94^\circ$$

$$G(\theta) = 35.1 - 20 \log \theta \quad \text{dBi} \quad \text{for } 0.94^\circ < \theta \leq 3.82^\circ$$

$$G(\theta) = 29 + 20 \log \left(\frac{\sin 0.479\theta}{0.479\theta} \right) \quad \text{dBi} \quad \text{for } 3.82^\circ < \theta \leq 5.61^\circ$$

$$G(\theta) = 27.27 - 18.75 \log \theta \quad \text{dBi} \quad \text{for } 5.61^\circ < \theta \leq 12.16^\circ$$

$$G(\theta) = 34.05 - 25 \log \theta \quad \text{dBi} \quad \text{for } 12.16^\circ < \theta \leq 48^\circ \quad (1e)$$

$$G(\theta) = -8 \quad \text{dBi} \quad \text{for } 48^\circ < \theta \leq 180^\circ \quad (1f)$$

where:

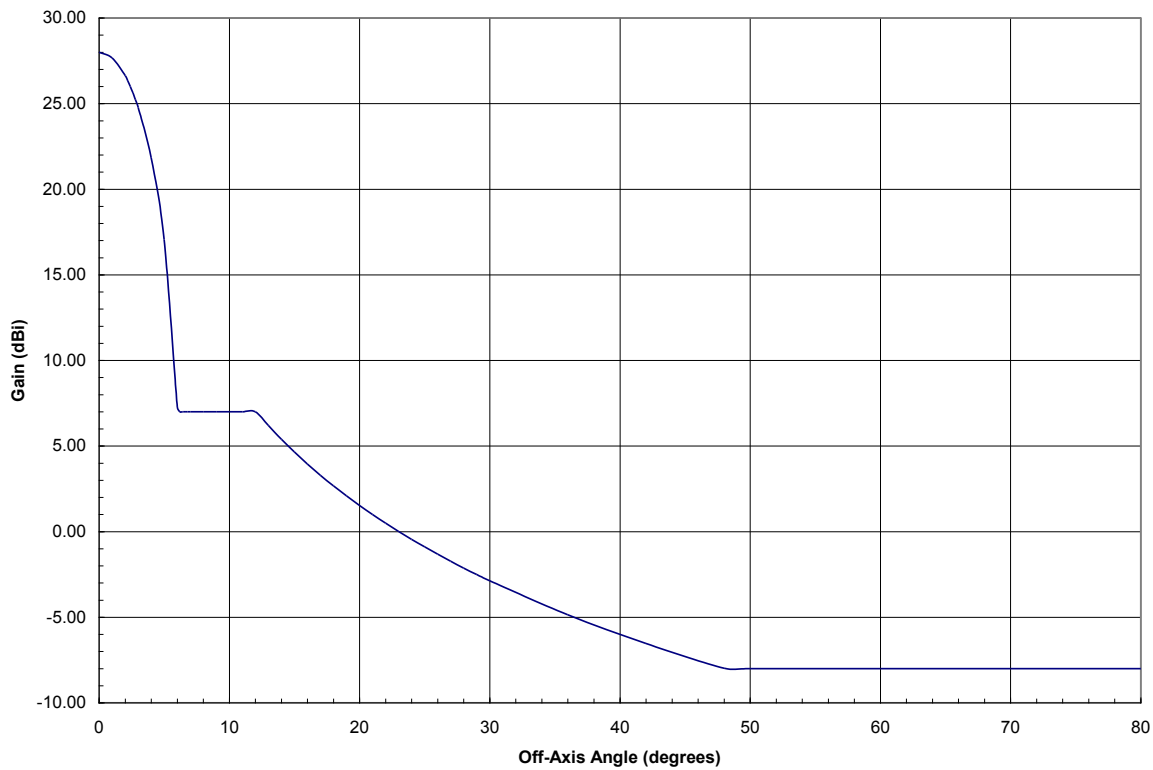
$G(\theta)$: UACS ground antenna gain (dBi);

θ : off-axis angle (degrees);

Figure 7 gives the relevant UACS's tracking antenna gain for off-axis angles between 0° and 80° .

FIGURE 7

Pattern of unmanned aircraft control station ground antenna defined by Recommendation ITU-R M.1459



6.2 Fixed satellite characteristics

From the Report ITU-R M.2118, the FSS system parameters are listed in Tables 8 and 9. The gain of the spacecraft feeder link receive antenna is shown in Fig. 8.

TABLE 8

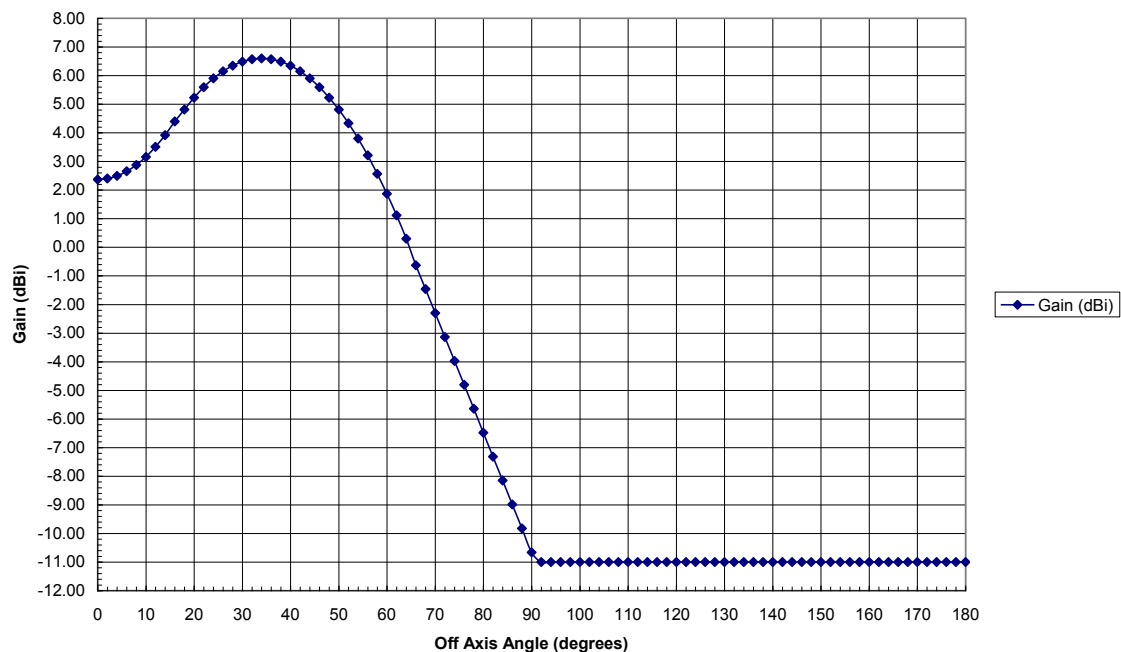
Parameters for mobile satellite system feeder uplink, transmit

Parameter	HIBLEO-4FL
Satellite Orbit Altitude (km)	1414
EIRP/User (dBW)	30.6
Maximum EIRP (dBW)	48.6
Transmit Bandwidth (MHz)	1.23
Transmit Antenna Gain (dBi)	47.6
3 dB Beamwidth (pk – pk) (degrees)	0.78
Antenna Rolloff Characteristic (ITU-R S.465-6)	32-25 log (theta)

TABLE 9
Parameters for mobile satellite system feeder uplink, receive

Parameter	HIBLEO-4 FL
Satellite receiver noise temperature T (K)	550
Polarization discrimination L_p (dB)	1
Feed loss L_{feed} (dB)	2.9
Satellite receiver bandwidth B (MHz)	1.23
Mean satellite receiver antenna gain (dBi)	4 (see Fig. 8)
Noise level (dBm)	-110.3

FIGURE 8
Spacecraft feeder uplink receive antenna pattern



6.3 Aeronautical mobile (route) service - ground surface application characteristics

The airport surface applications include the transmissions of situational awareness, video streaming, electronic flight bag data and de-icing data, etc. One candidate architecture is the ANLE system which would be based on the IEEE 802.16e standard with the maximum operation range of 3 km.

According to Recommendation ITU-R M.1828 and Report ITU-R M.2118, the main parameters of the ANLE system are given in Table 10.

TABLE 10

ANLE system parameters

Parameters	ANLE
Transmitter power (dBm)	32.2
Transmitter antenna gain (dBi)	8 (Base station)/6 (aircraft)
Receiver antenna gain (dBi)	6 (aircraft)/8 (Base station)
Receiver bandwidth (MHz)	20
Receiver noise temperature (K)	290
Receiver noise figure (dB)	10
Receiver noise level (dBm)	-91
Protection criteria I/N (dB)	-6
Tolerable interference power (dBm)	-97

6.4 Aeronautical mobile telemetry characteristics

The aeronautical mobile telemetry (AMT) system is used to transmit telemetry information from flight test aircraft to a ground station during flight test operations. In general, protection of AMT ground stations in the frequency band 5 091–5 150 MHz and in other frequency bands (typically the 1.4 GHz and 2.3 GHz frequency bands, as described in Recommendation ITU-R M.1459) is accomplished by restricting the pfd of an interfering signal, as measured at the aperture of an AMT ground station receive antenna, to a value of between -177 and -180 dBW/m² in 4 kHz. This is necessary to account for AMT ground station signal to noise requirements and, especially, the fade margin/angular dependence of the propagation channel and of the aircraft's telemetry antenna gain. Respectively, these add 10-20 dB and 3–5 dB to the required link margin.

An example link budget is shown in Table 11. Note that the link budget applies to 5 GHz systems, but that it is completely consistent with the 1.4 GHz and 2.3 GHz analyses in Recommendation ITU-R M.1459. This consistency is because the changes in signal wavelength when AMT systems operate at 5 GHz, instead of at the lower frequencies described in Recommendation ITU-R M.1459, are accompanied by corresponding changes in AMT receive antenna effective diameters. This keeps the diameter-to-wavelength ratios of the antennas the same, thus keeping antenna gain factors and beam widths unchanged despite the change in signal frequency to 5 GHz.

TABLE 11
Aeronautical mobile telemetry system parameters*

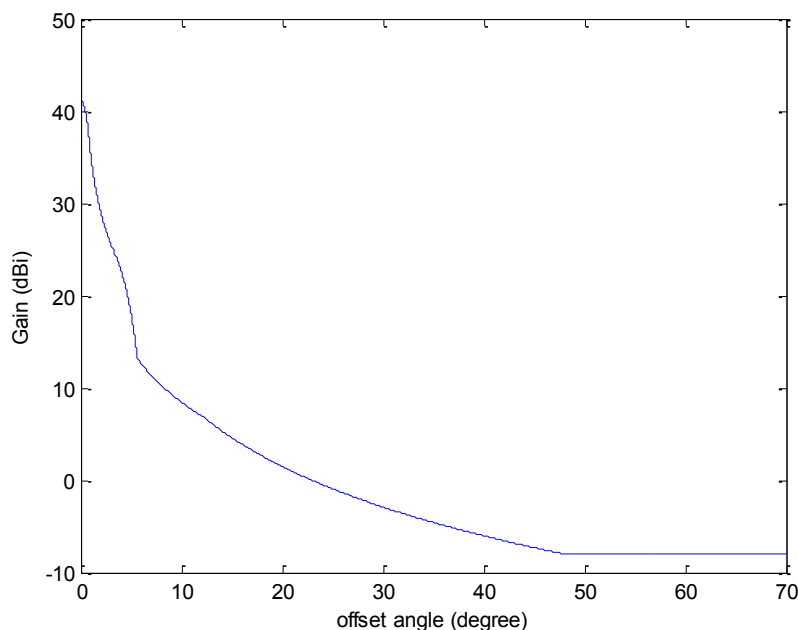
Type of parameter	
Modulation type	PCM/FM
Transmitter output level (dBm)	46
Transmitter aircraft antenna gain: omni (dBi)	0
Cable / guide and diplexer insertion losses (dB)	3
Transmitted e.i.r.p./10 MHz (dBm)	43
Propagation losses at LOS horizon range (dB)	156.22 @ 300 km
Receiving ground station antenna gain (dBi)	40
Polarization losses (dB)	3
Receiver carrier level, C, in 10 MHz (dBm)	-76.22
Receiver bandwidth (MHz)	10
Receiver noise level (dBm)	-99.72
Achieved C/N (dB)	23.5
Required fade margin (dB)	13
S/N ratio requirement (SNR) (dB)	10
Margin (dB)	.5 dB
I/N for 0.5 dB margin (dB)	-9.2
Interference power at receiver input (dBm)	-108.9
Corresponding pfd protection threshold at AMT receive antenna (dBW/m ² in 4 kHz)	-177

* NOTE – Other systems may use different modulations and have different SNR and fade margin requirements.

Figure 9 shows the antenna pattern to be used, in accordance with Recommendation ITU-R M.1459, for the purpose of computing interference to an AMT ground station. The pattern below combines the mainlobe pattern of a 40 dBi antenna with the sidelobe patterns of a 28 dBi antenna. This provides an accurate model that accounts simultaneously for both the high gain, narrow beamwidth of the 40 dBi antenna and the wider beamwidth sidelobes of a 28 dBi antenna. Again, this composite pattern is applicable in the 1.4 GHz, 2.3 GHz, and 5 GHz frequency bands.

This composite antenna simplifies greatly the calculations, described in detail in the Recommendation, that provide a single pfd level, measured at the aperture of an AMT ground station receive antenna, that is required for protection of the telemetry signal. It is a significant achievement of the Recommendation that a single value accurately describes the protection levels needed for a wide variety of AMT antenna diameters. Thus, protection of AMT systems can be accomplished without the need for site specific technical details of individual AMT stations at which a variety of different antenna diameters are routinely in use.

FIGURE 9

Aeronautical mobile telemetry receiver antenna pattern (Recommendation ITU-R M.1459)**7 Conclusions**

Compatibility studies between proposed UAS terrestrial CNPC links and incumbent services in the frequency band 5 091-5 150 MHz show that:

- For the compatibility analysis between UAS terrestrial CNPC links and FSS:

Two studies show that the increase of noise temperature in FSS satellites would exceed acceptable limits and would prevent the use of both UAS uplink and downlink. The use of UACS tracking antennas would not reduce the interference to acceptable limits due to the fact that non-GSO FSS satellite in this frequency band can be everywhere in the sky and that the UACS antenna will track the UA in all directions. Therefore, it is not possible for the UACS antenna to avoid pointing towards the satellite nor possible to interrupt the UACS transmission during such potentially long periods due the required availability of UA to UACS link.

Another study, based on the use of UAS tracking antenna, shows that when only FSS and UAS are considered within the affected region of the satellite beam, sharing of the frequency band 5 091-5 150 MHz may be possible. In any other cases where other services, such as ARNS, AM(R)S and AMS, are sharing the frequency band, within the affected region of the satellite feeder link beam taken into account in this study, the sharing would be difficult and the sharing conditions would need to be re-evaluated.

- For the compatibility analysis between UAS terrestrial CNPC links and AM(R)S (ANLE), geographic separation distances (on the order of tens of kilometres) are required to obtain compatibility. However, these separation distances would prevent UAS from operating in large areas around airports equipped with ANLE systems, which goes against the scenarios foreseen for UAS. The probability of interference between UAS and ANLE would put the safety-related communications at risk.
- For the compatibility analysis between UAS terrestrial CNPC links and AMS (AMT), geographic separation distances (on the order of hundreds of kilometres) are required to

obtain compatibility. However, these separation distances would prevent UAS from operating in large areas in the order of hundreds of km in all directions around locations where AMT antennas are deployed, which goes against the scenarios foreseen for UAS and AMT operation.

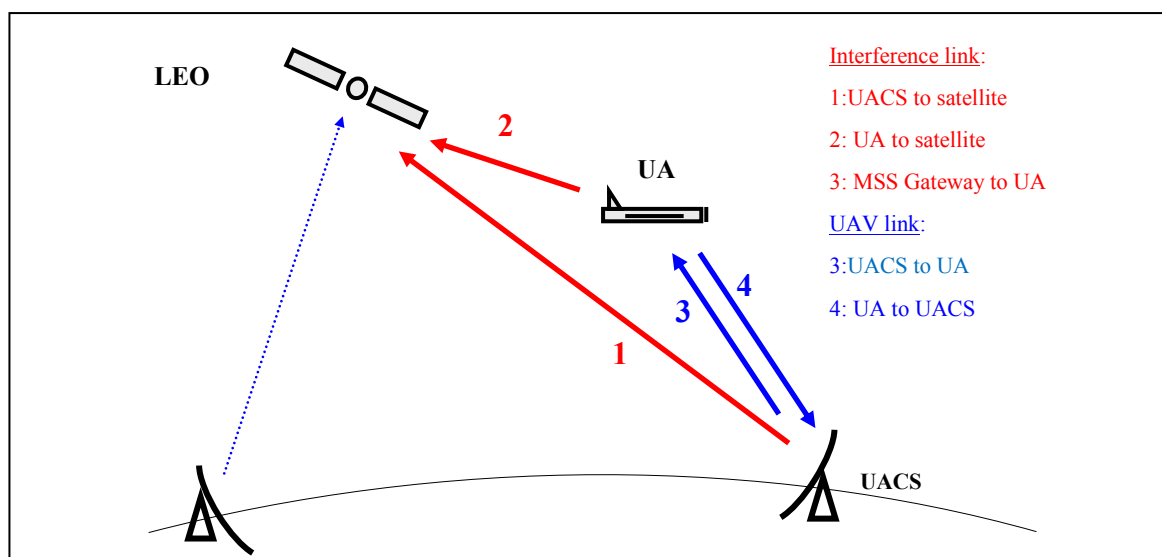
ANNEX 1

Compatibility analysis between unmanned aircraft system terrestrial command and non-payload communication links and systems operating in the fixed satellite service

Introduction

The compatibility analysis scenario used in the studies is shown in Fig. A1-1 below:

FIGURE A1-1
Compatibility analysis scenario



Three separate analyses of interference from UAS uplink to the FSS have been produced. The details of these three studies are present in Appendices 1 to 3 of this Annex 1 of this report.

APPENDIX 1 TO ANNEX 1

Potential interference from unmanned aircraft system uplinks to systems operating in the fixed satellite service in the frequency band 5 091-5 150 MHz (Study 1)

1 Potential interference from unmanned aircraft system uplinks to systems operating in the fixed satellite service

The uplink from UACS to UA may cause potential interference to the FSS receiver. Figure A1-2 is the scenario of interference from UACS located at the nadir point of the satellite to FSS and Fig. A1-3 is the scenario of interference from UACS located at the edge of the satellite visible area to FSS.

FIGURE A1-2

Scenario of interference from unmanned aircraft control system located at the nadir point of the satellite to satellites operating in the fixed satellite service

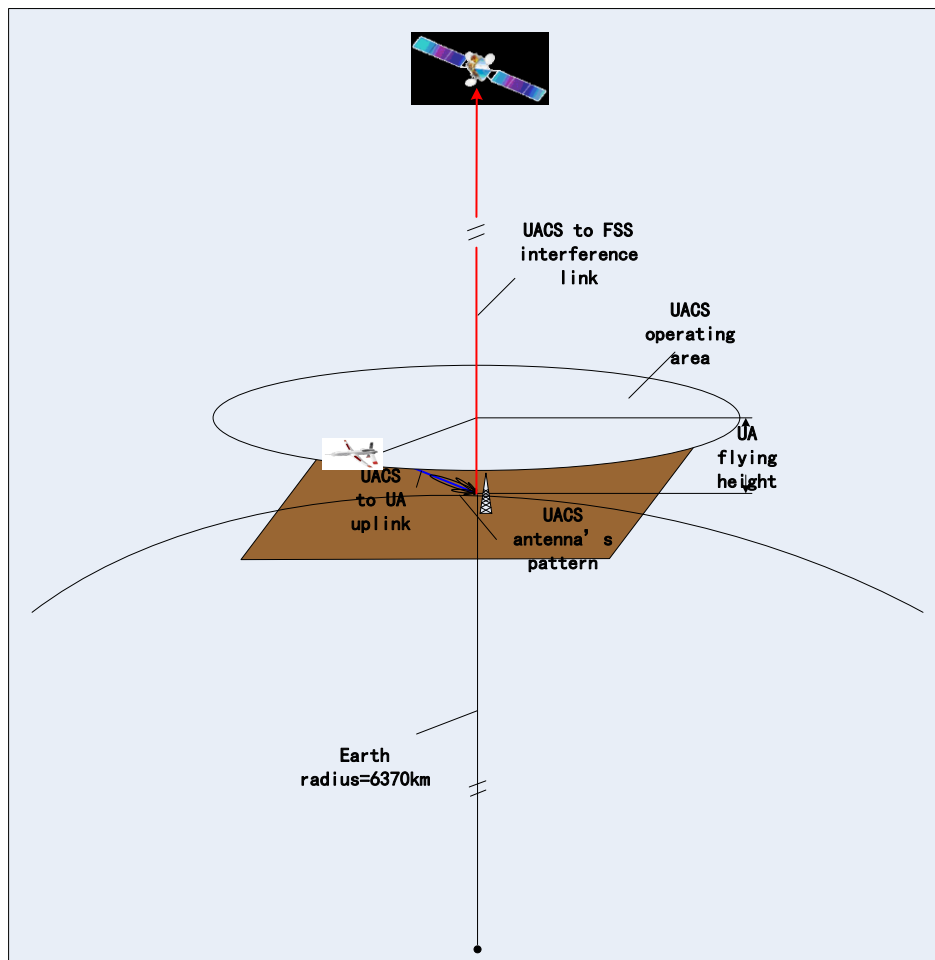
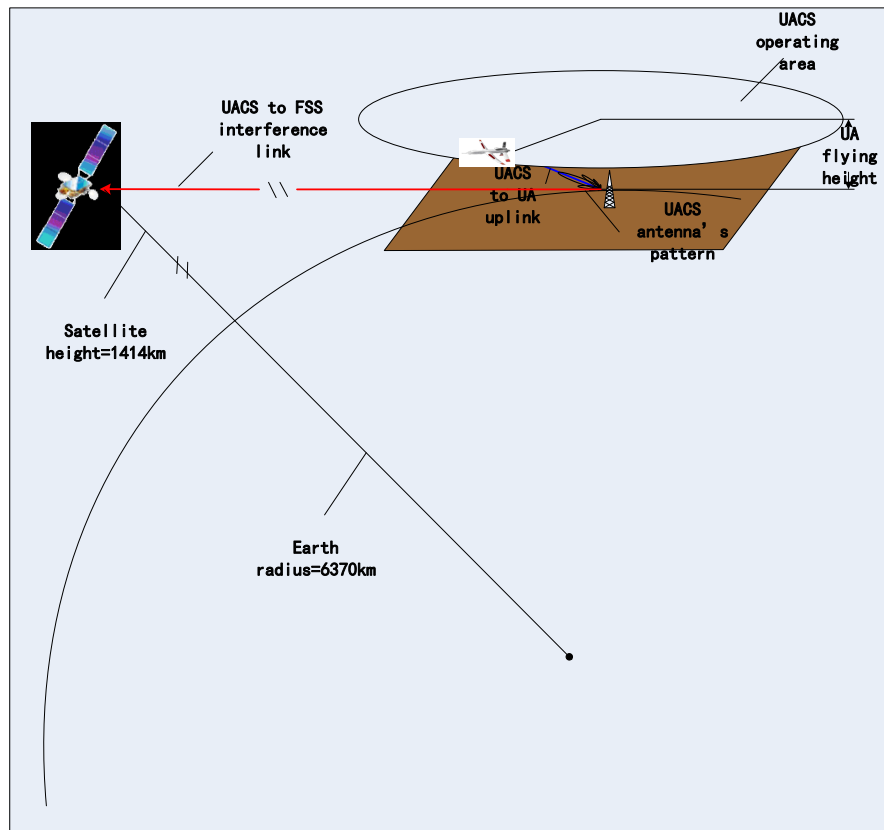


FIGURE A1-3

Scenario of interference from unmanned aircraft control station located at the edge of the satellite visible area to satellite system operating in the fixed satellite service

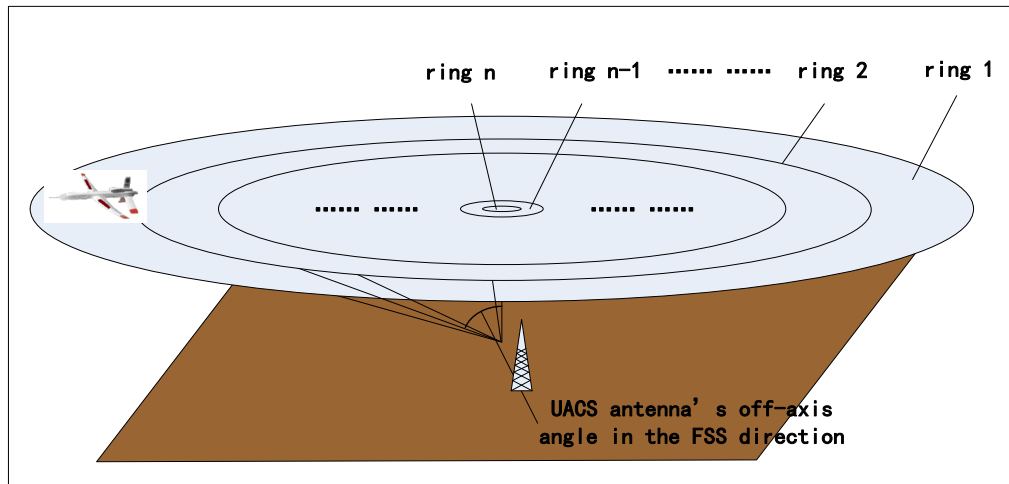


It can be assumed that an UA will fly at an uniform velocity, so the possibility of its appearance at a certain place within an UACS operating area is evenly distributed. Considering the operating range of the UACS (200 km) is much larger than the flying height of UA (5.5 km), the elevation angle of the UACS antenna will be very low for the majority of time.

Firstly, it can be calculated the averaged interference from the UACS located at the satellite's nadir point to the FSS. The operating area of the UACS can be divided into numerous concentric rings with several degrees step (e.g. 2 degrees), as shown in Fig. A1-4.

FIGURE A1-4

Concentric rings of unmanned aircraft control station operating area at the nadir of the satellite to satellite system of the fixed satellite service



To facilitate the interference calculation, it is assumed that the UACS antenna's off-axis angle is constant in each ring, so it can be calculated the interference distributed in this ring by multiplying the transmitting power, the antenna gain in the FSS direction, the time percentage of this ring and the path loss.

The interference distributed in ring i can be calculated as equation (A1-1):

$$I_i = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - L_p + 10 \log (\text{area percentage}) \quad (\text{A1-1})$$

where:

- P_t is the UACS transmitter power, 29 dBm;
- G_t is the UACS transmitter antenna's off-axis gain, defined by Recommendation ITU-R F.1245 as depicted in Fig. 6 of the main part of the report;
- G_r is the FSS satellite receiver antenna's gain, depicted in Fig. 8 of the main part of the report ;
- L_t is the UACS transmitter cable loss, 1 dB;
- L_r is the FSS receiver cable loss, 2.9 dB;
- L_{cross} is the cross polarization loss, 3 dB (taking into account that the HIBLEO-4FL link employs both right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP), while the UACS usually employs linear polarization).
- L_p is the free-space propagation loss (dB).

The interference averaged in the operating area of the UACS can be obtained by sum up the interference distributed in all the rings, as shown in Table A1-1. In this table, the off-axis angle begins from 88.425 degrees due to the fact that the lowest elevation angle of the UACS is $\arctg(5.5/200)=1.575$ degrees. The radius1 and radius 2 are the outer and inner radius of the ring, respectively.

TABLE A1-1

Interference from unmanned aircraft control station to satellite systems operating in the fixed satellite service averaged in the operating area of unmanned aircraft control station

Ring number	Off-axis angle (degrees)	Radius1 (km)	Radius2 (km)	Ring area (km ²)	Time percentage (%) [*]	UACS antenna's gain (dB) ^{**}	Interference distributed in the ring (W)
1	88.425	200.00	88.03	101317.00	80.60133	-7.075	7.02E-19
2	86.425	88.03	56.35	14372.38	11.43375	-7.075	9.96E-20
3	84.425	56.35	41.36	4600.62	3.65996	-7.075	3.19E-20
4	82.425	41.36	32.60	2034.03	1.61814	-7.075	1.41E-20
5	80.425	32.60	26.85	1074.26	0.85461	-7.075	7.45E-21
6	78.425	26.85	22.78	635.48	0.50554	-7.075	4.40E-21
7	76.425	22.78	19.73	406.75	0.32359	-7.075	2.82E-21
8	74.425	19.73	17.36	275.92	0.21950	-7.075	1.91E-21
9	72.425	17.36	15.47	195.70	0.15568	-7.075	1.36E-21
10	70.425	15.47	13.91	143.79	0.11439	-7.075	9.97E-22
11	68.425	13.91	12.60	108.71	0.08648	-7.075	7.53E-22
12	66.425	12.60	11.49	84.16	0.06695	-7.075	5.83E-22
13	64.425	11.49	10.53	66.46	0.05287	-7.075	4.61E-22
14	62.425	10.53	9.69	53.38	0.04246	-7.075	3.70E-22
15	60.425	9.69	8.95	43.49	0.03460	-7.075	3.01E-22
16	58.425	8.95	8.29	35.89	0.02855	-7.075	2.49E-22
17	56.425	8.29	7.69	29.94	0.02382	-7.075	2.08E-22
18	54.425	7.69	7.15	25.22	0.02006	-7.075	1.75E-22
19	52.425	7.15	6.65	21.42	0.01704	-7.075	1.48E-22
20	50.425	6.65	6.20	18.34	0.01459	-7.075	1.27E-22
21	48.425	6.20	5.78	15.79	0.01257	-7.075	1.09E-22
22	46.425	5.78	5.39	13.68	0.01089	-6.7438	1.02E-22
23	44.425	5.39	5.03	11.92	0.00948	-6.26569	9.95E-23
24	42.425	5.03	4.69	10.42	0.00829	-5.76555	9.77E-23
25	40.425	4.69	4.36	9.15	0.00728	-5.24125	9.67E-23
26	38.425	4.36	4.06	8.06	0.00641	-4.69035	9.67E-23
27	36.425	4.06	3.77	7.11	0.00566	-4.10999	9.76E-23
28	34.425	3.77	3.49	6.29	0.00500	-3.49685	9.94E-23
29	32.425	3.49	3.23	5.57	0.00443	-2.847	1.02E-22
30	30.425	3.23	2.98	4.94	0.00393	-2.15576	1.06E-22
31	28.425	2.98	2.73	4.37	0.00348	-1.41751	1.11E-22
32	26.425	2.73	2.50	3.87	0.00308	-0.62537	1.18E-22
33	24.425	2.50	2.27	3.42	0.00272	0.229136	1.27E-22
34	22.425	2.27	2.05	3.01	0.00239	1.156689	1.39E-22
35	20.425	2.05	1.83	2.63	0.00209	2.170948	1.53E-22
36	18.425	1.83	1.62	2.29	0.00182	3.289813	1.73E-22
37	16.425	1.62	1.41	1.97	0.00157	4.537366	1.98E-22

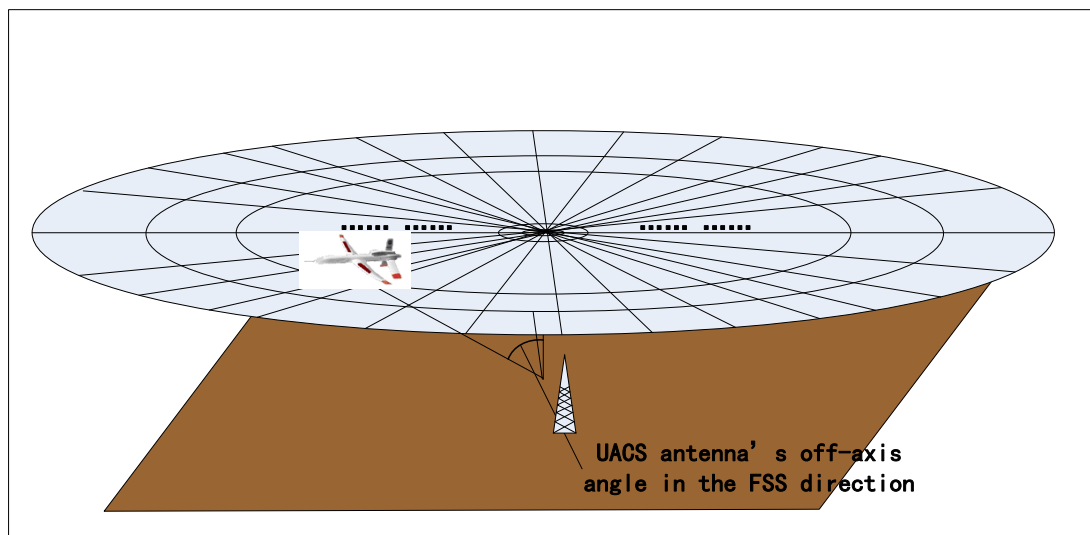
Ring number	Off-axis angle (degrees)	Radius1 (km)	Radius2 (km)	Ring area (km ²)	Time percentage (%) [*]	UACS antenna's gain (dB) ^{**}	Interference distributed in the ring (W)
38	14.425	1.41	1.21	1.67	0.00133	5.947104	2.33E-22
39	12.425	1.21	1.01	1.40	0.00111	7.56759	2.82E-22
40	10.425	1.01	0.81	1.13	0.00090	12.40977	6.97E-22
41	8.425	0.81	0.62	0.88	0.00070	16.43028	1.37E-21
42	6.425	0.62	0.43	0.64	0.00051	19.59763	2.05E-21
43	4.425	0.43	0.23	0.40	0.00032	21.91183	2.19E-21
44	2.425	0.23	0.04	0.17	0.00013	23.37286	1.27E-21
one UACS interference to FSS in the operating area (W)							8.8E-19
one UACS interference to FSS in the operating area (dBm)							-150.55
$\Delta T/T$							0.00944%

- * Time percentage is the ratio between the area of the ring and the whole operation area of a UACS.
- ** The UACS antenna's gain is defined by Recommendation ITU R F.1245-1 and depicted in Fig. 6 of the main part of the report.

From the table above, it can be concluded that the interference from the UACS located at the nadir of the satellite is 0.00944%.

To calculate the interference from the UACS at the edge of the visible area of the satellite, the UACS operating area into cells can be divided according to both the elevation angle and the azimuth angle, as shown in Fig. A1-5.

FIGURE A1-5
Cells of unmanned aircraft control stations operating area at the edge of the visible area of the satellite



Then the interference distributed in every cell can be calculated by multiplying the transmitting power, the antenna gain of the off-axis angle, the time percentage of this cell and the path loss.

The off-axis angle of the UACS antenna towards the satellite can be calculated as equation (A1-2):

$$\text{off-axis angle} = \arccos(\cos(\text{elevation angle}) \cos(\text{azimuth angle})) \tag{A1-2}$$

Thus the interference distributed in cell i can be calculated as equation (A1-3):

$$I_i = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - L_p + 10 \log(\text{area percentage}) \quad (\text{A1-3})$$

where:

- P_t is the UACS transmitter power, 29 dBm;
- G_t is the UACS transmitter antenna's off-axis gain, defined by Recommendation ITU-R F.1245 as depicted in Fig. 6 of the main report;
- G_r is the FSS satellite receiver antenna's gain at the satellite's horizon direction, 3.5 dB;
- L_t is the UACS transmitter cable loss, 1 dB;
- L_r is the FSS receiver cable loss, 2.9 dB;
- L_{cross} is the cross polarization loss, 3 dB (taking into account that the HIBLEO-4FL link employs both right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP), while the UACS usually employs linear polarization);
- L_p is the free-space propagation loss (dB), 179.6 dB.

Then the interference of all the cells can be summed up to obtain the interference averaged in the operating area of the UACS at the edge of the visible area of the satellite. The result is $\Delta T/T = 0.0355\%$.

For small UACS, the aggregate $\Delta T/T$ can be calculated to be 0.00092% by the same method as the large UAS.

The aggregated interference of all the UACS in the visible area of the satellite should be calculated by summing up the interference from each UACS. However, to simplify the calculation, the interference from the UACS at the edge of the visible area of the satellite can be assumed as the worst case, then multiplying this interference with the number of UACS in the visible area of the satellite.

Assuming one UA needs one UACS to control, the total number of UACS in the visible area of the satellite can be obtained by multiplying the density of the UA with the visible area of the satellite $4.6 \times 10^7 \text{ km}^2$.

However, not all these UACS are in one 1.23 MHz bandwidth of the satellite. The ratio between 1.23 MHz and the 59 MHz bandwidth of the 5 091-5 150 MHz is 2.1% (the reverse ratio is 48). If it is assumed that the UACS operating uniformly in this frequency band, then the number of UACS that could interference with the FSS receiver is product of the UACS number in the area with the ratio. The resulted aggregated interference is shown in Table A1-2.

TABLE A1-2

Aggregated interference from unmanned aircraft control stations to satellite systems operating in the fixed satellite service

	large UACS	medium UACS	small UACS
UACS density (number/km ²)	0.000044	0.000195	0.000803
visible area of the satellite (km ²)	46000000	46000000	46000000
UACS number in the area	2024	8970	36938
UACS number uniformly in 1.23 MHz	42	187	770
Interference to FSS($\Delta T/T$) per UACS	0.03550%	0.03550%	0.00092%
aggregated interference to FSS($\Delta T/T$)	1.5%	6.6%	0.7%
Total $\Delta T/T$	8.8%		

It should be noted that the power of large UACS and medium UACS in the above calculation are the same. However, in the actual situation, the power of medium UACS may be lower than the large UACS. If the power of medium UACS is 3 dB lower than the large UACS, the aggregated interference to FSS is $\Delta T/T=3.3\%$, and the total $\Delta T/T=5.5\%$.

2 Potential interference from unmanned aircraft system downlinks to satellite systems operating in the fixed satellite service

The downlink from UA to UACS may also cause interference to the FSS receiver. Considering the satellite receiver could see many UAs at the same time, the aggregate interference of the UAs should be evaluated.

The total number of UA in the visible area of the satellite can be obtained by multiplying the density of the UA with the visible area of the satellite 4.6×10^7 km². And the number of UA that could interference with the FSS receiver is the product of the total UA number in the area with the ratio $1.23 \text{ MHz}/59 \text{ MHz} = 2.1\%$, assuming the UAs operation frequency band is uniformly distributed in the 5 091-5 150 MHz frequency band.

To estimate the aggregate interference of the UAs, the satellite's visible area can divided into 10 concentric rings according to the UA antenna's elevation angle with equal degrees step. Assuming the UAs are uniformly distributed in the visible area, then the UA numbers within each ring can be obtained by multiplying the area percentage of each ring in the visible area with the total number of UA.

To facilitate the interference calculation, as the worst case, it is assumed the antenna's gain of every UA in each ring to be the maximum value in that ring and the slant range to the satellite to be the minimum value in that ring, then the aggregate interference of the UAs in that ring can be obtained.

The interference from ring i can be calculated as equation (A1-4):

$$I_i = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - L_p + 10 \log(\text{number in the ring}) \quad (\text{A1-4})$$

where:

P_t is the UA transmitter power (dBm);

G_t is the UA transmitter antenna's off-axis gain, defined by Table 5 of the main part of the report;

- G_r is the FSS satellite receiver antenna's gain at the satellite's horizon direction, depicted in Fig. 8 of the main part of the report;
- L_t is the UA transmitter cable loss, 1 dB;
- L_r is the FSS receiver cable loss, 2.9 dB;
- L_{cross} is the cross polarization loss, 3 dB (taking into account that the HIBLEO-4FL link employs both right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP), while the UA usually employs linear polarization);
- L_p is the free-space propagation loss (dB).

The interference of all the 10 rings can be summed up to get the aggregate interference of the UAs, as shown in Tables A1-3, A1-4 and A1-5.

TABLE A1-3

Unmanned aircraft to satellite links operating in the fixed satellite service aggregate interference (large unmanned aircraft)

theta	deg	elevation angle	0.00	9.00	18.00	27.00	36.00	45.00	54.00	63.00	72.00	81.00	90.00
P_t	dBm	UA transmitter power	40	40	40	40	40	40	40	40	40	40	40
G_t	dB	UA antenna gain	-2.43	-6.42	-9.93	-11.14	-11.75	-12.7	-14.51	-17.19	-20.99	-23.44	-22.21
G_r	dB	FSS satellite receiver antenna gain	3.5	4	4.5	5.5	6	6.5	6	5.5	4	2.8	2.2
L_t	dB	UA cable loss	2	2	2	2	2	2	2	2	2	2	2
L_r	dB	FSS receiver cable loss	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
L_{cross}	dB	Cross polarization loss	3	3	3	3	3	3	3	3	3	3	3
d	km	Slant distance	4474	3587	2919	2435	2090	1844	1671	1551	1473	1428	1414
L_p	dB	Free-space propagation	179.55	177.63	175.84	174.27	172.94	171.85	171.00	170.35	169.90	169.63	169.55
I	dBm	Calculated interference power	-146.38	-147.95	-149.17	-147.81	-146.59	-145.95	-147.41	-149.94	-154.79	-158.17	-157.46
R1	km		3900.2	3009.88	2323.11	1799.38	1394.52	1072.18	805.87	577.07	372.65	182.88	0.00
R2	km		3009.9	2323.11	1799.38	1394.52	1072.18	805.87	577.07	372.65	182.88	0.00	-
p	%	area percentage	40.44%	24.08%	14.19%	8.50%	5.23%	3.29%	2.08%	1.28%	0.69%	0.22%	0.00%
N		number of UAs uniformly in 1.23 MHz	42	42	42	42	42	42	42	42	42	42	42
n		number of UAs within elevation angle	16.99	10.11	5.96	3.57	2.20	1.38	0.87	0.54	0.29	0.09	0.00
I/N	dB		-23.78	-27.60	-31.12	-31.98	-32.87	-34.25	-37.69	-42.35	-49.85	-58.22	-
$\Delta T/T$			0.42%	0.17%	0.08%	0.06%	0.05%	0.04%	0.02%	0.01%	0.00%	0.00%	-
Total $\Delta T/T$			0.85%										

TABLE A1-4

Unmanned aircraft to satellite links operating in the fixed satellite service aggregate interference (medium unmanned aircraft)

theta	deg	elevation angle	0.00	9.00	18.00	27.00	36.00	45.00	54.00	63.00	72.00	81.00	90.00
P_t	dBm	UA transmitter power	40	40	40	40	40	40	40	40	40	40	40
G_t	dB	UA antenna gain	-2.43	-6.42	-9.93	-11.14	-11.75	-12.7	-14.51	-17.19	-20.99	-23.44	-22.21
G_r	dB	FSS satellite receiver antenna gain	3.5	4	4.5	5.5	6	6.5	6	5.5	4	2.8	2.2
L_t	dB	UA cable loss	2	2	2	2	2	2	2	2	2	2	2
L_r	dB	FSS receiver cable loss	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
L_{cross}	dB	Cross polarization loss	3	3	3	3	3	3	3	3	3	3	3
d	km	Slant distance	4474	3587	2919	2435	2090	1844	1671	1551	1473	1428	1414
L_p	dB	Free-space propagation	179.55	177.63	175.84	174.27	172.94	171.85	171.00	170.35	169.90	169.63	169.55
I	dBm	Calculated interference power	-146.38	-147.95	-149.17	-147.81	-146.59	-145.95	-147.41	-149.94	-154.79	-158.17	-157.46
R1	km		3900.2	3009.88	2323.11	1799.38	1394.52	1072.18	805.87	577.07	372.65	182.88	0.00
R2	km		3009.9	2323.11	1799.38	1394.52	1072.18	805.87	577.07	372.65	182.88	0.00	-
p	%	area percentage	40.44%	24.08%	14.19%	8.50%	5.23%	3.29%	2.08%	1.28%	0.69%	0.22%	0.00%
N		number of UAs uniformly in 1.23 MHz	187	187	187	187	187	187	187	187	187	187	187
n		number of UAs within elevation angle	75.63	45.03	26.54	15.90	9.77	6.15	3.89	2.39	1.30	0.41	0.00
I/N	dB		-17.29	-21.12	-24.63	-25.49	-26.39	-27.76	-31.21	-35.86	-43.36	-51.73	-
$\Delta T/T$			1.87%	0.77%	0.34%	0.28%	0.23%	0.17%	0.08%	0.03%	0.00%	0.00%	-
Total $\Delta T/T$			3.77%										

TABLE A1-5

Unmanned aircraft to satellite links operating in the fixed satellite service aggregate interference (small unmanned aircraft)

theta	deg	elevation angle	0.00	9.00	18.00	27.00	36.00	45.00	54.00	63.00	72.00	81.00	90.00
P_t	dBm	UA transmitter power	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5
G_t	dB	UA antenna gain	-2.43	-3.8	-5.6	-6	-6.3	-7	-8.1	-10.7	-10.7	-12.5	-12
G_r	dB	FSS satellite receiver antenna gain	3.5	4	4.5	5.5	6	6.5	6	5.5	4	2.8	2.2
L_t	dB	UA cable loss	2	2	2	2	2	2	2	2	2	2	2
L_r	dB	FSS receiver cable loss	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
L_{cross}	dB	Cross polarization loss	3	3	3	3	3	3	3	3	3	3	3
d	km	Slant distance	4474	3587	2919	2435	2090	1844	1671	1551	1473	1428	1414
L_p	dB	Free-space propagation	179.55	177.63	175.84	174.27	172.94	171.85	171.00	170.35	169.90	169.63	169.55
I	dBm	Calculated interference power	-161.88	-160.83	-160.34	-158.17	-156.64	-155.75	-156.50	-158.95	-160.00	-162.73	-162.75
R1	km		3900.16	3009.88	2323.11	1799.38	1394.52	1072.18	805.87	577.07	372.65	182.88	0.00
R2	km		3009.88	2323.11	1799.38	1394.52	1072.18	805.87	577.07	372.65	182.88	0.00	-
p	%	area percentage	40.44%	24.08%	14.19%	8.50%	5.23%	3.29%	2.08%	1.28%	0.69%	0.22%	0.00%
N		number of UAs uniformly in 1.23 MHz	770	770	770	770	770	770	770	770	770	770	770
n		number of UAs within elevation angle	311.41	185.40	109.29	65.46	40.25	25.32	16.02	9.83	5.34	1.69	0.00
I/N	dB		-26.65	-27.85	-29.66	-29.71	-30.29	-31.42	-34.15	-38.72	-42.43	-50.15	-
$\Delta T/T$			0.22%	0.16%	0.11%	0.11%	0.09%	0.07%	0.04%	0.01%	0.01%	0.00%	-
Total $\Delta T/T$			0.82%										

From Tables A1-3, A1-4 and A1-5, the total $\Delta T/T$ can be obtained from UA is $0.85\% + 3.77\% + 0.82\% = 5.44\%$.

APPENDIX 2 TO ANNEX 1

**Compatibility study between unmanned aircraft system and satellite links
operating in the fixed satellite service in the frequency
band 5 091-5 150 MHz (Study 2)****1 Computer Simulation**

The MSS system is assumed to have the same characteristics as the HIBLEO-4 ITU-R system with a 48 spacecraft constellation. A Gateway Earth Station for that system is situated in the Republic of Korea and the UAS aircraft and associated earth stations are assumed to also be in the same geographic area. At the Gateway Earth Station, there are three antennas tracking three separate spacecraft, the highest, the second highest and the third highest. The e.i.r.p of the gateway station for a single CDMA channel is 30.6 dBW. The Gateway station transmit antenna gain is 47.6 dBi and the 3 dB beamwidth is 0.78 degrees peak-to-peak. The receive antenna gain pattern for the 5 GHz feeder link is shown in Fig. 8 and the noise temperature of the spacecraft receiver is 550 K.

The UAS aircraft are assumed to operate in an area with a 412 km radius around the CNPC earth station which is assumed to be in the same area as the MSS gateway earth station.

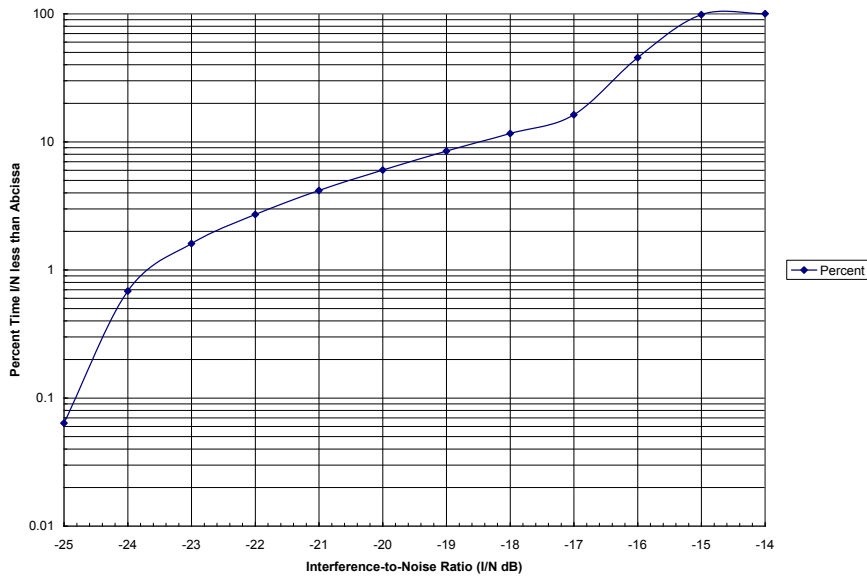
In the first interference situation, interference from UAS aircraft stations into MSS spacecraft receivers was modelled. Fifty UAS aircraft stations were assumed to be operating in an area of approximately 500 000 square kilometres. The roll and pitch of the aircraft were varied in a random fashion with a normal distribution between the limits $\pm 40^\circ$ and $\pm 15^\circ$, respectively.

In the second interference situation, interference from UAS earth stations into MSS spacecraft receivers was modelled. Forty-five UAS aircraft were assumed to be operating, again, over approximately a 500 000 square kilometre area. Each UAS Control Station was communicating with one aircraft. The e.i.r.p. of each control station was assumed to be 37 dBW.

1.1 Simulation Results from unmanned aircraft system to satellite link operating in the fixed satellite service

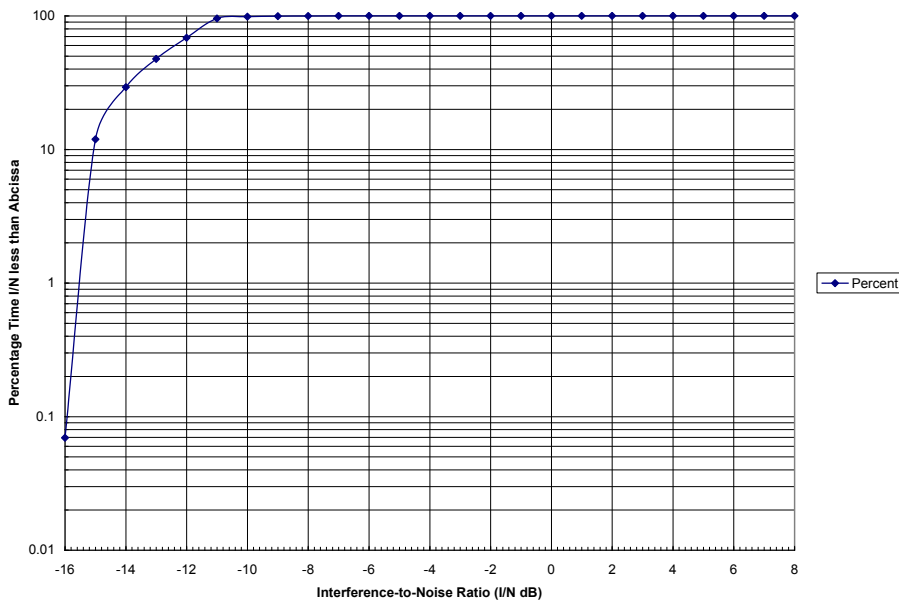
The results of the simulation of the first interference situation are shown in Fig. A1-6. The average value of I/N is -15.4 dB and the I/N will be less than or equal to -15 dB for 98% of the time.

FIGURE A1-6
**Interference-to-noise ratio at spacecraft of the mobile satellite service
 from 50 unmanned aircraft system aircraft stations**



The results of the simulation of the second interference situation are shown in Fig. A1-7. Here, the average value of I/N is -12.1 dB and the I/N will be less than or equal to -10 dB for 98.6% of the time.

FIGURE A1-7
**Interference-to-noise ratio at spacecraft of the mobile satellite service from
 45 unmanned aircraft control stations**



1.2 Analysis of Interference from satellite link operating in the fixed satellite service to unmanned aircraft system

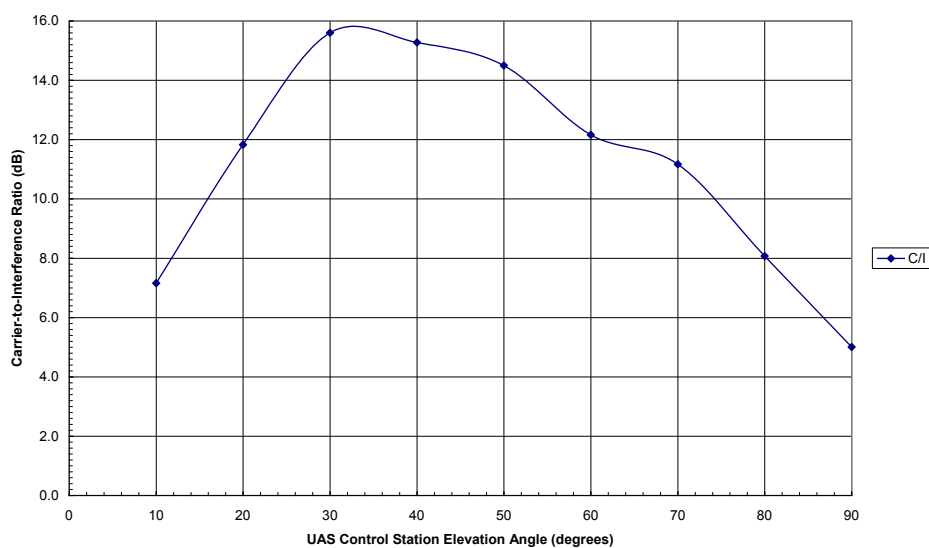
The third interference situation is treated analytically rather than by computer simulation. Interference can be caused to UAS Aircraft Stations from a MSS feeder uplink earth station when a

UAS aircraft flies through a feeder uplink transmission. MSS feeder uplink stations begin transmissions to a MSS spacecraft at elevation angles between 6 and 10 degrees, with an e.i.r.p. of 46 dBW. The maximum e.i.r.p. of the UAS control station is 37 dBW, (i.e. transmit power 10 dBW, antenna gain 28 dBi, line loss 1 dB) (see methodology 1 of Report ITU-R M.2237).

The amount of interference received by the UAS aircraft station can be assumed to remain constant, modelling the situation where the range to the MSS earth station would be constant at 56.5 kilometres. The antenna gain of the UAS aircraft station is taken from methodology 1 of Report ITU-R M.2237). The cross polarization discrimination is assumed to be 1 dB. Assuming that the range to the UAS control station could vary, between 56.5 and 10 kilometres, the carrier-to-interference ratio (C/I) that would be experienced by the UAS aircraft station is shown in Fig. A1-8 as a function of the elevation angle of the UAS control station.

FIGURE A1-8

C/I at Unmanned aircraft system aircraft stations vs. unmanned aircraft control station elevation angle



As is apparent, the C/I varies between a maximum of 15.6 dB and a minimum of 5 dB.

2 Discussion of Simulation Results

This simulation results indicate that a $\Delta T/T$ of 6% would be exceeded for approximately 98% of the time. Although the positions of the MSS spacecraft could be predicted relatively well, given the random nature of UA flight operations both in area and time, it would be necessary to organize a coordination scheme that would allow UAS Control Earth stations to cease transmissions when a MSS spacecraft would be in view of the Control Station. Ceasing transmissions from a Control Station would also be potentially a high risk procedure in that control of the UAS aircraft would be lost during the time that transmissions were stopped. Permanent control of the UAS aircraft would require Control Station diversity which would further increase the cost of the UAS.

APPENDIX 3 TO ANNEX 1

Compatibility analysis between unmanned aircraft system terrestrial command and non-payload communication links and satellite links operating in the fixed satellite service in the frequency band 5 091-5 150 MHz (study 3)

1 Potential interference from an unmanned aircraft system uplink to a satellite link operating in the fixed satellite service

The uplink from UACS to UA may cause potential interference to the FSS receiver. The compatibility analysis for a single UACS transmitter controlling a medium or large UA with a omnidirectional (in azimuth) antenna is analyse in the Table A1-6 below. The value of the interference power can be calculated by the following equation:

$$I = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - L_p \quad (\text{A1-5})$$

Where the parameters are given in Table 4 and correspond to UAS parameters of type 2:

Table A1-6

Interference from an unmanned aircraft system uplink using omnidirectional antennas to a satellite link operating in the fixed satellite service

Value	Description	UACS maximum antenna gain (perigee)
P_t	UACS transmitter power (dBm)	43
G_t	UACS antenna gain (dBi)	10
G_r	FSS satellite receiver antenna gain (dBi)	4
L_t	UACS cable loss (dB)	1
L_r	FSS receiver cable loss (dB)	2.9
L_{cross}	Cross polarization loss (dB)	1
d	Distance between the UACS and the satellite (km)	4476
L_p	Free-space propagation (dB)	179.6
I	Calculated interference power (dBm)	-127.5
B_r	Satellite receiver bandwidth (MHz)	1.23
T_r	Satellite receiver temperature (K)	550
N	Satellite receiver noise level (dBm)	-110.3
I/N	(dB)	-17.2
$\Delta T/T$	(%)	1.91

According to this single entry interference calculation, the increase of the noise temperature is 1.91% in the worst case.

When considering multiple UACS and the probability for UACS to be seen from the satellite at a certain off-axis angle (see Fig. A1-9), the interference level increases as presented in the following table.

FIGURE A1-9

Probability of an unmanned aircraft control station location depending on the satellite off-axis angle

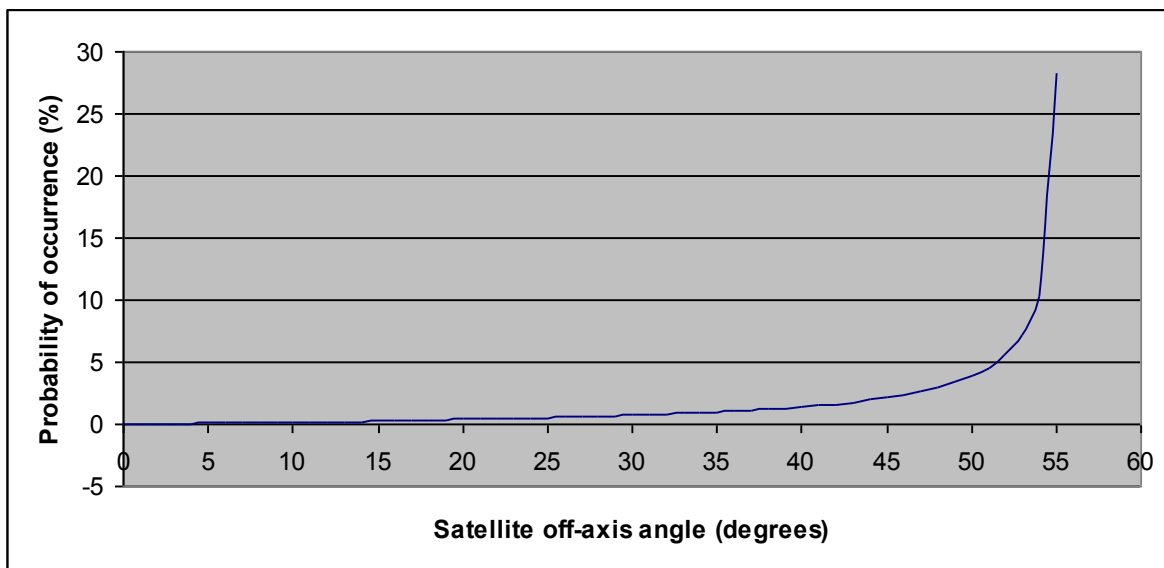


Table A1-7

Interference from an unmanned aircraft system uplink using omnidirectional antennas to a satellite link operating in the fixed satellite service

Number of UACS in visible from satellite	2	3	4	5	7	10
$\Delta T/T$ (%)	2.27	2.96	3.46	3.96	5.32	6.81

According to all these studies, it is therefore clear that UACS using omnidirectional (in azimuth) antennas and FSS cannot share the same frequency band.

In Table A1-8, it is considered that a single UACS transmitter controlling a medium or large UA has a tracking antenna. In this case, the value of the interference power is calculated with equation (A1-5) and the following parameters:

Table A1-8

Interference from an unmanned aircraft system uplink using tracking antennas to a satellite link operating in the fixed satellite service

Value	Description	UACS maximum antenna gain (perigee)
P_t	UACS transmitter power (dBm)	29
G_t	UACS antenna gain (dBi)	24
G_r	FSS satellite receiver antenna gain (dBi)	4
L_t	UACS cable loss (dB)	1
L_r	FSS receiver cable loss (dB)	2.9
L_{cross}	Cross polarization loss (dB)	1
D	Distance between the UACS and the satellite (km)	4476
L_p	Free-space propagation (dB)	179.6
I	Calculated interference power (dBm)	-127.5
B_r	Satellite receiver bandwidth (MHz)	1.23
T_r	Satellite receiver temperature (K)	550
N	Satellite receiver noise level (dBm)	-110.3
I/N	(dB)	-17.2
$\Delta T/T$	(%)	1.91

Due to the fact that non-GSO FSS satellite in this frequency band can be everywhere in the sky and that the UACS antenna will track the UA in all directions, it is not possible for the UACS antenna to avoid to point towards the satellite.

Moreover, noting that the 3 dB beamwidth of the tracking antenna is around 10 degrees, the level of interference calculated above for a single UACS transmitter to one satellite can be reached around 2.8% of the time. In addition, one UACS will always have several satellites in visibility, and therefore the period of interference to the FSS will increase. Therefore, it cannot be possible to interrupt the UACS transmission during such long periods due the required availability of UA to UACS link.

It can also be noted that more than one UACS will operate within the satellite footprint and thus, the interference level to the FSS will increase.

2 Potential interference from an unmanned aircraft system downlink to a satellite link operating in the fixed satellite service

The downlink from UA to UACS may also cause potential interference to the FSS receiver due to the omnidirectional nature of UA transmitter antenna.

The interference power can be calculated by the following equation:

$$I = P_t + G_t + G_r - L_t - L_r - L_{cross} - L_p - L_{mask} \quad (A1-6)$$

where:

Table A1-9

Interference from an unmanned aircraft system downlink to a satellite link in the fixed satellite service

Value	Description		
P_t	UA transmitter power	(dBm)	39
G_t	UA antenna gain	(dBi)	3
G_r	FSS satellite receiver antenna gain	(dBi)	4
L_t	UA cable loss	(dB)	2
L_r	FSS receiver cable loss	(dB)	2.9
L_{cross}	Cross polarization loss	(dB)	1
d	Distance between the UACS and the satellite	(km)	1414
L_p	Free-space propagation	(dB)	169.4
L_{mask}	UA body masking loss	(dB)	10^1
I	Calculated interference power	(dBm)	-139.3
I/N		(dB)	-29
$\Delta T/T$		(%)	0.13

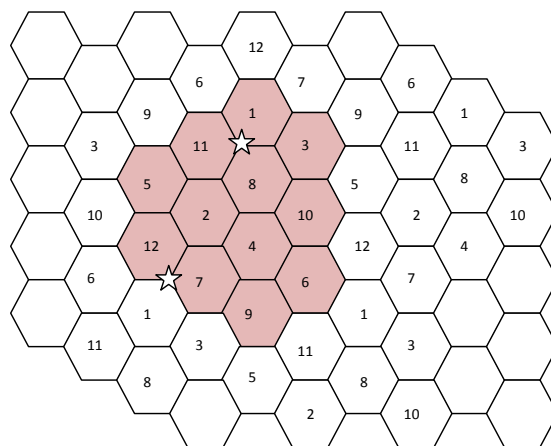
Considering the medium and large UA’s body size, the upward power radiated from UA’s airborne antenna could be attenuated due to the body masking effect. Referring the body masking attenuation values of manned aircraft given in the Report ITU-R M.2118, it can be assumed that the averaged body masking attenuation value towards the satellite direction is 10 dB.

The number of UAs which could interfere with the satellite receiver on the basis of satellite parameters can be estimated.

Considering the possible potential AM(R)S architecture described in section 3.1.1.1 of Report ITU-R M.2237, which defines the UAS frequency reuse pattern shown in Fig. A1-10 below, the minimum UAS frequency reuse area is $5 \times 10^5 \text{ km}^2$ (i.e. 12 cells).

FIGURE A1-10

K=12 pattern with adjacent-channel protection



According to Recommendation ITU-R M.1184, the maximum beam size of HIBLEO-4FL is $2.3 \times 10^6 \text{ km}^2$, thus the frequency reuse factor R in the satellite beam range is $230/50 = 4.6$.

The number of UAs which could interfere with the satellite receiver can be calculated by the following equation:

The maximum number of interfering UAs = (satellite receiver bandwidth/UA bandwidth) \times R

The calculated number of interfering UAs within the field of view of the satellite beam is 151.

Table A1-10

Unmanned aircraft to satellite links operating in the fixed satellite service aggregate interference

theta	elevation angle	(Deg)	0	10	20	30	40	50	60	70	80	90
P_t	UA transmitter power	(dBm)	39	39	39	39	39	39	39	39	39	39
G_t	UA antenna gain	(dBi)	-2.43	-7.22	-10.52	-11.36	-11.79	-13.21	-15.82	-20.08	-23.44	-22.57
G_r	FSS satellite receiver antenna gain	(dBi)	4	4	4	4	4	4	4	4	4	4
L_t	UA cable loss	(dB)	2	2	2	2	2	2	2	2	2	2
L_r	FSS receiver cable loss	(dB)	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
L_{cross}	Cross polarization loss	(dB)	1	1	1	1	1	1	1	1	1	1
D	Slant distance	(km)	4470	3388	2847	2306	2066	1826	1586	1528.7	1471.4	1414
L_p	Free-space propagation	(dB)	179.54	177.13	175.62	173.79	172.84	171.77	170.54	170.22	169.89	169.55
N_{UA}	number of UAs within elevation angle*		26.5	43.5	26.2	20.9	14.0	8.7	6.2	3.4	1.5	0.1
I	Calculated interference power	(dBm)	-127.69	-127.52	-131.95	-131.91	-132.72	-135.18	-137.98	-143.66	-150.48	-163.04
I/N		(dB)	-17.4	-17.2	-21.6	-21.6	-22.4	-24.9	-27.7	-33.4	-40.2	-52.7
$\Delta T/T$		(%)	1.82	1.90	0.68	0.69	0.57	0.33	0.17	0.05	0.01	< 0.01
Total $\Delta T/T$		(%)	6.22									

* This number assumes around 151 UAs in the view of the satellite, uniformly distributed in the beam area.

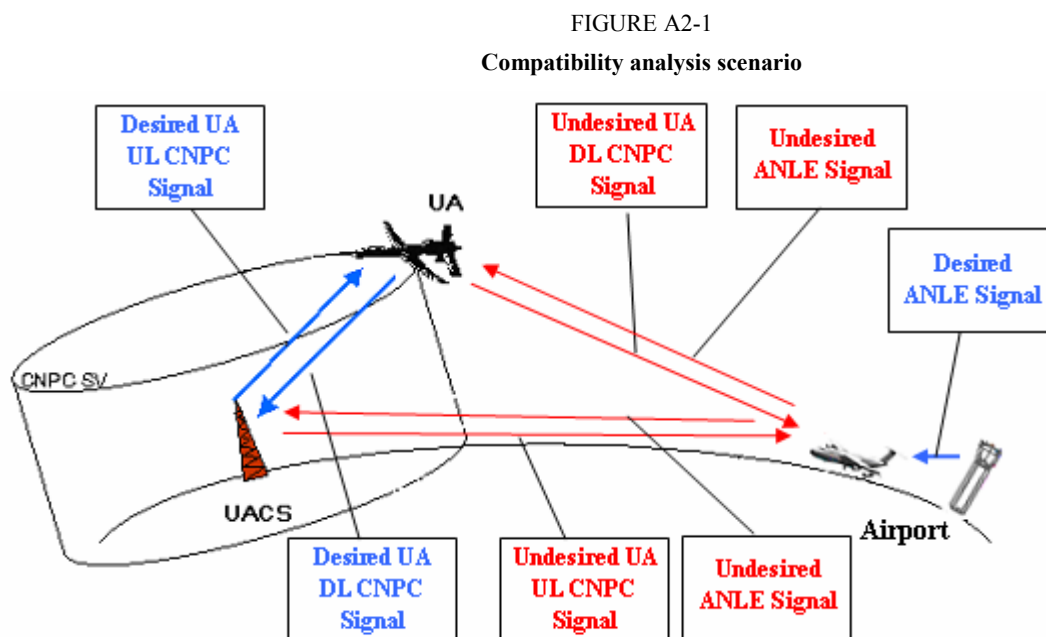
ANNEX 2

Compatibility analysis between unmanned aircraft system terrestrial command and non-payload communication links and systems operating in the aeronautical mobile service in the frequency band 5 091-5 150 MHz

Introduction

According to Radio Regulations No. 5.444B, the frequency band 5 091-5 150 MHz is allocated to the AM(R)S for the airport surface applications, and to the AMS which includes two applications: aeronautical flight telemetry (AMT), and aeronautical security systems. The compatibility analysis between UAS terrestrial CNPC links and the three applications are described in following sections respectively.

The scenario of interference from the UAS terrestrial CNPC links to the ANLE system is shown in Fig. A2-1.



Two separate analyses of interference from UAS uplink to the FSS have been produced. The details of these two studies are present in appendices 1 and 2 of this annex 2 of this report.

APPENDIX 1 TO ANNEX 2

Compatibility analysis of unmanned aircraft system terrestrial command and non-payload communication links and airport surface applications in the frequency band 5 091-5 150 MHz (study 1)

1 Potential interference from an unmanned aircraft system uplink transmitter to an ANLE receiver

The UACS can track a UA at quite low elevation angle. Therefore, the ANLE system can be seen from the main lobe (or almost) of the UACS antenna. The maximum UACS antenna gain of 24 dBi should be used in the study. However, considering that the UACS antenna is directional, the probability of interference from the main lobe of the UACS antenna stays very low and the potential interference to ANLE is caused mainly by side lobes of the UACS transmitter. Two examples of interference are computed in the table below (main lobe and first side lobe of 9.6°)

Thus, the required attenuation for the UACS to protect the ANLE can be calculated by:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - I \quad (\text{A2-1})$$

where:

TABLE A2-1

Required separation distance from an unmanned aircraft control station transmitter to an ANLE receiver

Value	Description	UACS maximum antenna gain	UACS first side lobe antenna gain
P_t	UACS transmitter power (dBm)	29	29
G_t	UACS antenna gain (dBi)	24	14.2
G_r	ANLE receiver antenna gain (dBi)	8	8
L_t	UACS cable loss (dB)	1	1
L_r	ANLE receiver cable loss (dB)	2	2
L_{cross}	Cross polarization loss* (dB)	10	10
I	ANLE tolerable interference power (dBm)	-97	-97
L_p	Required attenuation for the UACS (dB)	145	135.2
d1	Required separation distance (f = 5 091 MHz) using free space loss (km)	83.8	27.1
d2	Required separation distance (f = 5 091 MHz) using Recommendation ITU-R P.526 (both Tx and Rx antenna height are assumed to be 30 metres above the ground) (km)	36.9	26.4
d3	Required separation distance (f = 5 091 MHz) using Recommendation ITU-R P.452 (both Tx and Rx antenna height are assumed to be 30 meters above the ground and time percentage=1%) (km)	71	42.6

* As ANLE antenna is only vertically polarized, UAS antenna is assumed to be horizontally polarized in the study.

From the table above, the required separation distance from UACS transmitter to ANLE receiver depends on the choice of propagation model. However, since both of the UACS and ANLE are ground based, Recommendation ITU-R P.526 or ITU-R P.452 may be more appropriate.

2 Potential interference from an unmanned aircraft system downlink transmitter to an ANLE receiver

For the UAS downlink case, the UA's transmitting antenna can be simplified to be an omnidirectional antenna with 0 dBi gain.

The analysis method derived from the Section 1 also applies here.

TABLE A2-2

Required separation distance from an unmanned aircraft transmitter to an ANLE receiver

Value	Description	
P_t	UA transmitter power (dBm)	40
G_t	UA antenna gain (dBi)	0
G_r	ANLE receiver antenna gain (dBi)	8
L_t	UA cable loss (dB)	2
L_r	ANLE receiver cable loss (dB)	2
L_{cross}	Cross polarization loss* (dB)	10
I	ANLE tolerable interference power (dBm)	-97
L_p	Required attenuation for one UA (dB)	131
d	Required separation distance for one UA ($f = 5\,091$ MHz) (km)	16.6

* As ANLE antenna is only vertically polarized, UAS antenna is assumed to be horizontally polarized in the study.

From the table above, the required separation distance from UA transmitter to ANLE receiver is 16.6 km. This distance may be practical in the coordination process of the two systems.

To assess the UA's aggregate interference, the required separation distance can be calculated for a given number of UAs, and then determine the probability of every number of UAs appearing in that distance range using the densities of UA proposed in Report ITU-R M.2171.

The probability determination process could be based on the method described in Report ITU-R M.2237, which assumes the actual number of UAs in a given range follows a Poisson distribution. The Poisson equation is $P(n) = e^{-N} (N^n / n!)$, with N being the average number and can be estimated by multiplying the density of UA with the given range area.

The calculation process and results are shown in Table A2-3 to Table A2-5 respectively relating to large, medium and small UA.

TABLE A2-3

Large unmanned aircraft aggregated interference into ANLE

UA Tx power (dBm)	40	40	40	40	40	40	40	40
UA number (n)	1	2	3	4	5	6	7	8
UA Tx ant. Gain (dB)	0	0	0	0	0	0	0	0
Aggregate EIRP (dBm)	40.0	43.0	44.8	46.0	47.0	47.8	48.5	49.0
ANLE Rx ant. Gain (dB)	8	8	8	8	8	8	8	8
UA cable loss (dB)	2	2	2	2	2	2	2	2
ANLE cable loss (dB)	2	2	2	2	2	2	2	2
Cross polarization loss (dB)	10	10	10	10	10	10	10	10
Interference threshold (dB)	-97	-97	-97	-97	-97	-97	-97	-97
Free space loss (dB)	131.0	134.0	135.8	137.0	138.0	138.8	139.5	140.0
Separation distance, D (km)	16.7	23.6	29.0	33.4	37.4	41.0	44.2	47.3
Density of UA (UA/km ²)	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.4E-05
AREA (πD^2)	878.1	1756.2	2634.3	3512.4	4390.5	5268.6	6146.7	7024.8
N (in Poisson equation)	0.039	0.077	0.116	0.155	0.193	0.232	0.270	0.309
Probability of n within AREA	3.7E-02	2.8E-03	2.3E-04	2.0E-05	1.8E-06	1.7E-07	1.6E-08	1.5E-09

TABLE A2-4

Medium unmanned aircraft aggregated interference into ANLE

UA Tx power, as large UA (dBm)	40	40	40	40	40	40	40	40
UA number (n)	1	2	3	4	5	6	7	8
UA Tx ant. Gain (dB)	0	0	0	0	0	0	0	0
Aggregate EIRP (dBm)	40.0	43.0	44.8	46.0	47.0	47.8	48.5	49.0
ANLE Rx ant. Gain (dB)	8	8	8	8	8	8	8	8
UA cable loss (dB)	2	2	2	2	2	2	2	2
ANLE cable loss (dB)	2	2	2	2	2	2	2	2
Cross polarization loss (dB)	10	10	10	10	10	10	10	10
Interference threshold (dBm)	-97	-97	-97	-97	-97	-97	-97	-97
Free space loss (dB)	131.0	134.0	135.8	137.0	138.0	138.8	139.5	140.0
Separation distance, D (km)	16.7	23.6	29.0	33.4	37.4	41.0	44.2	47.3
Density of UA (UA/km ²)	1.95E-04	1.95E-04	1.95E-04	1.95E-04	1.95E-04	1.95E-04	1.95E-04	1.95E-04
AREA (πD^2)	878.1	1756.2	2634.3	3512.4	4390.5	5268.6	6146.7	7024.8
N (in Poisson equation)	0.171	0.342	0.514	0.685	0.856	1.027	1.199	1.370
Probability of n within AREA	1.4E-01	4.2E-02	1.4E-02	4.6E-03	1.6E-03	5.8E-04	2.1E-04	7.8E-05

TABLE A2-5

Small unmanned aircraft aggregated interference into ANLE

UA Tx power (dBm)	29	29	29	29	29	29	29	29
UA number (n)	1	2	3	4	5	6	7	8
UA Tx ant. Gain (dB)	0	0	0	0	0	0	0	0
Aggregate EIRP (dBm)	29.0	32.0	33.8	35.0	36.0	36.8	37.5	38.0
ANLE Rx ant. Gain (dB)	8	8	8	8	8	8	8	8
UA cable loss (dB)	2	2	2	2	2	2	2	2
ANLE cable loss (dB)	2	2	2	2	2	2	2	2
Cross polarization loss (dB)	10	10	10	10	10	10	10	10
Interference threshold (dBm)	-97	-97	-97	-97	-97	-97	-97	-97
Free space loss (dB)	120.0	123.0	124.8	126.0	127.0	127.8	128.5	129.0
Separation distance, D (km)	4.7	6.7	8.2	9.4	10.5	11.5	12.5	13.3
Density of UA (UA/km ²)	8.03E-04	8.03E-04	8.03E-04	8.03E-04	8.03E-04	8.03E-04	8.03E-04	8.03E-04
AREA (πD^2)	69.7	139.5	209.2	279.0	348.7	418.5	488.2	558.0
N (in Poisson equation)	0.056	0.112	0.168	0.224	0.280	0.336	0.392	0.448
Probability of n within AREA	5.3E-02	5.6E-03	6.7E-04	8.4E-05	1.1E-05	1.4E-06	1.9E-07	2.6E-08

The tables above show that, although the required separation distances will become larger with the number of UAs increasing, the probability of that number of UAs appearing in the required range will decrease rapidly. That means that the probability of UAs aggregated interference to ANLE is very low.

3 Potential interference from an ANLE transmitter to an unmanned aircraft control station receiver

The required attenuation for the ANLE to protect the UACS receiver is expressed by the following equation:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - I + R_B \quad (\text{A2-2})$$

where:

TABLE A2-6

**Required separation distance from an ANLE transmitter to
an unmanned aircraft control station receiver**

Value	Description	UACS maximum antenna gain	UACS first side lobe antenna gain
P_t	ANLE transmitter power (dBm)	32.2	32.2
G_t	ANLE antenna gain (dBi)	8	8
G_r	UACS receiver antenna gain (dBi)	24	14.2
L_t	ANLE cable loss (dB)	2	2
L_r	UACS receiver cable loss (dB)	1	1
L_{cross}	Cross polarization loss* (dB)	10	10
Value	Description	UACS maximum antenna gain	UACS first side lobe antenna gain
I	UACS tolerable interference power (based on I/N = 0 dB) (dBm)	-126	-126
R_B	Bandwidth ratio (20 MHz to 37.5 kHz) (dB)	-27.3	-27.3
L_p	Required attenuation for the ANLE transmitter (dB)	149.9	140.1
d1	Required separation distance (f = 5 091 MHz) using free space loss (km)	147.3	47.7
d2	Required separation distance (f = 5 091 MHz) using Recommendation ITU-R P.526 (both Tx and Rx antenna height are assumed to be 30 metres above the ground) (km)	38.9	34.8
d3	Required separation distance (f = 5 091 MHz) using Recommendation ITU-R P.452 (both Tx and Rx antenna height are assumed to be 30 metres above the ground and time percentage=1%) (km)	98.1	51.1

* As ANLE antenna is only vertically polarized, UAS antenna is assumed to be horizontally polarized in the study.

From the table above, the required separation distance from ANLE transmitter to UACS receiver depends on the choice of propagation model. Considering both of the ANLE and UACS are ground based, Recommendation ITU-R P.526 or ITU-R P.452 may be more appropriate.

4 Potential interference from an ANLE transmitter to an unmanned aircraft receiver

The analysis method in Section 3 also applies here.

Table A2-7

Required separation distance from an ANLE transmitter to an unmanned aircraft receiver

Value	Description	
P_t	ANLE transmitter power (dBm)	32.2
G_t	ANLE antenna gain (dBi)	8
G_r	UA receiver antenna gain (dBi)	0
L_t	ANLE cable loss (dB)	2
L_r	UA receiver cable loss (dB)	2
L_{cross}	Cross polarization loss* (dB)	10
I	UA tolerable interference power (based on $I/N = 0$ dB) (dBm)	-126
R_B	Bandwidth ratio (20 MHz to 37.5 kHz) (dB)	-27.3
L_p	Required attenuation for the ANLE transmitter (dB)	124.9
d	Required separation distance ($f = 5\,091$ MHz) (km)	8.2

* As ANLE antenna is only vertically polarized, UAS antenna is assumed to be horizontally polarized in the study.

From the table above, the required separation distance from ANLE transmitter to UA receiver is 8.2 km. This distance may be practical in the coordination process of the two systems.

APPENDIX 2 TO ANNEX 2

Compatibility analysis of unmanned aircraft system terrestrial command and non-payload communication links and airport surface applications in the frequency band 5 091-5 150 MHz (study 2)

1 Potential interference from an unmanned aircraft system uplink transmitter to an ANLE receiver

The UACS can track a UA at quite low elevation angle. Therefore, the ANLE system can be seen from the main lobe (or almost) of the UACS antenna. The maximum UACS antenna gains of 10 and 24 dBi should be used in the study. However, when considering a gain of 24 dBi, the UACS antenna is directional and thus the probability of interference from the main lobe of the UACS antenna stays very low and the potential interference to ANLE is caused mainly by side lobes of the UACS transmitter. Therefore, three examples of interference are computed in the table below: main lobe and offset of 14.5° for the directional antenna and the omnidirectional (in azimuth) antenna.

Thus, the required attenuation for the UACS to protect the ANLE can be calculated by:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{cross} - I \quad (\text{A2-3})$$

where:

Table A2-8

Interference from an unmanned aircraft system uplink transmitter to an ANLE receiver

Value	Description	UACS with a directional antenna		UACS with an omnidirectional (in azimuth) antenna
		maximum antenna gain	side lobe antenna gain	
P_t	UACS transmitter power (dBm)	29	29	43
G_t	UACS antenna gain (dBi)	24	5.9 (offset of 14.5°) ¹	10
G_r	ANLE receiver antenna gain (dBi)	8	8	8
L_t	UACS cable loss (dB)	1	1	1
L_r	ANLE receiver cable loss (dB)	2	2	2
L_{cross}	Cross polarization loss (dB)	10	10	10
I	ANLE tolerable interference power (dBm)	-97	-97	-97
L_p	Required attenuation for the UACS (dB)	145	126.9	145
d	Required separation distance (f = 5 091 MHz) using free space loss (km)	45 ²	10.4	45 ²

¹ See UACS antenna gain calculated with ITU-R Recommendation F.1245-1

² Based on equation A2-2, the separation distances is beyond line-of-sight. Therefore, the actual separation distance requirements of 45 km can be calculated via standard equation $4.12 \times (\sqrt{H_1} + \sqrt{H_2})$, where H_1 is the height of the UACS transmitter antenna (30 m) and H_2 is the height of the ANLE receiver antenna (30 m).

It can be concluded that the required protection distance from the UAS uplink transmitter to ANLE receiver is LOS distance.

Using directional antennas would not solve the issue due to the fact that the UACS antenna will track the UA in all directions and therefore, it is not possible for the UACS antenna to avoid pointing towards the ANLE. Noting that it cannot be possible to interrupt the UACS transmission due the required availability of UA to UACS link, the required protection distance from the UAS uplink transmitter to ANLE receiver will be the LOS distance.

2 Potential interference from an unmanned aircraft system downlink transmitter to an ANLE receiver

For the UAS downlink case, UA transmits signals through an omni-directional antenna and could interfere with the ANLE receiver.

The analysis method derived from the Section 1 also applies here.

Table A2-9

Interference from an unmanned aircraft system downlink transmitter to an ANLE receiver

Value	Description	
P_t	UA transmitter power (dBm)	40
G_t	UA antenna gain (dBi)	3
G_r	ANLE receiver antenna gain (dBi)	8
L_t	UA cable loss (dB)	2
L_r	ANLE receiver cable loss (dB)	2
L_{cross}	Cross polarization loss (dB)	10
I	ANLE tolerable interference power (dBm)	-97
L_p	Required attenuation for one UA (dB)	134
d	Required separation distance for one UA ($f = 5\,091$ MHz) (km)	23.4

Even when considering only 1 UA, the required separation distances between the UA and the ANLE receiver located at the airport is more than 23 km.

3 Potential interference from an ANLE transmitter to an unmanned aircraft control station receiver

The required attenuation for the ANLE to protect the UACS receiver is expressed by the following equation:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{cross} - I + R_B \quad (A2-4)$$

where:

Table A2-10

Interference from an ANLE transmitter to an unmanned aircraft control station receiver

Value	Description	UACS with a directional antenna		UACS with an omnidirectional (in azimuth) antenna
		maximum antenna gain	side lobe antenna gain	
P_t	ANLE transmitter power (dBm)	32.2	32.2	32.2
G_t	ANLE antenna gain (dBi)	8	8	8
G_r	UACS receiver antenna gain (dBi)	24	5.9 (offset of 14.5°) ¹	10
L_t	ANLE cable loss (dB)	2	2	2
L_r	UACS receiver cable loss (dB)	1	1	1
L_{cross}	Cross polarization loss (dB)	10	10	10
I	UACS tolerable interference power (based on I/N = 0 dB for a receiver bandwidth of 37.5 kHz/ 300 kHz) (dBm)	-126 / -117	-126 / -117	-126 / -117
R_B	Bandwidth ratio (20 MHz to 37.5 kHz/or 300 kHz) (dB)	-27.3/-18.2	-27.3/-18.2	-27.3/-18.2
L_p	Required attenuation for the ANLE transmitter (dB)	150	131.9	136
D	Required separation distance (f = 5 091 MHz) (km)	45 ²	18.4	29.5

¹ See Fig. 6.² Based on equation A2-4, the separation distances is beyond line-of-sight. Therefore, the actual separation distance requirements of 45 km can be calculated via standard equation $4.12 \times (\sqrt{H_1} + \sqrt{H_2})$, where H_1 is the height of the UACS transmitter antenna (30 m) and H_2 is the height of the ANLE receiver antenna (30 m).

From the results of table A2-10, the required protection distance from a single ANLE transmitter to UACS can be up to the LOS (45.1 km).

4 Potential interference from an ANLE transmitter to an unmanned aircraft receiver

The analysis method in Section 3 also applies here.

Table A2-11

Interference from ANLE transmitter to an unmanned aircraft receiver

Value	Description	
P_t	ANLE transmitter power (dBm)	32.2
G_t	ANLE antenna gain (dBi)	8
G_r	UA receiver antenna gain (dBi)	3
L_t	ANLE cable loss (dB)	2
L_r	UA receiver cable loss (dB)	2
L_{cross}	Cross polarization loss (dB)	10
I	UA tolerable interference power (based on $I/N = 0$ dB) (dBm)	-126
R_B	Bandwidth ratio (20 MHz to 37.5 kHz) (dB)	-27.3
L_p	Required attenuation for the ANLE transmitter (dB)	127.9
d	Required separation distance ($f = 5\ 091$ MHz) (km)	11.6

When considering only 1 ANLE transmitter, the required separation distances between the UA and the ANLE receiver located at the airport is more than 11 km.

ANNEX 3

Compatibility analysis between unmanned aircraft terrestrial command and non-payload control links and aeronautical mobile telemetry systems in the frequency band 5 091-5 150 MHz

Introduction

The AMT system is used to transmit telemetry information from the airplanes to the ground stations during flight test operations.

Three separate analyses of interference from UAS uplink to the FSS have been produced. The details of these three studies are present in Appendices 1 to 3 of Annex 3 of this report.

APPENDIX 1 TO ANNEX 3

Compatibility analysis of unmanned aircraft terrestrial command and non-payload communication links and aeronautical mobile telemetry systems in the frequency band 5 091-5 150 MHz (study 1)

1 Potential interference from an unmanned aircraft system uplink to aeronautical mobile telemetry system receivers

The UACS can track a UA at quite low elevation angles. Therefore, the main lobe of the UACS antenna is visible to the AMT ground station antenna.

In order to achieve a protection level of -177 dBW/m^2 in 4 kHz at the aperture of the AMT ground station receive antenna, the following analysis applies for the worst-case condition of AMT to UAS ground station mainbeam-to-mainbeam conjunction:

UAS ground station EIRP = 40 dBm + 28 dB antenna gain – 1 dB coupling loss = 67 dBm.

Maximum allowed pfd at the AMT ground station antenna = -177 dBW/m^2 in 4 kHz.

Required separation distance assuming free-space line of sight propagation:

$$-177 \text{ dBW} / (\text{m}^2 \text{ in } 4 \text{ kHz}) = \frac{\text{EIRP}_{\text{UASgroundstation}}}{4\pi \cdot r^2} \cdot \frac{4 \text{ kHz}}{37.5 \text{ kHz}} \quad (\text{A3-1})$$

This gives a minimum line of sight separation distance r of 4.6×10^9 meters, which is many orders of magnitude beyond the nominal 45 km line of sight between two antennas raised above ground level on 30 meter tall towers.

Since AMT and UAS ground station antennas rotate in order to track their respective aircraft, and since at long range, both UA and flight test aircraft are at elevation angles to the horizon of 2 degrees or less, it must be assumed that mainlobe-to-mainlobe conjunction will occur on a regular basis. Furthermore, the aggregation of UAS aircraft will be accompanied by a corresponding aggregation of UAS ground station uplinks, under circumstances in which any of the large number of UAS ground stations is within line of sight of any AMT ground station.

In summary, the estimated distance exceeds the line-of-sight distance ($4.12 \times (\sqrt{h_1} + \sqrt{h_2}) = 45.1 \text{ km}$) between UACS and the AMT ground station, provided that both antenna are 30 meters high, as is typical for AMT. Thus the required protection distance from the UACS to AMT system is LOS distance (45.1 km).

2 Potential interference from an unmanned aircraft transmitter to aeronautical mobile telemetry ground station receiver

A single UA aircraft appears to a flight test ground station as a flight test aircraft whose entire transmit power is constrained to a bandwidth of 37.5 kHz, as opposed to 10 MHz. Since flight test aircraft operate to maximum line of sight distances, and since interference from a UA aircraft must be 9 dB less in order to achieve an I/N ratio of -9 dB . Visibility of the UAS aircraft within the mainlobe of an AMT ground station antenna must always be avoided. Furthermore, since the AMT aircraft can be at any azimuth angle with respect to the AMT ground station, the AMT ground station tracking antenna can point in any direction. Thus, the diminished sidelobe response of the AMT ground station antenna is of little practical consequence.

One could, of course, use statistical techniques such as the Poisson approximation to compute the probability that a section of flight test airspace is temporarily free of UAS aircraft.

3 Potential interference from aeronautical mobile telemetry system to an unmanned aircraft control station ground station receiver

The UACS can track a UA at quite low elevation angles. Therefore, AMT aircraft can be seen by the main lobe of the UAS ground station antenna. The maximum UACS antenna gain of 28 dBi should be used in the study.

The required attenuation for the AMT station to protect the UACS receiver can also be expressed as equation A3-2:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - I + R_B \quad (\text{A3-2})$$

where:

Table A3-1

Interference to an unmanned aircraft control station ground station from an aeronautical mobile telemetry flight test aircraft

Value	Description	UACS maximum antenna gain	UACS side lobe antenna gain
P_t	AMT transmitter power (dBm)	46	46
G_t	AMT antenna gain (dBi)	0	0
G_r	UACS receiver antenna gain (dBi)	28	5 (offset of 14.5°)
L_t	AMT cable loss (dB)	3	3
L_r	UACS receiver cable loss (dB)	1	1
L_{cross}	Cross polarization loss (dB)	3	3
I	UACS tolerable interference power (based on I/N = 0 dB) (dBm)	-126	-126
R_B	Bandwidth ratio (10 MHz to 37.5 kHz/300 kHz) (dB)	-24.3/-15.2	-24.3/-15.2
L_p	Required attenuation for the AMT transmitter (dB)	168.7/177.8	145.7/154.8
d	Required separation distance ($f = 5\,091$ MHz) (km)	1280/3640	90.4/257.7

The estimated distance exceeds the line-of-sight distance ($4.12 \times (\sqrt{h_1} + \sqrt{h_2}) = 510.1$ km) between the flight test aircraft and the UACS ground station, provided that the test aircraft is 14 000 meters high and the UACS antenna is raised 30 m above ground level. Thus the required protection distance from the AMT aircraft to the UACS ground station antenna is the line of sight distance (510.1 km).

4 Potential interference from an aeronautical mobile telemetry flight test aircraft to an airborne unmanned aircraft system receiver

An AMT aircraft spreads its 40 dBm signal across a channel bandwidth of 10 MHz, whereas the receiver bandwidth of a UAS aircraft receiver is only 37.5 kHz. Both types of aircraft utilize omni-directional antennas, low gain antennas.

Unless an AMT aircraft is formation flying at close range with a UAS aircraft, interference from the AMT aircraft to the UAS will be of no consequence.

Since AMT aircraft will not be receiving telemetry signal uplinks in this frequency band (in order not to interfere with satellites such as HIBLEO-4, i.e., Globalstar), there is no possibility of interference to an AMT aircraft.

APPENDIX 2 TO ANNEX 3

Compatibility analysis of unmanned aircraft system terrestrial command and non-payload communication links and aeronautical mobile telemetry systems in the frequency band 5 091-5 150 MHz (study 2)

1 Compatibility analysis between unmanned aircraft system terrestrial command and non-payload communication links and aeronautical mobile telemetry systems

The AMT system is used to transmit telemetry information from the airplanes to the ground stations during flight test operations. According to Report ITU-R M.2221 the main parameters of the AMT system are given in Table A3-2.

Table A3-2

Aeronautical mobile telemetry system parameters

Parameters	AMT
Transmitter power (dBm)	46
Transmitter antenna gain (dBi)	0
Cable loss (dB)	3
Transmitter EIRP (dBm)	43
Bandwidth (MHz)	10
Receiver antenna main lobe gain (dBi)	40
Receiver antenna side lobe gain (dBi)	6*
Polarization losses (dB)	3
Receiver noise level (dBm)	-99.72
Protection criteria I/N (dB)	-9.2
Tolerable interference power (dBm)	-108.9

* According to Recommendation ITU-R M.1459, the AMT antenna's side lobe gain ≤ 5.9 dBi when the angle between side lobes and main lobe $\geq 10^\circ$.

2 Potential interference from an unmanned aircraft system uplink to aeronautical mobile telemetry system receivers

The UACS can track a UA at quite low elevation angles. Therefore, the AMT system can be seen from the main lobe (or almost) of the UACS antenna. The maximum antenna gain of 24 dBi should be used in the study.

Vice versa, the AMT system is also tracking the aircraft at low elevation angles.

Different examples of interference are computed in the table below (main lobe and side lobe for both the AMT and the UACS antenna)

The required attenuation for the UACS to protect the AMT station can also be expressed as the following equation:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - I \quad (\text{A3-3})$$

where:

Table A3-3

Case of interference into the main lobe of the aeronautical mobile telemetry station

Value	Description	UACS maximum antenna gain	UACS side lobe antenna gain
P_t	UACS transmitter power (dBm)	29	29
G_t	UACS antenna gain (dBi)	24	14.2 (offset of 9.6°)
G_r	AMT receiver antenna gain (dBi)	40	40
L_t	UACS cable loss (dB)	1	1
L_r	AMT receiver cable loss (dB)	3	3
L_{cross}	Cross polarization loss (dB)	3	3
I	AMT tolerable interference power (dBm)	-108.9	-108.9
L_p	Required attenuation for the UACS (dB)	194.9	185.1
d1	Required separation distance (f = 5 091 MHz) using free space loss (km)	26 194	8 476
d2	Required separation distance (f = 5 091 MHz) using Recommendation ITU-R P.526 (both Tx and Rx antenna height are assumed to be 30 metres above the ground) (km)	71.5	61.9
d3	Required separation distance (f = 5 091 MHz) using Recommendation ITU-R P.452 (both Tx and Rx antenna height are assumed to be 30 metres above the ground and time percentage=1%) (km)	354	299.9

Table A3-4

Case of interference into the side lobe of the aeronautical mobile telemetry station

Value	Description	UACS maximum antenna gain	UACS side lobe antenna gain
P_t	UACS transmitter power (dBm)	29	29
G_t	UACS antenna gain (dBi)	24	14.2
G_r	AMT receiver side lobe antenna gain (dBi)	[6]	[6]
L_t	UACS cable loss (dB)	1	1
L_r	AMT receiver cable loss (dB)	3	3
L_{cross}	Cross polarization loss (dB)	3	3
I	AMT tolerable interference power (dBm)	-108.9	-108.9
L_p	Required attenuation for the UACS (dB)	160.9	151.1
d1	Required separation distance ($f = 5\,091$ MHz) using free space loss (km)	522.6	169.1
d2	Required separation distance ($f = 5\,091$ MHz) using Recommendation ITU-R P.526 (both Tx and Rx antenna height are assumed to be 30 metres above the ground) (km)	44.6	39.8
d3	Required separation distance ($f = 5\,091$ MHz) using Recommendation ITU-R P.452 (both Tx and Rx antenna height are assumed to be 30 metres above the ground and time percentage=1%) (km)	166.7	105.5

From the two tables above, the required separation distance from UACS transmitter to AMT receiver depends on the choice of propagation model. Considering both of the UACS and AMT are ground based, Recommendation ITU-R P.526 or ITU-R P.452 may be more appropriate.

3 Potential interference from unmanned aircraft transmitters to aeronautical mobile telemetry system receivers

To assess the UA's aggregate interference, the analysis method derived from the Section 2 also applies here.

The calculation process and results are shown in Table A3-5 to Table A3-7 respectively relating to large, medium and small UA.

Table A3-5

**Large unmanned aircraft aggregated interference into
an aeronautical mobile telemetry system**

UA Tx power (dBm)	40	40	40	40	40	40	40	40
UA number (n)	1	2	3	4	5	6	7	8
UA Tx ant. Gain (dBm)	0	0	0	0	0	0	0	0
Aggregate EIRP (dBm)	40.0	43.0	44.8	46.0	47.0	47.8	48.5	49.0
AMT Rx ant. Gain (dB)	6	6	6	6	6	6	6	6
UA cable loss (dB)	2	2	2	2	2	2	2	2
AMT cable loss (dB)	3	3	3	3	3	3	3	3
Cross polarization loss (dB)	3	3	3	3	3	3	3	3
Interference threshold (dBm)	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9
Free space loss (dB)	146.9	149.9	151.7	152.9	153.9	154.7	155.4	155.9
Separation distance, D (km)	104.3	147.5	180.6	208.6	233.2	255.4	275.9	294.9
Density of UA (UA/km ²)	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.4E-05	4.4E-05
AREA (πD^2)	34162.0	68324.1	102486.1	136648.1	170810.2	204972.2	239134.2	273296.2
N (in Poisson equation)	1.50	3.01	4.51	6.01	7.52	9.02	10.52	12.03
Probability of n within AREA	3.3E-01	2.2E-01	1.7E-01	1.3E-01	1.1E-01	9.1E-02	7.6E-02	6.5E-02

Table A3-6

**Medium unmanned aircraft aggregated interference into
an aeronautical mobile telemetry system**

UA Tx power (dBm)	40	40	40	40	40	40	40	40
UA number (n)	1	2	3	4	5	6	7	8
UA Tx ant. Gain (dB)	0	0	0	0	0	0	0	0
Aggregate EIRP (dBm)	40.0	43.0	44.8	46.0	47.0	47.8	48.5	49.0
AMT Rx ant. Gain (dB)	6	6	6	6	6	6	6	6
UA cable loss (dB)	2	2	2	2	2	2	2	2
AMT cable loss (dB)	3	3	3	3	3	3	3	3
Cross polarization loss (dB)	3	3	3	3	3	3	3	3
Interference threshold (dBm)	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9
Free space loss (dB)	146.9	149.9	151.7	152.9	153.9	154.7	155.4	155.9
Separation distance, D(km)	104.3	147.5	180.6	208.6	233.2	255.4	275.9	294.9
Density of UA (UA/km ²)	1.95E-04	1.95E-04	1.95E-04	1.95E-04	1.95E-04	1.95E-04	1.95E-04	1.95E-04
AREA (πD^2)	34162.0	68324.1	102486.1	136648.1	170810.2	204972.2	239134.2	273296.2
N (in Poisson equation)	6.66	13.32	19.98	26.65	33.31	39.97	46.63	53.29
Probability of n within AREA	8.5E-03	1.5E-04	2.8E-06	5.6E-08	1.2E-09	2.5E-11	5.3E-13	1.2E-14

Table A3-7

**Small unmanned aircraft aggregated interference into
an aeronautical mobile telemetry system**

UA Tx power (dBm)	29	29	29	29	29	29	29	29
UA number (n)	1	2	3	4	5	6	7	8
UA Tx ant. Gain (dB)	0	0	0	0	0	0	0	0
Aggregate EIRP (dBm)	29.0	32.0	33.8	35.0	36.0	36.8	37.5	38.0
AMT Rx ant. Gain (dB)	6	6	6	6	6	6	6	6
UA cable loss (dB)	2	2	2	2	2	2	2	2
AMT cable loss (dB)	3	3	3	3	3	3	3	3
Cross polarization loss (dB)	3	3	3	3	3	3	3	3
Interference threshold (dBm)	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9	-108.9
Free space loss (dB)	135.9	138.9	140.7	141.9	142.9	143.7	144.4	144.9
Separation distance, D (km)	29.4	41.6	50.9	58.8	65.7	72.0	77.8	83.1
Density of UA (UA/km ²)	8.03E-04	8.03E-04	8.03E-04	8.03E-04	8.03E-04	8.03E-04	8.03E-04	8.03E-04
AREA (πD^2)	2713.6	5427.2	8140.8	10854.3	13567.9	16281.5	18995.1	21708.7
N (in Poisson equation)	2.18	4.36	6.54	8.72	10.90	13.07	15.25	17.43
Probability of n within AREA	2.5E-01	1.2E-01	6.7E-02	3.9E-02	2.4E-02	1.5E-02	9.1E-03	5.7E-03

4 Potential interference from an aeronautical mobile telemetry system to an unmanned aircraft control system receiver

The UACS can track a UA at quite low elevation angles. Therefore, the AMT system can see the UACS antenna from the main lobe (or almost). The maximum UACS antenna gain of 24 dBi should be used in the study.

The required attenuation for the AMT station to protect the UA receiver can also be expressed as the following equation:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - I + R_B \quad (\text{A3-4})$$

where:

Table A3-8

Required separation distance from an aeronautical mobile telemetry transmitter to an unmanned aircraft control station receiver

Value	Description	UACS maximum antenna gain	UACS side lobe antenna gain
P_t	AMT transmitter power (dBm)	46	46
G_t	AMT antenna gain (dBi)	0	0
G_r	UACS receiver antenna gain (dBi)	24	14.2
L_t	AMT cable loss (dB)	3	3
L_r	UACS receiver cable loss (dB)	1	1
L_{cross}	Cross polarization loss (dB)	3	3
I	UACS tolerable interference power (based on $I/N = 0$ dB) (dBm)	-126	-126
R_B	Bandwidth ratio (10 MHz to 37.5 kHz/300 kHz) (dB)	-24.3	-24.3
L_p	Required attenuation for the AMT transmitter (dB)	164.7	154.9
d1	Required separation distance ($f = 5\ 091$ MHz) using free space loss (km)	809.5	261.9
d2	Required separation distance ($f = 5\ 091$ MHz) using Recommendation ITU-R P.526 (both Tx and Rx antenna height are assumed to be 30 metres above the ground) (km)	46.7	41.4
d3	Required separation distance ($f = 5\ 091$ MHz) using Recommendation ITU-R P.452 (both Tx and Rx antenna height are assumed to be 30 metres above the ground and time percentage=1%) (km)	192.1	128.5

From the table above, the required separation distance from AMT transmitter to UACS receiver depends on the choice of propagation model. Considering both of the AMT and UACS are ground based, Recommendation ITU-R P.526 or ITU-R P.452 may be more appropriate.

5 Potential interference from an aeronautical mobile telemetry system to an unmanned aircraft receiver

The analysis method in Section 4 also applies here.

Table A3-9

Required separation distance from an aeronautical mobile telemetry transmitter to an unmanned aircraft receiver

Value	Description	
P_t	AMT transmitter power (dBm)	46
G_t	AMT antenna gain (dBi)	0
G_r	UA receiver antenna gain (dBi)	0
L_t	AMT cable loss (dB)	3
L_r	UA receiver cable loss (dB)	2
L_{cross}	Cross polarization loss (dB)	3
I	UACS tolerable interference power (based on I/N = 0 dB) (dBm)	-126
R_B	Bandwidth ratio (10 MHz to 37.5 kHz) (dB)	-24.3
L_p	Required attenuation for the AMT transmitter (dB)	139.7
d	Required separation distance ($f = 5\,091$ MHz) (km)	45.3

From the table above, the required separation distance from AMT transmitter to UA receiver is 45.3 km. This distance may be practical in the coordination process of the two systems.

APPENDIX 3 TO ANNEX 3

Compatibility analysis of unmanned aircraft station terrestrial command and non-payload communication links and aeronautical mobile telemetry systems in the frequency band 5 091-5 150 MHz (study 3)

1 Potential interference from an unmanned aircraft system uplink to aeronautical mobile telemetry system receiver

The UACS can track a UA at quite low elevation angles. Therefore, the AMT system can be seen from the main lobe (or almost) of the UACS antenna. The maximum UACS antenna gains of 10 and 24 dBi should be used in the study. However, when considering a gain of 24 dBi, the UACS antenna is directional and thus the probability of interference from the main lobe of the UACS antenna stays very low and the potential interference to AMT is caused mainly by side lobes of the UACS transmitter. Vice versa, the AMT system is also tracking the aircraft at low elevation angles.

Therefore, six examples of interference are computed in the tables below:

- main lobe for both the AMT and UACS directional antennas;
- main lobe for the AMT directional antenna and offset of 14.5° for the UACS directional antennas;

- main lobe for the UACS directional antenna and offset of 14.5° for the AMT directional antennas;
- offset of 14.5° for both the AMT and UACS directional antennas;
- main lobe for the AMT directional antenna and the omnidirectional (in azimuth) antenna for the UACS;
- offset of 14.5° for the AMT directional antenna and the omnidirectional (in azimuth) antenna for the UACS.

The required attenuation for the UACS to protect the AMT station can also be expressed as in the following equation:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{\text{cross}} - I \quad (\text{A3-5})$$

where:

Table A3-10

Case of interference into the main lobe of the aeronautical mobile telemetry station

Value	Description	UACS with a directional antenna		UACS with an omnidirectional (in azimuth) antenna
		maximum antenna gain	side lobe antenna gain	
P_t	UACS transmitter power (dBm)	29	29	43
G_t	UACS antenna gain (dBi)	24	5.9 (offset of 14.5°)	10
G_r	AMT receiver antenna gain (dBi)	40	40	40
L_t	UACS cable loss (dB)	1	1	1
L_r	AMT receiver cable loss (dB)	3	3	3
L_{cross}	Cross polarization loss (dB)	3	3	3
I	AMT tolerable interference power (dBm)	-108.9	-108.9	-108.9
L_p	Required attenuation for the UACS (dB)	194.9	176.8	194.9
d	Required separation distance ($f = 5\,091$ MHz) (km)	26000	3240	26000

Table A3-11

Case of interference into the side lobe of the aeronautical mobile telemetry station

Value	Description	UACS with a directional antenna		UACS with an omnidirectional (in azimuth) antenna
		maximum antenna gain	side lobe antenna gain	
P_t	UACS transmitter power (dBm)	29	29	43
G_t	UACS antenna gain (dBi)	24	5.9 (offset of 14.5°)	10
G_r	AMT receiver antenna gain (offset of 14.5°) (dBi)	5	5	5
L_t	UACS cable loss (dB)	1	1	1
L_r	AMT receiver cable loss (dB)	3	3	3
L_{cross}	Cross polarization loss (dB)	3	3	3
I	AMT tolerable interference power (dBm)	-108.9	-108.9	-108.9
L_p	Required attenuation for the UACS (dB)	159.9	141.8	159.9
d	Required separation distance ($f = 5\ 091$ MHz) (km)	462	57.5	462

The actual LOS separation distance can be calculated via standard equation $4.12 \times (\sqrt{h_1} + \sqrt{h_2}) = 45$ km, where h_1 is the height of the UACS transmitter antenna (30 m) and h_2 is the height of the ANLE receiver antenna (30 m). Therefore, based on equation A3-5, the separation distances is beyond line-of-sight (45 km) for all scenarios in Tables A3-10 and A3-11, and it can be concluded that on a co-frequency basis, UAS and AMT cannot share the frequency band.

2 Potential interference from an unmanned aircraft transmitter to an aeronautical mobile telemetry system receiver

The analysis method derived from the Section 1 also applies here.

Table A3-12

Case of interference into the side lobe of the aeronautical mobile telemetry station

Value	Description	AMT main lobe gain	AMT side-lobe gain
P_t	UA transmitter power (dBm)	40	40
G_t	UA antenna gain (dBi)	3	3
G_r	AMT receiver antenna gain (dBi)	40	5 (offset of 14.5°)
L_t	UA cable loss (dB)	2	2
L_r	AMT receiver cable loss (dB)	3	3
L_{cross}	Cross polarization loss (dB)	3	3
I	AMT tolerable interference power (dBm)	-108.9	-108.9
L_p	Required attenuation for one UA (dB)	183.9	148.9
d	Required separation distance for one UA ($f = 5\,091$ MHz) (km)	7330	130

Even when considering only 1 UA, the required separation distances between the UA and the AMT receiver located at an airport is more than 130 km.

3 Potential interference from an aeronautical mobile telemetry system to an unmanned aircraft control station receiver

The UACS can track a UA at quite low elevation angles. Therefore, the AMT system can see the UACS antenna from the main lobe (or almost). The maximum UACS antenna gain of 24 dBi (for a UACS directional antenna) or 10 dBi (for a UACS omnidirectional in azimuth antenna) should be used in the study.

The required attenuation for the AMT station to protect the UACS receiver can also be expressed as in the following equation:

$$L_p = P_t + G_t + G_r - L_t - L_r - L_{cross} - I + R_B \quad (\text{A3-6})$$

where:

Table A3-13

Interference from an aeronautical mobile telemetry system to an unmanned aircraft control station receiver

Value	Description	UACS with a directional antenna		UACS with an omnidirectional (in azimuth) antenna
		maximum antenna gain	side lobe antenna gain	
P_t	AMT transmitter power (dBm)	46	46	46
G_t	AMT antenna gain (dBi)	0	0	0
G_r	UACS receiver antenna gain (dBi)	24	5.9 (offset of 14.5°)	10

Table A3-13 (*end*)

Value	Description	UACS with a directional antenna		UACS with an omnidirectional (in azimuth) antenna
L_t	AMT cable loss (dB)	3	3	3
L_r	UACS receiver cable loss (dB)	1	1	1
L_{cross}	Cross polarization loss (dB)	3	3	3
I	UACS tolerable interference power (based on I/N = 0 dB for a receiver bandwidth of 37.5 kHz/ 300 kHz) (dBm)	-126 / -117	-126 / -117	-126 / -117
R_B	Bandwidth ratio (10 MHz to 37.5 kHz/300 kHz) (dB)	-24.3/-15.2	-24.3/-15.2	-24.3/-15.2
L_p	Required attenuation for the UACS (dB)	164.8	146.7	150.8
d	Required separation distance (f = 5 091 MHz) (km)	813	101	162

The actual LOS separation distance can be calculated via standard equation $4.12 \times (\sqrt{h_1} + \sqrt{h_2}) = 510$ km, where h_1 is the height of the tested plane (14000 m) and h_2 is the height of the ground UACS antenna (30 m). Therefore, based on equation A3-5, the separation distances can be up to beyond line-of-sight between AMT transmitter and UACS receiver.

4 Potential interference from an aeronautical mobile telemetry system to an unmanned aircraft receiver

The analysis method in Section 3 also applies here.

Table A3-14

Interference from an aeronautical mobile telemetry system to an unmanned aircraft control station receiver

Value	Description	
P_t	AMT transmitter power (dBm)	46
G_t	AMT antenna gain (dBi)	0
G_r	UA receiver antenna gain (dBi)	3
L_t	AMT cable loss (dB)	3
L_r	UA receiver cable loss (dB)	2
L_{cross}	Cross polarization loss (dB)	3
I	UACS tolerable interference power (based on I/N = 0 dB) (dBm)	-126
R_B	Bandwidth ratio (10 MHz to 37.5 kHz) (dB)	-24.3
L_p	Required attenuation for the AMT transmitter (dB)	142.7
d	Required separation distance (f = 5 091 MHz) (km)	63.8

ANNEX 4

Glossary

AM(R)S	Aeronautical-mobile (route) service
AMS	Aeronautical-mobile service
AMS(R)S	Aeronautical-mobile satellite (route) service
AMSS	Aeronautical-mobile satellite service
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
BLOS	Beyond line-of-sight
CNPC	Control and non-payload communications
dB	Decibel(s)
dBc	dB relative to the carrier
dBHz	dB referred to one hertz
dB _i	dB referred to the gain of an isotropic antenna
dB _m	dB referred to one milliwatt
dB _m /Hz	dB referred to one milliwatt per hertz
dB _r	dB relative to a maximum value
dBW	dB referred to one watt
DL	Downlink
e.i.r.p.	Equivalent isotropically radiated power
FL	Forward link
FSS	Fixed-satellite service
GS	Ground station (for terrestrial CNPC system)
G/T	Ratio of receiving-antenna gain to receiver thermal noise temperature in kelvins
HIBLEO-4	A non-geostationary-orbit satellite network
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
IEEE 802.16e	IEEE standard for mobile broadband wireless access systems)
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
kHz	Kilohertz
LOS	Line-of-sight
MHz	Megahertz
MLS	Microwave Landing System
MS	Mobile service
MSS	Mobile-satellite service
PFD	Power flux density
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
SNR	Signal-to-noise ratio
Tx	Transmitter
UA	Unmanned aircraft
UACS	UA control station
UAS	UA system(s)
UL	Uplink
W	Watt
WiMAX	Worldwide Interoperability for Microwave Access
WRC	World Radiocommunication Conference
WRC-07	WRC 2007
WRC-12	WRC 2012