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Results of studies of the AM(R)S allocation in the band 960-1 164 MHz and of the AMS(R)S allocation in the band 5 030-5 091 MHz to support control and non-payload communications links for unmanned aircraft systems

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REPORT ITU-R M.2205

Results of studies of the AM(R)S allocation in the band 960-1 164 MHz and of the AMS(R)S allocation in the band 5 030-5 091 MHz to support control and non-payload communications links for unmanned aircraft systems

(2010)

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Objective

Numerous unmanned aircraft (UA) applications have been demonstrated or are planned that will significantly increase the numbers of UA worldwide. With integration of UA into non-segregated airspace, it is essential that adequate spectrum be found to support UA operations. At the 2007 World Radiocommunication Conference (WRC-07), a new agenda item was approved for the WRC-12 to consider the spectrum requirements for unmanned aircraft system (UAS) including the spectrum requirements for command and control and air traffic control (ATC) relay systems. This Report is focused on the study of the AM(R)S allocation in the bands 960-1 164 MHz and of the AMS(R)S allocation in the band 5 030-5 091 MHz to support CNPC links for UAS.

1 Introduction

Significant growth is forecast in the 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 UAs 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 a 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). Currently, many of these bands do not have the safety aspect required to enable UA flight in non-segregated airspace.

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

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

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

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

The objective of this Report is to study the AM(R)S allocation in the band 960-1 164 MHz and the AMS(R)S allocation in the band 5 030-5 091 MHz[1] to support control links for UAS 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 (UA) designates all types of remotely controlled aircraft.

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

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

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

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

– UACS subsystem;

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[1] Other bands exist, in which operational systems are already in use, which could ensure safe, reliable, and effective UA flight operation. Consequently no studies have been undertaken in these bands in this Report.

- Air traffic control (ATC) communication subsystem (not necessarily relayed through the UA);
- S&A subsystem;
- Payload subsystem (e.g., video cameras)[2].

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

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[3].

The Report provides the analyses for determining the amount of spectrum required for the operation of a projected number of UAS sharing non-segregated airspace with manned air vehicles as required by Resolution 421 (WRC-07) and in response to WRC-12 Agenda item 1.3.

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

The maximum amounts of spectrum required for UAS are:

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

4 Principles applying to services allocations

Figure 1 illustrates the kinds of terrestrial LoS links in the system.

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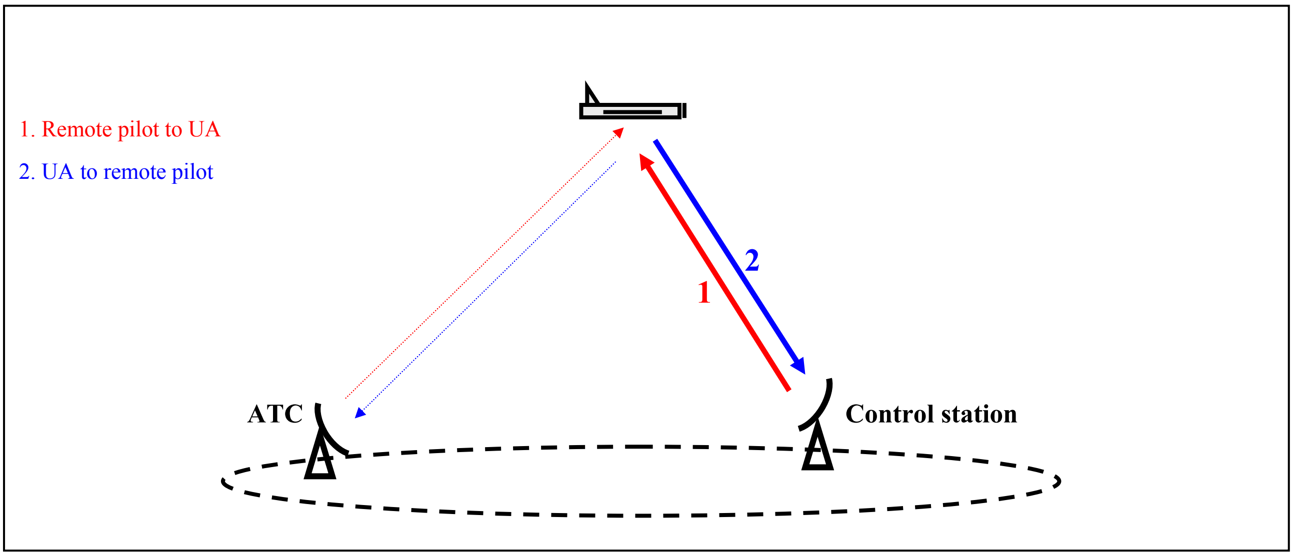
[2] UAS payload communications are not covered in this Report.

[3] Report ITU-R M.2171 – Characteristics of unmanned aircraft systems (UAS) and spectrum requirements to support their safe operation in non-segregated airspace.

FIGURE 1

Links involved in line-of-sight communications



For LoS links:

– the remote pilot stations satisfy the definition Radio Regulations[4] (RR) No. 1.81 (aeronautical station);

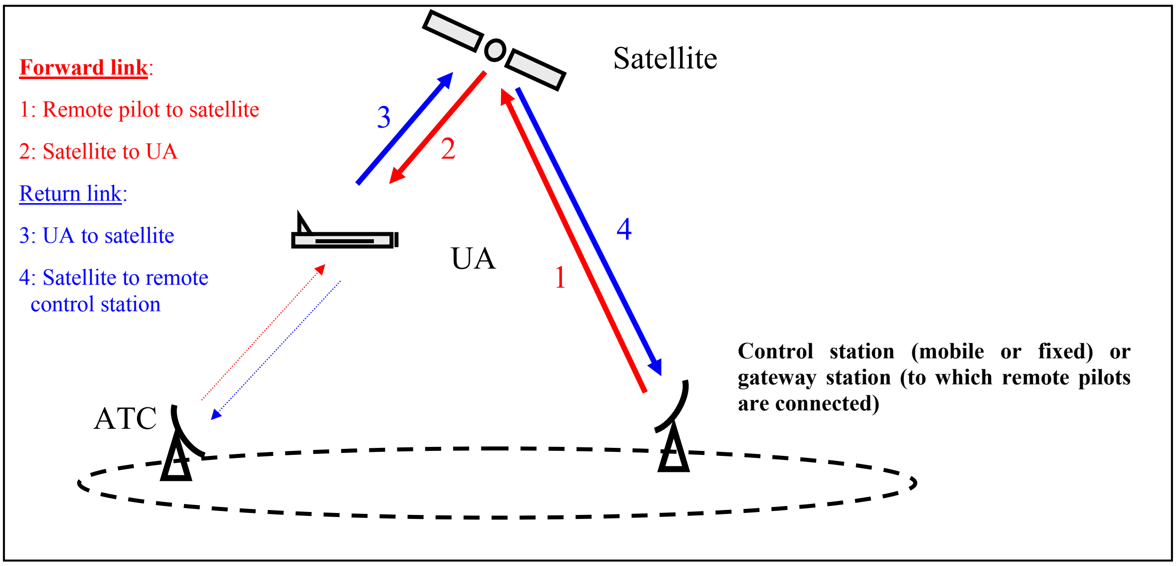
– the UA corresponds to definition RR No. 1.83 (aircraft station).

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 2 depicts the various kinds of satellite links in the system.

FIGURE 2

Links involved in beyond line-of-sight communications via satellite



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[4] All references to the RR are related to the RR Edition of 2008.

Case 1: Mobile UACS

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

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

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

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

Case 2: Fixed UACS

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

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

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

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

Case 3: Control station providing feeder-link station functions

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

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

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

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

5 Criteria for evaluating candidate frequency bands

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

There are four levels for AM(R)S and AMS(R)S allocations:

1. Spectrum that is or could be explicitly and exclusively allocated to AM(R)S or AMS(R)S.
2. Spectrum that is or could be explicitly allocated to AM(R)S or AMS(R)S but shared with other "aviation services" managed by civil aviation authorities.
3. Spectrum that is or could be allocated explicitly to AM(R)S or AMS(R)S but shared with other services than those managed by civil aviation authorities.
4. Spectrum that is or could be allocated to AM(R)S or AMS(R)S through an MS, MSS, AMS or AMSS allocation and shared with other services than those managed by civil aviation authorities.

The first two levels identified above concern frequency bands managed exclusively by civil aviation authorities, while the last two concern those whose management is shared with other entities.

Spectrum obtainability: The essence is the ease or difficulty of gaining access to certain bands based on compatibility with incumbent services, the amount of negotiation required in individual countries, or the number of regulatory bodies involved in the decision on allowing UAS to use the particular spectrum. Therefore, each potential solution should be evaluated on whether the spectrum would be obtained through the WRC process and how much coordination would be needed relative to the host nations to allocate UAS operations in the frequency range.

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

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

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

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

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

1. The frequency band to be used.
2. Minimum and maximum antenna sizes, and the corresponding transmitting and receiving antenna gains of the earth station and of the airborne station.
3. Minimum and maximum effective isotropically radiated powers (e.i.r.p.s) 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 for the satellite-/UA link and the satellite/control-station link;
    g) the minimum and maximum acceptable latency in the transmission to and from the UA and UACS.

Co-site compatibility: This metric evaluates the relative feasibility of operating future UAS control-link radios in the band under consideration, without causing unacceptable 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.

6 Frequency bands under consideration

The frequency bands listed below are considered for the use of UAS provided the safety aspects are ensured. In the context of the criteria outlined in § 4 these bands have been suggested for further detailed analyses.

– 960-1 164 MHz (AM(R)S allocation) for a terrestrial component;
– 5 030-5 091 MHz (part of the AMS(R)S allocation in 5 000-5 150 MHz) for a satellite component.

These bands are evaluated separately in the following subsections.

6.1 960-1 164 MHz terrestrial line-of-sight communications

The inherent physical properties of this band are highly favourable for UAS control links. Rain losses are negligible in the 960-1 164 MHz band. Free-space losses are low enough to permit reliable long-range LoS communication between relatively low-power radios using omnidirectional and medium-gain antennas. Omnidirectional antennas suitable for airborne use are conveniently small in this band. These propagation and antenna characteristics are particularly desirable for use by smaller UA whose size, weight, and power (SWAP) budgets do not allow the use of satellite terminals.

The study in Annex 1 demonstrates that even though much of the band is heavily used by incumbent navigation systems, substantial sub-bands (960-976 and 1 151-1 156 MHz) are not used by airborne navaid transmitters and contain no fixed ground-based assignments in some countries. In such countries, it appears feasible for UAS CNPC to share 10.4 MHz of spectrum in this band without depriving existing systems of needed spectrum. In these countries, such an allocation would not be sufficient to meet all the spectral needs of UAS CNPC, but it would furnish small UA with badly needed access to protected spectrum and would provide UA of all types with the band diversity that is essential for reliable pilot-to-UA communications. In the 960-1 164 MHz band compatibility of UAS CNPC with non-ICAO ARNS systems operating in countries listed in RR No. 5.312 is not feasible. It has to be noted that this study does not take into account complementary studies on going in other fora in particular on the lower adjacent band issue.

6.2 5 030-5 091 MHz satellite communications

The study in Annex 2 show that it is possible to design an AMS(R)S system sharing the 5 030-5 091 MHz band with the MLS, even when considering worst-case assumptions. Though the AMS(R)S allocation extends from 5 000 to 5 150 MHz, the study concentrates specifically on the 5 030-5 091 MHz portion, which is allocated to ARNS and AMS(R)S only, and offers 61 MHz of aeronautical safety spectrum for both Earth-to-space (UA emission) and space-to-Earth (UA reception).

In particular, the study assumes a massive MLS deployment in Europe (i.e., approximately 800 MLS stations), which, as considered by ICAO, is a very conservative approach considering latest MLS requirements expressed by ICAO Member States, which are much below 800 stations.

However, even when using these worst-case assumptions, studies show that i) the protection criteria for MLS (in-band level below –130 dBm/150 kHz) is met for all interference scenarios and ii) UA spectrum requirements as derived from Report ITU-R M.2171 can be accommodated in the band 5 030-5 091 MHz.

Hence, a carefully designed AMS(R)S system in the band 5 030-5 091 MHz safeguards the long-term access to the band for MLS, while enabling additional aeronautical use of the band, which will increase spectrum efficiency.

7 Conclusions

1. Portion(s) of the existing AM(R)S allocation in the band 960-1 164 MHz can be used in some countries to support some UAS terrestrial spectrum requirements under the conditions used in this Report. The band cannot be used to meet the entire 34 MHz terrestrial spectrum requirement for UAS operations, but 10.4 MHz of spectrum within this band would suffice to meet all UAS CNPC requirements except for backup links, video, and downlinking of airborne weather-radar data in some countries.
2. Studies show that within the existing AMS(R)S allocation in the band 5 000-5 150 MHz, the band 5 030-5 091 MHz can be used to support UAS satellite spectrum requirements. It is possible to design an AMS(R)S system ensuring that:
   i) the protection criteria for MLS (in-band level below –130 dBm/150 kHz) can be met for all interference scenarios under assumptions used in this Report;
   ii) UA spectrum requirements as derived from Report ITU-R M.2171 can be accommodated in the band 5 030-5 091 MHz.

   Hence the long-term access to the band for MLS can be safeguarded, while enabling an additional aeronautical use of the band.

Annex 1

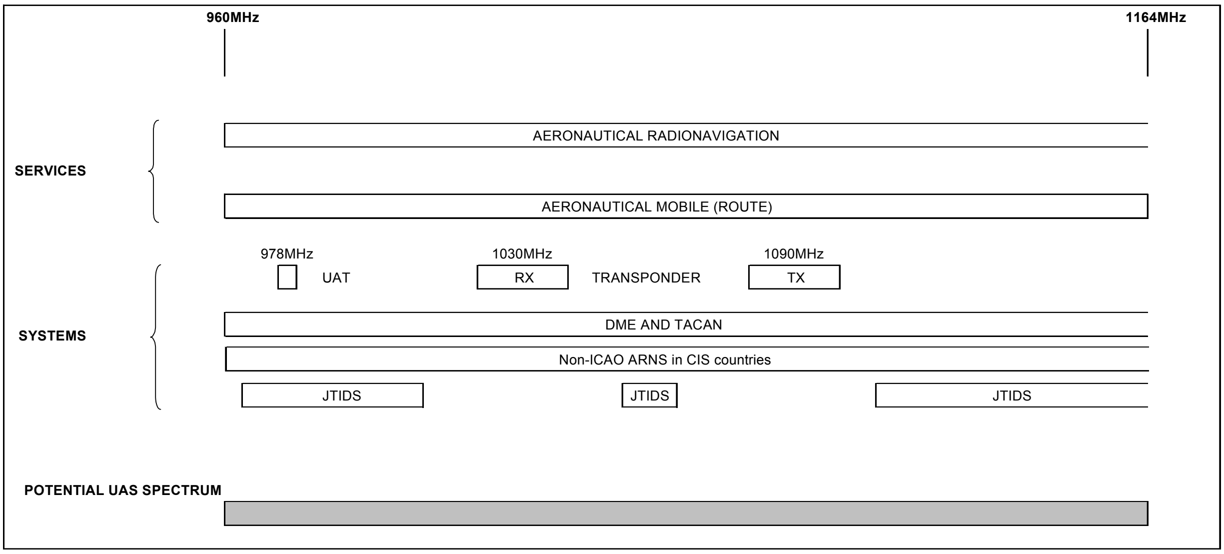
Sharing study for UAS terrestrial line-of-sight communications in the band 960-1 164 MHz

1 960-1 164 MHz allocations

Figure 1-1 depicts frequency use in the 960-1 164 MHz band. The ARNS has a worldwide primary allocation throughout the band, which is heavily utilized by distance measuring equipment (DME) and tactical air navigation (TACAN). WRC-07 gave the 960-1 164 MHz sub-band an additional AM(R)S allocation. Portions of the 960-1 164 MHz band could be considered to support UAS control links as well as other communications with manned aircraft. It is to be noted that the Global Navigation Satellite Systems (GNSSs) in the band 1 164-1 215 MHz need to be protected. The incumbent ARNS still has the right to operate throughout the 960-1 164 MHz frequency range, so sharing criteria will be required for any AM(R)S or UAS control link operation in that range.

FIGURE 1-1

Aeronautical frequency use in the 960-1 164 MHz band



Secondary surveillance radar (SSR), the Traffic Alert and Collision Avoidance System (TCAS), and Identification Friend or Foe (IFF) nominally operate at 1 030 and 1 090 MHz but generally require interference protection throughout the 1 020-1 040 and 1 080-1 100 MHz sub-bands. Even larger guardbands may be needed to protect against airborne co-site interference to or from those systems.

Two Automatic Dependent Surveillance – Broadcast (ADS-B) systems also use the band. The Universal Access Transceiver (UAT) system[5] operates on a single frequency, 978 MHz. Compatibility may be addressed by avoiding this frequency. The other ADS-B system in the band is

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

called 1090 Extended Squitter (1090ES)[6]. It is designed to coexist with other systems using 1 090 MHz. It is assumed that systems that are compatible with other users of this frequency will also be compatible with 1090ES.

The Joint Tactical Information Distribution System (JTIDS) operates within this band on 51 hopping channels, each 3 MHz wide. Their centre frequencies lie in three separate sub-bands (969-1 008, 1 053-1 065 and 1 113-1 206 MHz).

There are also ongoing research programmes to study the possibility of using the 960-1 164 MHz to support future ATC data communications. Two separate approaches are being considered. The L-band Digital Aeronautical Communications System 1 (L-DACS1) is a frequency-division duplex (FDD) system using orthogonal frequency-division multiplexing (OFDM), and L-DACS2 is a time-division duplex (TDD) system using a single carrier, constant envelope modulation. It is anticipated that these two choices will eventually be reduced to one as a result of further research. Because of the anticipated difficulty of fitting two new systems into the already congested band, it might make sense to consider one integrated system to support both ATC and CNPC sharing capacity in a flexible way to support localized needs. Another approach that might be possible, if both L-DACS candidates can be shown to be viable, is to use one for ATC data and the other for CNPC but this approach doesn’t take into account the fact that the total amount of spectrum defined for the future aeronautical communication system and allocated at the last WRC-07 was calculated to ensure the growing communication for aviation and allocated to cover only the needs for manned aircraft in order to face the actual VHF saturation.

The remainder of this section covers relevant characteristics of existing and potential in-band and adjacent-band systems, and uses this information to develop various considerations that may constrain the design of future 960-1 164 MHz CNPC links.

2 Existing in-band systems

The tables below summarize the publicly available RF characteristics of airborne systems currently occupying the 960-1 164 MHz band. The known parameters of relevant ICAO systems are presented in tabular form in Tables 1-1 and 1-2, which list the airborne transmitter and receiver characteristics, respectively. The footnotes and references shown after Table 1-2 apply to both tables. In both tables, values in cells with footnotes have been verified against the cited reference documentation. Table 1-3 lists non-ICAO system characteristics.

All of the aeronautical systems now using the band are pulsed systems with short pulses and low transmitter duty factors. They are also tolerant to relatively low success rates for individual signalling elements. In the case of information-bearing signals such as JTIDS or UAT, this is so because the systems employ strong forward error correction (FEC) techniques. Systems that rely primarily on the signal timing (e.g., DME) are designed to operate when the success rate for individual messages is significantly less than 100%. DME interrogators can operate even when the ground reply efficiency is substantially less than 100%. This means that the systems can successfully coexist, provided that the number of individual users is kept under control.

Thus, from a historical standpoint, a very low transmitter duty factor might seem to be a desirable characteristic for a UAS CNPC system operating in this band. On the other hand, a low duty factor implies a sacrifice in system throughput. In order to support data throughput rates that are

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[6] Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Service – Broadcast (TIS-B), DO-260A, RTCA.

acceptable for CNPC applications, the instantaneous bandwidth of any such candidate might have to be very large.

TABLE 1-1

Airborne transmitters in the 960-1 164 MHz band

Incumbent system	**Airborne transmitter characteristics**						
	Frequency (MHz)	**Power (dBm)**	**Emission BW (MHz)**	**PW (µs)**	**PRF (pps)**	**Duty factor (%)**	**Spurious emission (dBc)**
SSR transponder (Mode A and C replies)	1 090a)	48-57a)	4.5	20o)	200r)	0.40	76
SSR transponder (Mode S replies)	1 090a)	48-57a)	2.6	64o)	4.5o)	0.03	76
TCAS (Mode S interrogations)	1 030b)	56s)	2.6	20o)	5o)	0.01	76
TCAS (whisper-shout interrogations)	1 030b)	29-52	2.6	25o)	80o)	0.20	76
DME	1 041-1 150g)	47-54c)	0.4	19o)	70o)	0.13	50
ADS-B (extended squitter)	1 090e)	57e)	2.6	120e)	6	0.07	76
UAT	978d)	43-54d)	0.9	400	1	0.04	70p)
JTIDS/MIDS	969-1 008, 1 053-1 065, 1 113-1 206h)	53-60j)	3j)	6.4f)	648	0.41	70p)
TACAN	1 025-1 150g)	57		3.5g)	7 200		

TABLE 1-2

Airborne receivers in the 960-1 164 MHz band

Incumbent system	**Airborne receiver characteristics**												
	Frequency (MHz)	**Sensitivity (dBm)**	**RF Bandwidth (MHz)**							**Recovery time (µs)**	**Adj. chan. rejec. (dB)**	**Image rejec. (dB)**	**Spurious rejec. (dB)**
			3 dB	**6 dB**	**20 dB**	**40 dB**	**50 dB**	**60 dB**	**70 dB**				
SSR Transponder (Mode A and C replies)	1 030[a)]	–73±4 dB[a)]	6[a)]			30[a)]				15[a)]		80	70
SSR Transponder (Mode S replies)	1 030[a)]	–74±3 dB[a)]	6[a)]			30[a)]		50[a)]		45[a)]			
TCAS (Mode S interrogations)	1 090[b)]	–74±2 dB[s)]	11[s)]		20[s)]	30[s)]		50[s)]				80	70
DME	978-1 215[g)]	–83[c)]		1.8[k)]	2.1[k)]	2.6[k)]		3.0[k)]	6.0[k)]	8	50[c)]	80	80
ADS-B (extended squitter)	1 090[e)]	–84[e)]	11[t)]										
UAT	978[d)]	–93[d)]	1.2				4[d)]	20[d)]		15	40[r)]		
JTIDS/MIDS	969-1 008, 1 053-1 065, 1 113-1 206[h)]	–95[j)]											
TACAN	962-1 024, 1 151-1 213[g)]	–92											

References for Tables 1-1 and 1-2

[a] RTCA DO-181C, Minimum Operational Performance Standards (MOPS) for Air Traffic Control Radar Beacon System/Mode Select (ATCRBS/Mode S) Airborne Equipment.

[b] RTCA DO-300, Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II) Hybrid Surveillance.

[c] RTCA DO-189, Minimum Operational Performance Standards for Airborne Distance Measuring Equipment (DME) Operating within the Frequency Range of 960-1 215 MHz.

[d] RTCA DO-282A, Vol. 1, Minimum Operational Performance Standards for Universal Access Transceiver (UAT) Automatic Dependent Surveillance – Broadcast (ADS-B).

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

[f] CFR 47 Part 87.479.

[g] ICAO Annex 10 Volume I.

[h] Suitability of Civil Aviation Bands for the Future Communication Infrastructure, 14th meeting of ICAO ACP Working Group F, Malmo, Sweden, 22-26 August 2005.

[j] R. Echevarria and L. Taylor, “Co-Site Interference Tests of JTIDS, EPLRS, SINCGARS, and MSE (MSRT),” Proc. 1992 Tactical Communications Conf., Vol. 1, pp. 31-39, April 1, 1992.

[k] Compatibility between UMTS 900/1800 and Systems Operating in Adjacent Bands, Electronic Communications Committee (ECC) Report 96, Krakow, March 2007.

[m] ICAO Annex 10 Volume IV.

[o] RTCA SC-186 WG5, UAT-WP-11-12, ADS-B UAT MOPS, 4 March, 2002.

[p] ICAO ACP-WGF14/WP-11.

[r] RTCA DO-282A, Vol. 2, Minimum Operational Performance Standards for Universal Access Transceiver (UAT) Automatic Dependent Surveillance – Broadcast (ADS-B).

[s] RTCA DO-185B, Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II), Volume I.

[t] RTCA DO-260A, Vol. 2, Minimum Operational Performance Standards for 1 090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Services – Broadcast (TIS-B).

TABLE 1-3

Typical characteristics of the ARNS stations operating in the countries referred to in RR No. 5.312

ARNS system characteristics	**Type 1**	**Type 2**		**Type 3**	
Purpose	**Radio systems of short-range navigation**	**Radio systems of short-range navigation**		**Radio systems of approach and landing**	
Operating frequency range	960-1 000.5 MHz	960-1 164 MHz			
Radio link direction	“Earth-aircraft”	“Earth-aircraft”	“Aircraft-Earth”	“Earth-aircraft”	“Aircraft-Earth”
Operation range (km)	Up to 400	Up to 400	Up to 400	Up to 45	Up to 45
Transmitted information	Transmission of azimuthal signals, range response signals and request to indication	Transmission of azimuthal signals, range response signals and request to indication	Transmission of range request signal and indication response signal	Transmission of signals in glide path and course channels and range response signals	Transmission of range request
Transmitter characteristics					
Station name	Airport and en route path ground stations	Airport and en route path ground stations	Aircraft station	Airport ground station	Aircraft station
Signal type	Pulsed	Pulsed	Pulsed	Pulsed	Pulsed
Class of emission	700KPXX	4M30P1N	4M30P1D	700KP0X; 4M30P1N	700KP0X; 4M30P1N
Channel spacing (MHz)	0.7	0.7	0.7	0.7	2
Type of modulation	Pulsed	Pulsed	Pulsed	Pulsed	Pulsed
Transmitter power (pulsed) (dBW)	20-45	29-39	27-33	3-30	5-33
Mean output power (min/max) (dBW)	7.6/13.2	7.1/13.8	−8.2	−4/−6	−7.5
Pulse length (μs)	1.5; 5.5	1.25; 1.5; 5.5	1.5	1.7	1.7
Duty factor (%)	0.018; 0.066	0.064-0.3	0.00765	0.04; 0.025	0.009
Antenna type	Omnidirectional	Array antenna	Omnidirectional	Array antenna	Omnidirectional
Max/min antenna gain (dB)	**6/0**	15.6	−10/3	10/0	1.5/−3
Height above the ground (m)	10	10	Up to 12 000	10	Up to 12 000

TABLE 1-3 (*end*)

ARNS system characteristics	**Type 1**	**Type 2**		**Type 3**	
Purpose	**Radio systems of short-range navigation**	**Radio systems of short-range navigation**		**Radio systems of approach and landing**	
Receiver characteristics					
Receiving station	Aircraft station	Aircraft station	Airport and en-route path ground stations	Aircraft station	Airport ground station
Height above the ground (m)	Up to 12 000	Up to 12 000	10	Up to 12 000	10
Receiver passband (MHz)	1.5	22	22	7	7
Receiver noise temperature (K)	400	1 060	550	400	400
Max/min antenna gain (dB)	**1.5/−3**	3/−10	14	1.5/−3	10/0
Polarization	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal
Real receiver sensitivity (dBW)	**−120**	−118	−125	−110…−120	−113
Protection ratio *C*/*I* (dB)	25	17	20	25	25

2.1 DME and TACAN

DME and TACAN are very similar in their properties, so they will be discussed together. The discussion will focus on DME. Differences associated with TACAN will be pointed out when relevant. The relevant RF parameters are found in Table 1-1.

The DME system allows an airborne user to determine its distance from a ground site through a process of round trip timing. An airborne radio transmits a sequence of “pulse pairs” in which the gaps between the pairs are chosen pseudo-randomly. Ground stations reply to the received interrogations by transmitting their pulse pairs with a fixed time delay. The airborne receiver then searches for a sequence of replies with the same pseudorandom gaps that it used for transmission. This pseudorandom process allows a particular airborne unit to separate its own information from replies to interrogations from other airborne units by correlating over a number of pulse pairs. After the fixed delay is subtracted from the round trip time difference, the distance is determined using the speed of light.

Two modes of DME are commonly used: X-Mode and Y-Mode. They differ by their pulse-pair separations and by the frequencies used for interrogations and replies. (There are also definitions for a W-Mode and a Z-Mode, but these are not used.) For X-Mode the spacing for both interrogations and replies is 12 µs. For Y-Mode the spacing for interrogations is 36 µs and the spacing for replies is 30 µs. For each mode there are 126 potential channels whose interrogation and reply frequencies are on integer megahertz centres from 962 to 1 213 MHz. For a given channel the interrogation and reply frequencies are always separated by exactly 63 MHz; however, the reply frequency plan depends on the mode as shown in Fig. 1-2.

FIGURE 1-2

DME frequency plan

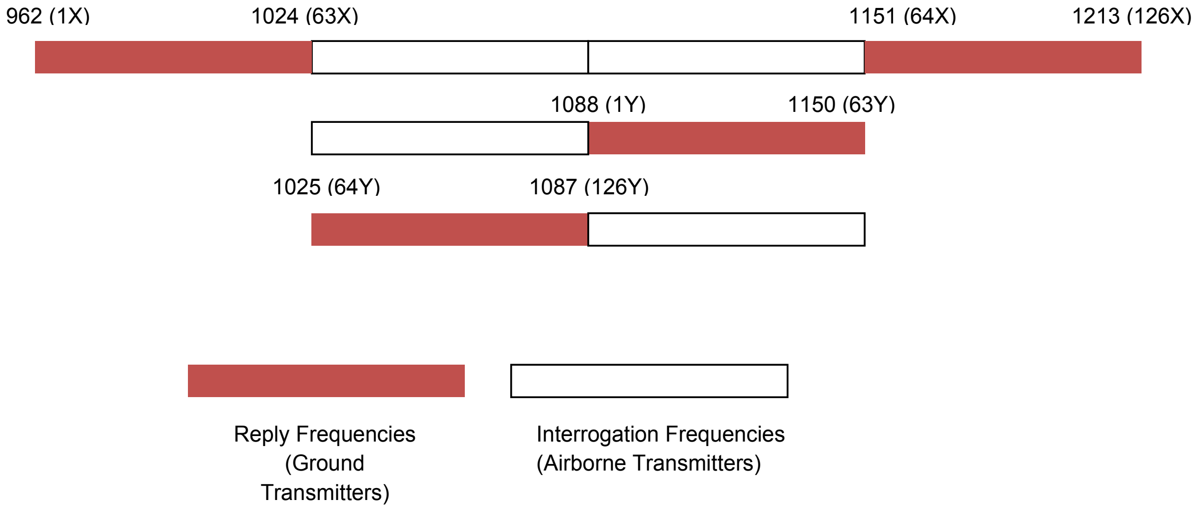
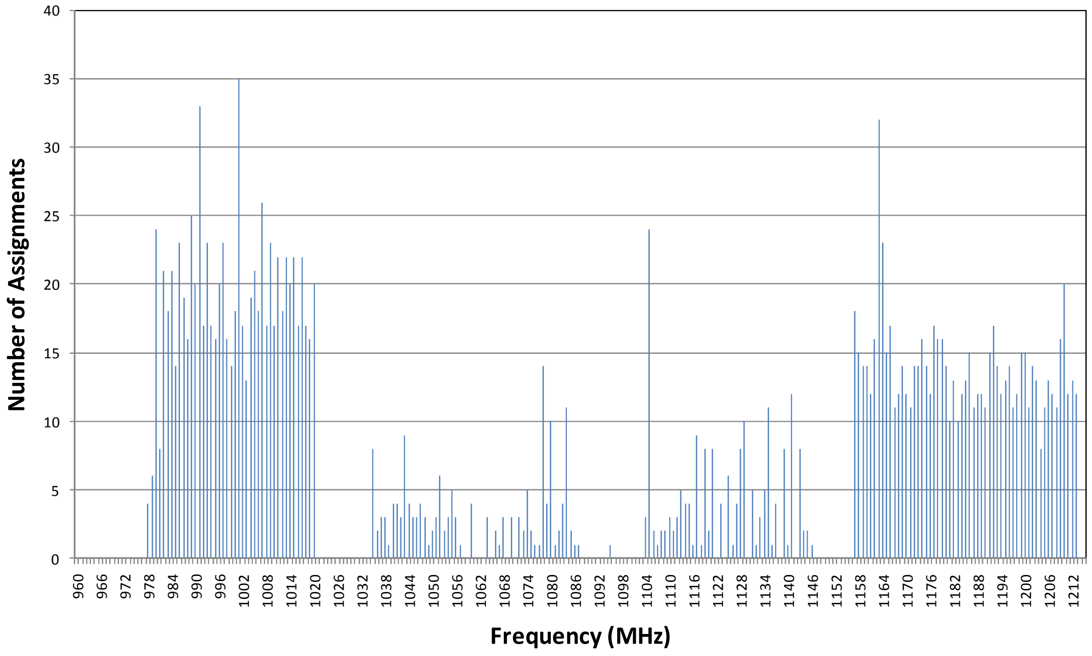


Figure 1-3 depicts recent actual usage of the DME reply frequencies in the United States of America and Canada. By comparing with Fig. 1-2, it can be observed that the X-Mode is more heavily used. It can also be seen that there are gaps in the assignments surrounding 1 030 and 1 090 MHz for the protection of SSR/TCAS (see below). There are also related gaps 63 MHz above and below these bands that are due to the DME frequency-pairing approach. For example, channels 1X through 16X are seldom assigned to fixed ground stations, and the corresponding band (up to 977 MHz) is not subject to international agreement and is relegated to national assignment status.

FIGURE 1-3

Spectral occupancy of DME and TACAN ground assignments



In the time domain, an X-Mode pulse pair looks like Fig. 1-4. The two pulses are separated by 12 µs, and each pulse has a raised cosine shape with a half-amplitude width of 3.5 µs. This shaping results in a compact spectrum, as shown in Fig. 1-5. The overall shape is due to the individual pulse shape and the finer details are due to the 12 µs spacing between pulses (assuming coherence between the two pulses). The occupied bandwidth of the signal is on the order of 400 kHz.

FIGURE 1-4

X-Mode DME pulse pair description

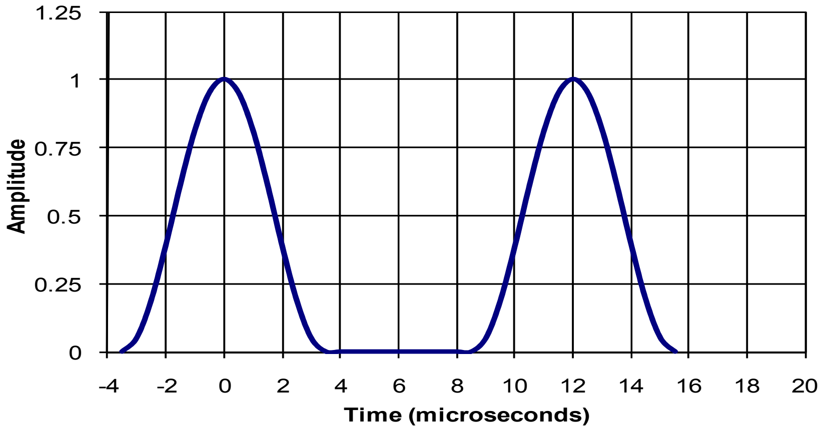
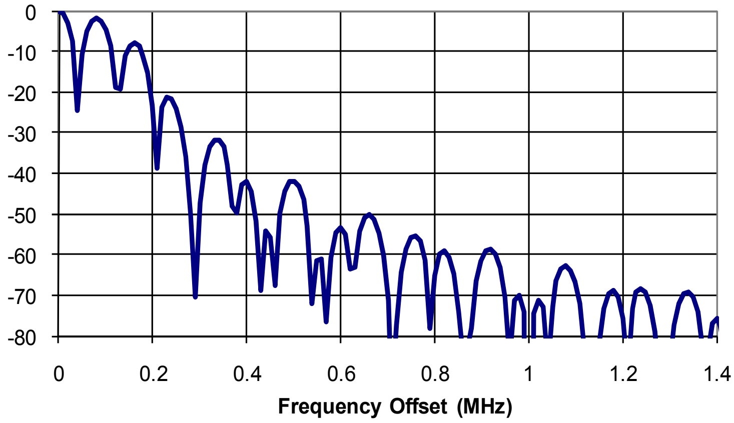


FIGURE 1-5

X-Mode DME spectrum



Even though the power of the DME signal is mostly contained within 300 kHz, DME receivers typically have bandwidths on the order of 1 MHz. This large bandwidth allows for accurate measurement of the timing of the rising edges of the pulses, and therefore an accurate measurement of the separation between pulses. Robust measurement of time is critical to accurate distance estimation.

In Fig. 1-6 the red dots represent measured selectivity values of a DME 442 receiver, the less selective of two commercially available airborne DME receivers chosen for testing in a recent compatibility study[7].

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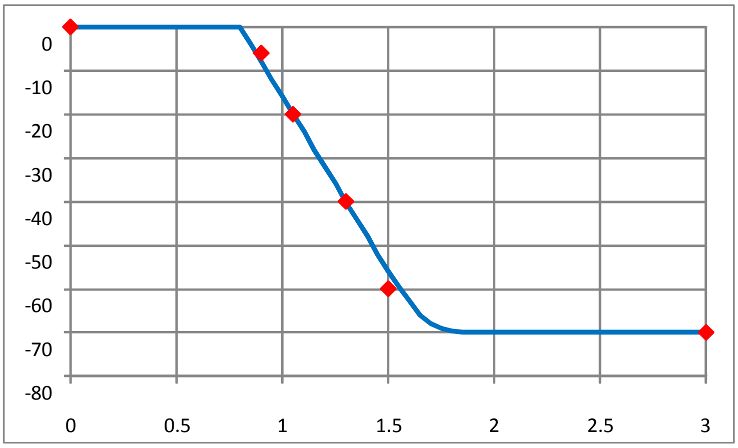
[7] *Compatibility between UMTS 900/1800 and Systems Operating in Adjacent Bands*, Electronic Communications Committee (ECC) Report 96, Krakow, March 2007.

FIGURE 1-6

Selectivity of a wideband DME receiver



Because the spacing of DME assignments is 1 MHz and the receiver bandwidths are also about 1 MHz, there are no “natural” frequency gaps between DME channels for other systems to occupy. In fact, a UAS CNPC link operating within a frequency-protected DME service volume (SV) would have to be separated by at least 1.5 MHz from the DME ground transmitter’s frequency to provide adequate interference protection to wideband DME receivers within the SV. This limits the options for new systems in the band, such as CNPC, to the following:

1. Coordinate with the spatial distribution of DME frequency usage to reduce co-channel interference.
2. Use a waveform with a low duty factor.
3. Use a part of the band not occupied by DMEs.

Computer simulations using an automated frequency-assignment tool and a North American database of 960-1 215 MHz navaid assignments have demonstrated that, in congested geographical regions where many DMEs are in use, there are very few opportunities to insert UAS CNPC links into in any sub-band and geographical region heavily occupied by DMEs without interfering with wideband DME receivers. This indicates that option 1 is not a viable method for coexistence of UAS CNPC links with navaids in regions where substantial numbers of DMEs are operating. And, as noted earlier, a low duty factor (option 2) might impose unacceptable restrictions on throughput and/or an unacceptably wide instantaneous bandwidth for the CNPC signal. Option 3 seems to be the most attractive and practical approach to achieving compatibility between CNPC and DME.

2.2 Secondary surveillance radar and TCAS (1 030/1 090 MHz)

Two types of aeronautical systems operate at 1 030 and 1 090 MHz: SSR (which includes Mode A, Mode C, and Mode S), and TCAS[8].

SSR provides cooperative surveillance information from appropriately equipped aircraft. An SSR can function either as a stand-alone system, or in conjunction with primary long range and terminal surveillance radars. SSR operation requires an uplink interrogation, a reception and response by a cooperative airborne transponder, and reception of the transponder’s downlink reply. The transponder’s response identifies the aircraft and is ordinarily much stronger than the reflection that would be received by a primary surveillance radar. A side-lobe suppression system is used to

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[8] RTCA Special Committee 185, *Aeronautical Spectrum Planning for 1997-2010,* RTCA/DO-237, 27 January 1997.

prevent false triggering of transponders by radiation emitted from the interrogator's antenna side lobes. All SSR systems use 1 030 MHz as the uplink frequency, and 1 090 MHz as the downlink frequency.

Mode A and Mode C provide identification and other flight information about an aircraft for tracking and management by air traffic controllers. They use ground-based interrogators that transmit pulses via a 1 030 MHz uplink to airborne transponders, which reply via a 1 090 MHz downlink. The interrogations are transmitted from a directional SSR antenna beam that rotates along with the primary radar antenna (if one is present). As the beam rotates toward the azimuth at which the aircraft is located, the airborne transponder begins to receive interrogations which result in transponder replies. Mode A and Mode C are "all-call" systems in which every transponder that is within the beamwidth of the interrogator antenna, and is capable of responding, does so.

Mode S is a discrete-address beacon system that selectively interrogates aircraft. As in Mode A and Mode C, the ground-based interrogators in Mode S transmit at 1 030 MHz and receive the transponders' replies at 1 090 MHz. Mode S has two principal modes of operation, which are interleaved in time: the all-call mode that Mode A and Mode C also use, and a roll-call mode. Mode S transponders will not respond with Mode A and Mode C replies to the modified Mode A and Mode C interrogations transmitted by a Mode S interrogator, but they will reply to all-call interrogations. The response to an all-call interrogation is a Mode S reply that contains the aircraft's 24-bit address.

TCAS provides pilots with traffic alerts of potential threats, and resolution advisories that supply manoeuvre guidance in the vertical plane to help pilots achieve separation from a threat. To ensure that the recommended manoeuvres of two TCAS-equipped aircraft do not conflict, the resolution advisories are coordinated using air-to-air Mode S data link communications. TCAS operates at 1 030 and 1 090 MHz and is independent of any ground system. TCAS employs a low-gain directional antenna array on top of the aircraft, along with an omnidirectional antenna on the bottom of the aircraft.

TCAS interrogates and tracks aircraft equipped with Mode S transponders by means of discrete interrogation and reply. Such aircraft are initially acquired by TCAS via unsolicited "squitter" reply transmissions that announce the transponder's identity. Interrogation and tracking of aircraft with Mode A and Mode C transponders is via a "whisper-shout" technique. This consists of a total of 84 modified Mode C interrogations spaced 1 ms apart, each preceded by a lower-power suppression pulse followed by another suppression pulse. Four sequences of interrogations are contained in the 84; from the top directional antenna the first 24 are radiated forward, the following 40 are radiated sequentially to both sides, the next 15 are radiated aft, and the last five are radiated downward by the bottom antenna. Power is lowered progressively through the sequence, so ideally each aircraft will respond only once per sequence, to the first reply for which the initial suppression pulse falls below the threshold. Preceding stronger interrogations should all cause transponder suppression, and following weaker interrogations should fall below receiver threshold. In practice, on about 10% of the whisper-shout sequences, an additional reply is elicited.

RF interference to the transponders used by SSR and TCAS can degrade their performance in several ways. These include:

- generation of undesired replies to nonexistent interrogations;
- overlooking and thus failing to reply to actual interrogations;
- garbling of replies.

Transponder selectivity curves of SSR and TCAS receivers have wide skirts, as noted in Table 1-2. This makes it difficult for them to coexist with other systems in the band unless large frequency separations (up to 25 MHz) are maintained. A suppression bus can be used to protect them from airborne co-site in-band interference, but unless the collocated potentially interfering transmitter has a low duty cycle (preferably 1% or less), transponder performance will suffer because interrogations will be missed during pulse-blanking intervals.

2.3 JTIDS and MIDS

The Joint Tactical Information Distribution System (JTIDS) and the Multifunctional Information Distribution System (MIDS) are identical at the RF level, and they are treated together. (They are both also referred to as Link 16.).

Many of the RF parameters of JTIDS were carefully chosen to achieve compatibility with the aeronautical systems then existing in the same band (DME/TACAN and SSR, at the time). These parameters can be found in Table 1-1. As an example of how the JTIDS design was influenced by compatibility with DME, the pulse length was chosen to be 6.4 μs and the spacing between pulses was chosen to be 13 μs. Furthermore, the frequency-hopping algorithm ensures that successive pulses will always be separated by at least 30 MHz. Taken together, these factors make it highly unlikely that a single JTIDS terminal could generate a signal that mimics a DME pulse pair.

Compatibility with 1 030/1 090 MHz operation is addressed by strictly limiting the power that a JTIDS terminal is allowed to radiate in the neighbourhoods of these frequencies. Every JTIDS terminal is required to have an autonomous receiving capability to monitor its emissions in these bands. If strict thresholds are exceeded, the terminal automatically shuts down. This is called the Interference Protection Function (IPF).

Additionally, the total number of JTIDS pulses that can be transmitted per second in any given geographic location is limited. Since JTIDS hops over 51 frequencies, the system duty factor on any given carrier frequency is low. On the other hand, it must be borne in mind that the instantaneous bandwidth of JTIDS is about 3 MHz, so more than one DME channel is affected by each hop.

Proving that JTIDS can operate on a non-interfering basis has been the subject of much analysis and testing spread out over several years and at least one Administration continues to monitor the number of JTIDS pulses transmitted per second.

2.4 UAT

The Universal Access Transceiver (UAT) operates at a single frequency, 978 MHz. Other relevant characteristics are listed in Table 1-2. UAT provides a number of aeronautical services including ADS-B, Traffic Information Service – Broadcast (TIS-B), Automatic Dependent Surveillance – Rebroadcast (ADS-R), and Flight Information Service – Broadcast (FIS-B). The transmissions of the first three types comprise short bursts of either 265 μs or 403 μs. Airborne users transmit one ADS-B burst each second. The FIS-B bursts are longer (4.27 ms), but they are transmitted by only ground stations. ADS-R and TIS-B bursts are also transmitted by only ground stations. ADS-B, TIS-B and ADS-R messages are sent at pseudorandom times chosen in a common time interval, so there can be non-negligible self-interference in dense aircraft environments. The deleterious effects of this self-interference are limited due to the very low duty factor of each airborne transmitter (0.0265% or 0.0403%) and the frequency modulation capture effect. On the other hand, the longer FIS-B message transmissions are separated in time from the other types and their mutual timing is tightly controlled in order to minimize self interference.

Each ADS-B message contains either 144 or 272 bits of user information, so the bit rate for individual airborne users is very low. Nevertheless, the messages are sufficient to convey all the necessary surveillance information at the required update rates. Each FIS-B burst carries 3 456 bits of user information, which may comprise weather maps, text messages, etc.

During the development of UAT Minimum Operational Performance Standards (MOPS) under the purview of RTCA SC-186 WG 5, there was extensive analysis, simulation and testing of the effects of interference between UAT and DME[9] and between UAT and JTIDS[10]. There were also studies of UAT with both DME and JTIDS[11, 12]. The scenarios were based on future traffic densities in Los Angeles, California and Core Europe, plus a prescribed JTIDS environment[13]. As a result of all this research, the FEC selected for the different UAT message types was strengthened to allow them to meet requirements in worst-case scenarios. Also, it was verified that the level of interference from UAT was acceptable.

Many of the studies mentioned in the previous paragraph were focused on interference between transmitters and receivers on separate platforms; however, some of them considered co-site interference. Although the effect of UAT airborne co-site interference on other systems is limited by its low duty factor, it was considered prudent to limit the effects even further; so it was agreed that a UAT transmitter would be able to provide an appropriate signal to an installed suppression bus to allow for receiver blanking if deemed necessary.

Note that subsequent to the publication of the UAT MOPS (DO-282) by RTCA, UAT was also addressed by ICAO. ICAO has published Standards and Recommended Practices (SARPs) for UAT[14].

2.5 Non-ICAO standardized aeronautical radionavigation system

National radionavigation systems are non-ICAO standard ARNS systems. Specifically the countries referred to in RR No. 5.312 operate the ARNS systems of the following three types:

– The ARNS systems of the first type are direction-finding and ranging systems. The systems are designed for finding an azimuth and a slant range of an aircraft as well as for area surveillance and inter-aircraft navigation. They are composed of airborne and ground-based stations. The airborne stations generate requesting signals transmitted via omnidirectional antennae and received at ARNS ground stations which also operate in an omnidirectional mode. The ground stations generate and transmit response signals containing azimuth/ranging information. Those signals are received and decoded at the ARNS airborne stations. The first type stations transmit the signals requesting the azimuth/ranging data outside the 960-1 164 MHz frequency band. After receiving a requesting signal the ARNS ground stations use the 960-1 164 MHz frequency band only for transmitting the ranging data to be received at the ARNS airborne stations. Thus the ARNS systems of the first type use the 960-1 164 MHz frequency band only for transmitting the signals in the surface-to-air direction. The maximum operation range for the first type ARNS systems is 400 km. It

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[9] RTCA Working Papers generated by Special Committee 186, Working Group 5: UAT WP2-05, 3-02, 3-10, 3-11, 4-13, 5-09A, 5-16, 6-12, 6-13, 6-14, 7-11, 7-12, 7-14, 7-15, 8-05, 8-09,10-6 and 11-12. These are available at http://adsb.tc.faa.gov/WG5.htm.

[10] RTCA Working Papers generated by Special Committee 186, Working Group 5: UAT WP1-04, 3-12, 4-04, 4-05, 4-16, 5-07, 6-02 and 6-03. These are available at http://adsb.tc.faa.gov/WG5.htm.

[11] RTCA Working Papers generated by Special Committee 186, Working Group 5: UAT WP3-07, 5-14, 8-10, 9-05, 9-06, 9-09, 11-16 and 11-19. These are available at http://adsb.tc.faa.gov/WG5.htm.

[12] Also, see Appendix O of the UAT MOPS (see footnote 3).

[13] Appendix G of RTCA DO282A, UAT MOPS (see footnote 3).

[14] ICAO Document 9861 *UAT Technical and Implementation Manuals.*

is expected that in some of the countries mentioned in RR No. 5.312 the usage of type 1 of ARNS mentioned above may be discontinued.

- The ARNS direction-finding and ranging systems of the second type are designed for the same missions as the first type ARNS systems. The primary difference of the second type stations refers to the fact that requesting signals are transmitted by the air-borne stations in the same frequency band as responding signals transmitted from the ground stations. Moreover the ground-based ARNS stations of the second type can operate in both directional and omnidirectional modes. Directional mode provides increased number of operational channels at the ARNS stations. The maximum operation range for the first type ARNS systems is 400 km. It is planned to use the overall frequency band 960-1 164 MHz allocated to ARNS in order to increase flexibility of operation of the second type ARNS systems. Application of the wideband tuning filter on the ARNS receiver front end is the design peculiarity of the second type ARNS systems which is stipulated by the necessity to receive signals on several channels simultaneously. The passband of this filter is 22 MHz and it allows receiving simultaneously up to 5 channels among 30 overlapping channels of 4.3 MHz each. The simultaneous usage of wideband filter and correlator allows to increase the accuracy of aircraft position data measurement and *C*/*N* ratio at the receiver front end as well. Type 2 of ARNS system can operate in a limited number of countries mentioned in RR No. 5.312.
- The ARNS systems of the third type are designed for operating at the approach and landing stages of flight. The system provides control functions of heading, range and glide path at aircraft approach and landing. The ARNS ground stations of the third type operate in both directional and omnidirectional modes. Operation range of the third type ARNS systems does not exceed 60 km. The 960-1 164 MHz frequency band is used for operation of the channels designed for control of the glide path and range between airborne and ground ARNS stations. Type 3 of ARNS system can operate in a limited number of countries mentioned in RR No. 5.312.

Thus the stations of the non-ICAO systems operate using the air-to-surface and surface-to-air links and are made up of ground and airborne receivers and transmitters. Technical parameters of these systems are presented in Table 1-3.

2.5.1 Results of compatibility studies between UAS and non-ICAO ARNS stations in the 960-1 164 MHz band

The compatibility studies used carrier-to-interference ratio (*C*/*I*) criteria at the receiver front end with the following conditions and assumptions:

1. Only scenarii between one transmitter to one receiver are studies.
2. For ground-to-air and air-to-air links the free-space propagation model from Recommendation ITU-R P.528 was used.
3. For ground-to-ground link the propagation model from Recommendation ITU-R P.1546 was used.
4. Typical characteristics of ARNS stations used in this study come from Table 1-3 of this Report.
5. Typical characteristics of UAS used in this study come from the Table 1-4:

TABLE 1-4

Sample link budget for narrow-band system

	Ground to air	**Air to ground**
Transmitter power (dBm)	40	40
Transmitting antenna gain (dBi) minus cable loss (dB)	14	–4
Transmitter e.i.r.p. (dBm)	54	36
Free-space path loss (1 GHz, 93 km (50 nmi)) (dB)	132	132
Receiving antenna gain (dBi) minus cable loss (dB)	–4	14
Received signal power (dBm)	–82	–82
Thermal noise @ 290ºK (dBm/Hz)	–174	–174
Receiver noise figure (dB)	6	6
Receiver bandwidth (dB.Hz)	57	57
Receiver noise power (dBm)	–111	–111
Carrier-to-noise ratio (C/N) (dB)	29	29
Theoretical C/N requirement (dB)	4.2	4.2
Implementation loss margin (dB)	3.8	3.8
Required C/N (dB)	8	8
Remaining margin (dB)	21	21

6. A case of co-channel interference without carrier frequency off-set was considered, where carrier frequency F = 1 000 MHz.
7. No loss in antenna cable was assumed.

The results of estimated interference levels and minimum separation distances are shown in Tables 1-5 and 1-6 for UAS transmitters causing interference to ARNS receivers and in Tables 1-7 and 1-8 for ARNS transmitters causing interference to UAS receivers.

TABLE 1-5

Minimum separations for UAS ground transmitter and ARNS receiver

	ARNS airborne receiver			**ARNS ground receiver**	
Parameters	**Type 1**	**Type 2**	**Type 3**	**Type 2**	**Type 3**
Interferer transmitter power (dBW)	10.0	10.0	10.0	10.0	10.0
Interferer antenna gain toward victim receiver (dBi)	14.0	14.0	14.0	14.0	14.0
Victim receiver antenna gain toward interferer (dBi)	1.5	3.0	1.5	14.0	10.0
Minimum signal power (dBW)	−120.0	−10.0	−125.0	−113.0	−113.0
Aeronautical safety margin (dB)	6.0	6.0	6.0	6.0	6.0
Protection ratio *C*/*I* (dB)	25.0	17.0	25.0	20.0	25.0
Permissible interference power (dBW)	−151.0	−133.0	−156.0	−139.0	−144.0
Minimum separation distance (km)	464.0	464.0	464.0	170.0	211.0

TABLE 1-6

Minimum separations for UAS airborne transmitter and ARNS receiver

	ARNS airborne receiver			**ARNS ground receiver**	
Parameters	**Type 1**	**Type 2**	**Type 3**	**Type 2**	**Type 3**
Interferer transmitter power (dBW)	10.0	10.0	10.0	10.0	10.0
Interferer antenna gain toward victim receiver (dBi)	−4.0	−4.0	−4.0	−4.0	−4.0
Victim receiver antenna gain toward interferer (dBi)	1.5	3.0	1.5	14.0	10.0
Minimum signal power (dBW)	−120.0	−110.0	−125.0	−113.0	−113.0
Aeronautical safety margin (dB)	6.0	6.0	6.0	6.0	6.0
Protection ratio *C*/*I* (dB)	25.0	17.0	25.0	20.0	25.0
Permissible interference power (dBW)	−151.0	−133.0	−156.0	−139.0	−144.0
Minimum separation distance (km)	903.0	903.0	903.0	464.0	464.0

TABLE 1-7

Minimum separations for ARNS transmitter and UAS airborne receiver

	ARNS ground transmitter			**ARNS airborne transmitter**	
Parameters	**Type 1**	**Type 2**	**Type 3**	**Type 2**	**Type 3**
Interferer transmitter power (dBW)	45.0	39.0	30.0	33.0	33.0
Interferer antenna gain toward victim receiver (dBi)	6.0	15.6	10.0	3.0	1.5
Victim receiver antenna gain toward interferer (dBi)	−4.0	−4.0	−4.0	−4.0	−4.0
Minimum signal power (dBW)	−112.0	−112.0	−112.0	−112.0	−112.0
Aeronautical safety margin (dB)	6.0	6.0	6.0	6.0	6.0
Protection ratio *C/I* (dB)(1)	10.0	10.0	10.0	10.0	10.0
Permissible interference power (dBW)	−128.0	−128.0	−128.0	−128.0	−128.0
Minimum separation distance (km)	464.0	464.0	464.0	903.0	903.0

(1) Assumed for calculations.

TABLE 1-8

Minimum separations for ARNS transmitter and UAS ground receiver

	ARNS ground transmitter			**ARNS airborne transmitter**	
Parameters	**Type 1**	**Type 2**	**Type 3**	**Type 2**	**Type 3**
Interferer transmitter power (dBW)	45.0	39.0	30.0	33.0	33.0
Interferer antenna gain toward victim receiver (dBi)	6.0	15.6	10.0	3.0	1.5
Victim receiver antenna gain toward interferer (dBi)	14.0	14.0	14.0	14.0	14.0
Minimum signal power (dBW)	−112.0	−112.0	−112.0	−112.0	−112.0
Aeronautical safety margin (dB)	6.0	6.0	6.0	6.0	6.0
Protection ratio *C/I* (dB)(1)	−7.0	−7.0	−7.0	−7.0	−7.0
Permissible interference power (dBW)	−111.0	−111.0	−111.0	−111.0	−111.0
Minimum separation distance (km)	160.0	192.0	69.2	464.0	464.0

(1) Assumed for calculations.

Analysis of Tables 1-5 to 1-8 shows that minimum separation distances for interference in air-to-air, ground-to-air and air-to-ground links correspond to line-of-sight distances between receivers and transmitters (903 km for air-to-air links and 464 km for air-to-ground and ground-to-air links). For interference in ground-to-ground links the minimum separation distances are within 69-211 km depending on types of ARNS and UACS interferers.

3 Potential in-band systems

Unlike the existing systems, the potential L-DACS systems do not employ pulsed, low-duty-factor signals-in-space. Thus, they must use other strategies to minimize interference. The basic idea is to use frequencies that are not locally used by the existing systems. Note that even if the frequency separations are sufficient to control interference between different, separated platforms, co-site interference between the systems must also be considered. This will be discussed further below.

Since L-DACS1 is an FDD system, its terminals must use two frequencies sufficiently separated to allow simultaneous transmission and reception. Although the design of L-DACS1 has not been finalized, a preliminary plan is to use the band from 985 to 1 009 MHz for ground transmissions and the band from 1 048 to 1 072 MHz for airborne transmissions. Frequency pairs are separated by 63 MHz, just as they are for DMEs. Because L-DACS1 overlaps X-Mode channels 24X through 48X, it would appear that there is a large potential for interference. The proposal by the L-DACS1 designers is to use gaps in the geographical distribution of DME frequency usage to find acceptable operating locations. This is explained in more detail below.

For L-DACS2, frequency separation is achieved by using carrier frequencies from 960.5 to 975 MHz. The band is well-separated from 1 030 and 1 090 MHz, and it is just below the UAT allocation (978 MHz). It is contained within a band (960 to 977 MHz) that is not governed internationally, and its usage is controlled on a nation-by-nation basis. It has this special status because it is approximately 63 MHz below the protected region around 1 030 MHz, so up link DME frequencies cannot be paired with usable down link frequencies. Thus, it is not commonly used for DME/TACAN. However, frequencies in this band are known to be sometimes allocated to shipborne TACAN units.

Note that L-DACS1 uses a combination of FDD and OFDM, while L-DACS2 employs a combination of TDD and a constant-envelope waveform. It is also possible to use other combinations such as FDD with constant-envelope or TDD with OFDM. For historical reasons, these other combinations did not become L-DACS candidates. The discussion of the two existing candidates should be sufficient to cover all the relevant issues.

3.1 L-DACS1

OFDM was selected as the modulation for L-DACS1 because it is expected to have high spectral efficiency combined with good multipath resistance. It is also attractive because of the possibility of using modern cellular telephone technology, which also uses OFDM. One disadvantage of OFDM is that it is not a constant envelope waveform, so that it requires a rather linear channel (including amplifiers) in which to operate. Linear amplifiers are less efficient than nonlinear ones. Whether this point is important for aeronautical applications needs to be studied.

FDD operation has the potential to provide double the throughput of a TDD system using the same signal-in-space (at the expense of using twice as much spectrum). It also simplifies the issue of frequency reuse since airborne transmissions do not interfere with the reception of ground transmissions. (In the current definition of L-DACS1[15], communication is strictly air-to-ground and ground-to-air. There are no air-to-air links.) In order to succeed, a FDD system must be able to transmit and receive simultaneously on a single platform. To make this possible, the forward and return link frequencies must be separated by a gap that is a significant fraction of either carrier frequency. For L-DACS1 the gap is always 63 MHz. If a typical frequency is taken to be 1 028.5 (average of the highest and lowest frequencies) then the frequency differences are about 6% of the carrier frequencies. Although this is a reasonably substantial gap, it will be a technical challenge to provide enough receive/transmit isolation using filtering and/or diplexing.

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[15] EUROCONTROL, *L-DACS1 System Definition Proposal v0.1*, 29 December 2008.

The L-DACS1 OFDM structure is based on subcarriers spaced by 9.765625 kHz (which is exactly $(102.4\ \mu s)^{-1}$). Fifty of these are modulated, so the total occupied bandwidth is approximately 500 kHz. The signals are centred on channels situated between the DME frequencies, i.e., on XXX.5 MHz. This "inlay" approach may help provide some degree of compatibility between L-DACS1 and DME. The individual subcarriers can be modulated in various ways ranging from QPSK to 64-QAM. When all overhead deductions are accounted for, the data rates that can be sustained vary from about 300 kbit/s to 1.4 Mbit/s in the ground-to-air direction and from about 200 kbit/s to 1.0 Mbit/s in the air-to-ground direction. As might be expected, the higher-rate modes are less robust and have smaller ranges.

The L-DACS1 approach to frequency compatibility[16] is to identify gaps in the geographical distribution of DME frequencies. For example, if in some region it can be shown that reply frequencies 981 and 982 MHz are not used, then there is a possibility that 981.5 MHz could be used for the L-DACS1 ground-to-air link. This is particularly true if the neighbouring frequencies – 980 and 983 MHz – are also not used very close-by. The L-DACS1 designers have done a preliminary study to determine if they could assign L-DACS1 frequencies in a cellular pattern throughout Europe. Although success was not completely achieved when the most conservative protection rules were applied, the overall results were encouraging. This study focused on protecting the reply (uplink) frequencies, because that was considered the worst case scenario for inter-site compatibility; however, interrogation (downlink) compatibility may be an issue in cases where co-site interference is important.

Table 1-9 lists various parameters of L-DACS1 OFDM. An important parameter is the subcarrier spacing. The OFDM symbol duration is inversely proportional to this spacing. Larger symbols result in lower inter-symbol interference. However, closer spacing carriers can result in increased inter-carrier interference due to Doppler shift.

TABLE 1-9

Parameters of L-DACS1 OFDM

Parameter	Value
Channel bandwidth (kHz)	498
Length of Fast Fourier Transform	64
Used subcarriers	50
Subcarrier spacing (kHz)	9.76
OFDM symbol duration with guard time (μs)	120
OFDM symbol duration w/o guard time (μs)	102.4
Overall guard time duration (μs)	17.6

3.2 L-DACS2

L-DACS2[17] is a TDD system, and so does *not* need to use two well-separated frequency bands. Thus, it is able to postulate using a single band within the 960-977 MHz band. Also, the spectrum of its single-carrier, constant-envelope signal-in-space is easier to control, even with non-linear

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[16] EUROCONTROL, *Draft B-AMC Frequency Plan: Report D2*, 27 April 2008.

[17] EUROCONTROL, *L-DACS2 System Definition Proposal: Deliverable D1 v0.34*, 11 March 2009.

amplification. This may simplify the problem of controlling interference with nearby systems. (The highest proposed L-DACS2 frequency is 975 MHz, which is only 3 MHz from the UAT frequency.)

The modulation chosen for L-DACS2 is Gaussian minimum-shift keying (GMSK) with a modulation rate of 270.833 kbit/s and with BT = 0.3. The bit rate cited is the raw channel bit rate and does not include any deductions for such overhead factors as error correction, guard times or net management; so all that can be said at this point is that the user data rate per channel will be considerably less than 270 kbit/s. The channels used by L-DACS2 are separated by 200 kHz.

Note that the channel spacing is smaller than the modulation rate; this is possible because of the spectral properties of GMSK. The designers of L-DACS2 state that 2 or more channels can be combined if some link has a throughput requirement larger than what can be provided by a single channel.

The development of the L-DACS2 is not as far along as that of L-DACS1 due to the sequencing of contractual arrangements. Therefore, various compatibility issues that will eventually need to be addressed have thus far remained unstudied. Similar to operational L-DACS1 issue, co-site interference issues will be of particular interest. For example, it may be difficult for a high duty factor transmission at 975 MHz to avoid causing unacceptable interference to a nearby (in frequency) victim such as a UAT receiver at 978 MHz or an airborne DME receiver at 980 MHz. If the top frequency of L-DACS2 needs to be lower than 975 MHz, there will be a corresponding decrease in overall system throughput.

4 Compatibility with GNSS Systems above 1 164 MHz

The centre frequency of the GPS L5 and Galileo E5a signal is 1 176.45 MHz. The centre frequency for Galileo E5b is 1 207.14 MHz. To protect radionavigation-satellite service (RNSS) systems in the 1164–1215 MHz band, recent ITU-R sharing studies have identified a need to limit the EIRPs of AM(R)S transmitters operating between 1 146.5 and 1 164 MHz. The maximum EIRPs of ground stations must decrease linearly from 34 to –62.9 dBW, and those of airborne stations must decrease linearly from 37.75 to –59.2 dBW, as frequency increases within that range. Table 1-10 shows the limits as they would apply in the 1 151-1 156 MHz frequency range, which has been considered for UAS CNPC because it is virtually unoccupied.

TABLE 1-10

Maximum EIRPs of 1 151-1 156 MHz AM(R)S transmitters

Centre frequency (MHz)		1 151	1 152	1 153	1 154	1 155	1 156
EIRP Limit (dBm)	Ground	38.9	33.4	27.8	22.3	16.8	11.3
	Airborne	42.6	37.1	31.6	26.0	20.5	15.0

5 Summary of 960-1 164 MHz sub-bands usages

The suitability of various 960-1 164 MHz sub-bands for UAS control links is briefly detailed below.

– The 960-977 MHz sub-band is used by shipborne TACAN and by DME on a national basis or land-based TACAN, and appears suitable for UAS CNPC, at least in areas where TACAN is not in use. It has also to be noted that this sub-band is foreseen for future aeronautical communication system (LDACS2).

- 978 MHz is the only frequency used by UAT and is also used for DME thus does not seem suitable for use by a new UAS control link service. It has also to be noted that this channel within the sub-band foreseen for future aeronautical communication system (LDACS1).
- The 979-1 020 MHz sub-band appears unattractive for UAS CNPC because of the poor selectivity of many DME receivers and their resultant inability to tolerate undesired signals from CNPC transmitters on the first adjacent channels. It has also to be noted that this channel within the sub-band foreseen for future aeronautical communication system (LDACS1).
- The 1 021-1 039 MHz sub-band would be very problematic for UAS CNPC use, particularly for UA equipped with 1 030-1 090 MHz transponders, since airborne co-site interference could result.
- The 1 040-1 080 MHz sub-band is heavily used by airborne as well as ground-based DME and TACAN transmitters and thus presents an interference environment that would be too unpredictable for reliable UAS CNPC use. It has also to be noted that this sub-band is foreseen for future aeronautical communication system (LDACS1).
- The 1 081-1 099 MHz sub-band is problematic for UAS CNPC use, because of the threat of co-site interference aboard UA equipped with 1 030-1 090 MHz transponders.
- The 1 100-1 150 MHz sub-band appears no more suitable for UAS control links than the 1 040-1 080 MHz sub-band. It has also to be noted that this sub-band is foreseen for future aeronautical communication system (LDACS1).
- The 1 151-1 156 MHz sub-band should be considered for UAS CNPC use because it is virtually unused by DME and TACAN, to avoid undesired interactions between those systems and transponders at 1 090 MHz. However, EIRP limits intended to protect RNSS systems above 1 164 MHz could drastically affect the distances over which CNPC links could operate in that sub-band, particularly near its upper end. It has also to be noted that this sub-band is foreseen for future aeronautical communication system (LDACS1).
- The 1 157-1 164 MHz sub-band is too close to the 1 164-1 215 MHz RNSS sub-band, for use by UAS CNPC. It has also to be noted that this channel within this sub-band is foreseen for future aeronautical communication system (LDACS1).
- In the 960-1 164 MHz band compatibility of UAS CNPC with non-ICAO ARNS systems operating in countries listed in RR No. 5.312 is hardly feasible. In most cases separation distances beyond LoS are required in order to provide compatibility between those systems. ARNS receivers need to be protected through sufficient frequency separation and/or distance separation.

6 Possible CNPC system architecture

A possible system architecture for providing UAS CNPC in a portion of the 960-1 164 MHz band is described below. In the following discussion the 960-1 164 MHz band will often be referred to as “1-GHz band” in accordance with widespread practice.

6.1 Preliminary design considerations

It will be assumed here that a 1-GHz band data link will be needed by all sizes of UA. The smaller UA types have very strict SWAP constraints, will not carry weather radar, and will probably not carry video cameras devoted to flying the UA. Since video constitutes the largest CNPC throughput requirement identified in Report ITU-R M.2171 and weather radar the second largest, this means that the maximum throughput required by any individual UA could be quite small. It will be assumed that any high-throughput requirement (i.e., video or downlinked weather-radar data) for larger UA will be addressed using a link in some other band, such as 5 030-5 091 MHz. That other band could also provide fully redundant backup for the lower-throughput 1-GHz band links described here.

Second, due to the limited size of UA, particularly the smaller types, there will be limited isolation between transmit and receive antennas for the various systems on board the UA. Thus, co-site issues will be very important if the UA carries any other systems that include airborne receivers operating in the same band. Some of the potential 1-GHz band "victim" receivers include UAT (978 MHz), SSR (1 030 MHz), TCAS and 1 090 Extended Squitter (1 090 MHz), GNSS (above 1 164 MHz) and DME (at various multiples of 1 MHz throughout the band). A CNPC transmitter can affect any of these systems in two ways. The transmitter can have a noise floor that injects power into the victim receiver IF filter. Also, the main lobe of the CNPC transmission can cause desensitization of the front ends of the victim receivers. Such issues (if any) can be addressed by adding appropriate filters (which add their own potential SWAP problems). A possible answer is to limit the duty factor of the airborne CNPC transmitter. This appears to be the method adopted by *all* of the previous occupants of the 1-GHz band. Low duty factor might be a viable option if the necessary throughput were small, as discussed in the previous paragraph. Unfortunately, this approach may not be possible due to repetition-rate requirements discussed below.

Third, because of the limited isolation discussed in the previous paragraph, it may be difficult to implement a CNPC system that has a Frequency Division Duplex (FDD) architecture requiring simultaneous transmission and reception. This may rule out the adoption of certain developmental systems such as L-DACS1 (which uses FDD); nevertheless, certain attractive aspects of L-DACS1 (such as the use of OFDM) may be adaptable to the CNPC system.

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

Based on these considerations a representative 1-GHz band design will be postulated in the following sections. The design is not necessarily meant to be a candidate for the future system. Instead, it is meant to include just enough detail to allow the determination of various performance measures.

6.2 Statistical considerations

Using the given UAS densities from the tables in Report ITU-R M.2171, we can determine that a hexagonal sector with radius 127 km (about 69 nmi) would have an average of 1.84 large UAS and 8.17 medium UAS, for an average total of 10.01 medium and large UAS combined. (Cell radius is defined here as the radius of the circle circumscribing a perfect hexagonal cell.)

We can also assume that the actual number of users of any type in any given cell follows a Poisson distribution. (We are assuming that the long-time geographical distribution of UA is constant and that the fluctuations are purely statistical. This is clearly only an approximation.) The Poisson equation is $P(n) = e^{-N} (N^n / n!)$, with N being the average number. The probability of the total number of cell occupants exceeding 20 is 0.0016, which means that if the resources allocated to the cell provide for up to 20 users, there could be blockage in 0.16% of the cells (or in a single cell 0.16% of the time).

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

6.3 Detailed designs

In this section we investigate the feasibility of providing terrestrial LoS control communications for UAS in the 960-1 164 MHz band. The purpose of the investigation is to assess whether or not it is possible to meet the preliminary system requirements found in Report ITU-R M.2171, and, if so, how much spectrum is required. Prior work on estimating frequency requirements has already been done, but this effort attempts to provide another level of detail by postulating a particular system architecture. This allows for a somewhat more detailed assessment of system overhead requirements. The proposed design should be considered as an existence proof, and there is no implied claim that the solution is optimal.

For all UAS types there is a requirement to support a channel access rate (or "repetition rate") of at least 20 Hz. This rapid rate is necessary to support operations involving manual, real-time control. The bandwidth requirements are abstracted from the *loading* requirements found in Report ITU-R M.2171 Table 13. Report ITU-R M.2171 *throughput* requirements (which include allowances for overheads) are not used, since the analysis below attempts to estimate the overheads more accurately based on a specific example. The requirements vary based on the size of the UAS, on the phase of flight, and on whether the channel is uplink or downlink. In the table below, the worst-case phase-of-flight requirements are listed. (Note that the worst case is typically the "terminal arrival" phase, while the aircraft is landing.) As explained above, video and downlinked weather-radar data are assumed not to be carried in this 1-GHz band system and so are not considered in Table 1-11.

TABLE 1-11

Assumed loading requirements for non-video, non-weather data

UA Type	Up (kbit/s)	Down (kbit/s)
Medium/large	7.0	13.6
Small	2.5	4.0

6.3.1 Medium/large UAS system design

This section contains a description of a possible design for a terrestrial CNPC system operating in the 1-GHz band from 960 to 1 164 MHz to support medium/large UAS. The following capabilities are provided:

– Every UA is assigned downlink time slots supporting an information data rate of 22.5 kbit/s. (Requirement = 13.6 kbit/s).

– Every UA is assigned uplink time slots supporting an information data rate of 7.5 kbit/s. (Requirement = 7 kbit/s).

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

It is assumed that the sectors are sized so that the average number of UA in any individual sector is 10; so the cell radius is 127 km (about 69 nautical miles). In the architecture each UAS gets the use of a 37.5 kHz wide control channel. The system is designed so that full duplex operation (simultaneous transmission and reception on a single aircraft) is not required.

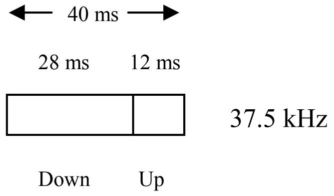
Finally, it is assumed that the physical location of the control station antenna for each UA can be anywhere within its operational sector. This does not preclude scenarios in which pilots are connected to their UA via a centralized radio antenna, but that is not required. This means it is ***not***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

6.3.1.1 Link layer description

A medium/large UA channel timing diagram appears in Fig. 1-7. In a 40 ms cycle, each user on a frequency channel has access to a 28 ms downlink time slot and a 12 ms uplink time slot. Assuming 4 ms of overhead (for guard time, synchronization, header, switching, encryption, etc.) per time slot, the downlink information rate is (24/40) x 37.5 kbit/s = 22.5 kbit/s, and the uplink information rate is (8/40) x 37.5 kbit/s = 7.5 kbit/s. This presumes that the signalling rate is 37.5 kbaud, the modulation is QPSK and the error correction code rate is 0.5. It would take 20 of these 37.5 kHz channels to support 20 UA. Note that the repetition rate of this scheme is 25 Hz.

FIGURE 1-7

Medium/large UAS channel



6.3.1.2 Spectrum requirements

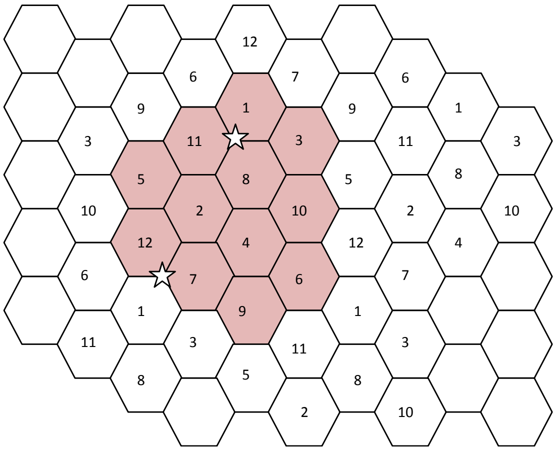
The spectrum requirements are based on at least two factors: the amount of bandwidth needed in a single sector, and the separation required between sectors to allow frequency reuse. The separation needed is related to the cochannel interference tolerance of the system's signal-in-space. This is usually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

The amount of spectrum needed to support 20 users in a region is 20 x 37.5 kHz for the basic channels – for a total of 0.75 MHz. If we assume that the channels are 37.5 kHz and that the channel spacing is 37.5 kHz, then there can be considerable adjacent channel interference. This leads to a requirement that adjacent frequency channels not be assigned to neighbouring sectors.

The smallest cell pattern for which this is possible is K = 12. With K = 12 the total bandwidth requirement is 12 × 0.75 MHz = 9 MHz.

FIGURE 1-8

K = 12 pattern with adjacent-channel protection



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

6.3.1.3 Medium/large UAS hardware requirements

In the medium/large UAS architecture described above, a single UA would need only one relatively narrow-band transceiver. A centralized ground station would need up to 20 narrow-band transceivers to support all of the simultaneous downlink and uplink signals. However, a ground station devoted to a single UA would need only one transceiver.

An alternative arrangement that requires less ground hardware may be feasible if the signal modulation is OFDM. It would be possible to assemble all the channels into a single 750-kHz-wide channel. The 750 kHz channel would comprise 20L subcarriers. (The value of L would be chosen based on the characteristics of the communications channel.) On the other hand, a UAS that only needed basic information exchange would be allocated an L subcarrier block (yielding 37.5 kHz). In each sector, the assortment of users would be assigned channels via some centralized authority in order to maximize efficiency. If this method is feasible, then each UA would require just one transceiver. A centralized ground station servicing a fully loaded net also would need only one OFDM transceiver. The centralized ground station transceiver would need to be able to process all 20L subcarriers, while a ground station servicing a single medium/large UAS would need to process only L channels.

6.3.1.4 Medium/large UAS link budget

A budget for a medium/large UAS link at a range equal to the 127-km (69-nmi) cell radius is shown in Table 1-12. A UA at 5 500 m (18 000 feet) above ground level (AGL) and a ground station with its antenna at the top of a 30-metre (100-foot) tower are assumed in the budget. The estimated ground-antenna gain of 8 dBi can be achieved with an array of a few stacked dipoles, resulting in a flattened omnidirectional pattern.

TABLE 1-12

Link budget for medium/large UAS channel at 127-km (69-nmi) range

Parameter	Uplink	Downlink
Transmitter power (dBm) (10 W)	40	40
Transmitting antenna gain (dBi)	8	5
Transmitter cable loss (dB)	1	1
Transmitter e.i.r.p. (dBm)	47	44
Free-space path loss (970 MHz, 127 km (69 nmi)) (dB)	134	134
Receiving antenna gain (dBi)	5	8
Receiver cable loss (dB)	1	1(1)
Received signal power (dBm)	–83	–83
Thermal noise at 290 K (dBm/Hz)	–174	–174
Receiver noise figure (dB)	2	2
Receiver bandwidth (dBHz) (37.5 kHz)	46	46
Receiver noise power (dBm)	–126	–126
Signal-to-noise ratio (SNR) (dB)	43	43
Theoretical SNR for BER = 10^{-6} (dB)(2)	4	4
Implementation loss margin (dB)	2	2
Required SNR (dB)	6	6
Aviation safety margin (dB)	6	6
Margin (dB)(3)	31	31

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

(2) QPSK with 1/2 – rate coding (concatenated Reed-Solomon and convolutional).

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

It should be borne in mind that the OFDM waveform requires a relatively linear transceiver system, which often results in the need to reduce amplifier efficiency by “backing-off” the amplifier gain. This can have a negative impact on SWAP and heat dissipation. For instance, the postulated 10 W of transmitter power might need to be generated by a transmitter amplifier rated at about 4 dB higher, i.e., 25 W.

Table 1-13 shows an alternative medium/large UAS link budget that would be applicable if the UA were flying 300 m (1 000 feet) AGL and 46 km (25 nmi) from its ground station.

TABLE 1-13

Link budget for medium/large UAS channel along 46 km (25-nmi) path

Parameter	Uplink	Downlink
Transmitter power (dBm) (10 W)	40	40
Transmitting antenna gain (dBi)	8	5
Transmitter cable loss (dB)	1	1
Transmitter e.i.r.p. (dBm)	47	44
Free-space path loss (970 MHz, 46 km (25 nmi)) (dB)	125	125
Receiving antenna gain (dBi)	5	8
Receiver cable loss (dB)	1	1(1)
Received signal power (dBm)	–74	–74
Thermal noise at 290 K (dBm/Hz)	–174	–174
Receiver noise figure (dB)	2	2
Receiver bandwidth (dBHz) (37.5 kHz)	46	46
Receiver noise power (dBm)	–126	–126
Signal-to-noise ratio (SNR) (dB)	52	52
Theoretical SNR for BER = 10^{-6} (dB)(2)	4	4
Implementation loss margin (dB)	2	2
Required SNR (dB)	6	6
Aviation safety margin (dB)	6	6
Margin (dB)(3)	40	40

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

(2) QPSK with 1/2 – rate coding (concatenated Reed-Solomon and convolutional).

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

6.3.2 Small UAS system design

This section describes a possible design for a terrestrial CNPC system operating in the 1-GHz band from 960 to 1 164 MHz to support small UAS. The following capabilities could be provided:

– Every UA is assigned downlink time slots supporting an information data rate of 7.5 kbit/s. (Requirement = 4 kbit/s.)

– Every UA is assigned uplink time slots supporting an information data rate of 2.5 kbit/s. (Requirement = 2.5 kbit/s.)

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

As with medium/large UAS, it is assumed that the sectors are sized so that there are, on average, 10 participating UAS in any individual sector. Based on the assumed densities of small UAS and the assumption that only half of them will participate (see Tables 35 and 36 of Report ITU-R M.2171), this corresponds to a cell radius of about 98 km (53 nmi). In the architecture, each participating UAS gets the use of a 12.5-kHz-wide control channel. This is less than the 37.5 kHz allotted to each Medium/Large UAS because small UAS traffic demands are lower, as documented in Report ITU-R M.2171.

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

6.3.2.1 Link layer description

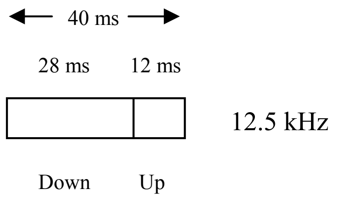
A small UAS channel timing diagram appears in Fig. 1-9. With less traffic to carry than its medium/large UAS counterpart, the small UAS frequency channel occupies only 12.5 instead of 37.5 kHz. In a 40-ms cycle, each user on a channel has access to a 28 ms downlink time slot and a 12 ms uplink time slot. Assuming 4 ms of overhead (for guard time, synchronization, header, switching, encryption, etc.) per time slot, the downlink information rate is:

(24/40) × 12.5 kbit/s = 7.5 kbit/s, and the uplink information rate is (8/40) × 12.5 kbit/s = 2.5 kbit/s.

This presumes that the signalling rate is 12.5 kbaud, the modulation is QPSK and the error correction code rate is 0.5. It would take 20 of these 12.5 kHz channels to support 20 UA. The access (repetition) rate of this scheme is 25 Hz.

FIGURE 1-9

Small UAS channel



6.3.2.2 Spectrum requirements

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

For small UAS a better approach would be to use a K = 4 pattern. For this pattern the minimum reuse distance is 170 km (92 nautical miles), which corresponds to the line-of-sight distance for a UA at 1 300 m (4 200 feet) and a ground antenna mounted on a 30-metre (100-foot) tower. Note that a K = 3 pattern is also a possibility; however, its minimum reuse distance is only 98 km (53 nmi), corresponding to a UA altitude of only 335 m (1 100 feet), with a 30-metre (100-foot) ground antenna tower. For either K = 3 or K = 4, in order to provide adjacent channel protection, there would need to be guard bands between channels. If we assume that the channel spacing is 17.5 kHz, then the required bandwidth using a K = 4 pattern would be:

$$4 \times 20 \times 17.5 \text{ kHz} = 1.4 \text{ MHz}.$$

Since the aggregate medium/large UAS spectral requirement was earlier shown to be 9 MHz, this means that a total of 9.0 + 1.4 = 10.4 MHz would suffice to meet in the 1-GHz band the spectral requirements of large, medium, and small UAS, except for video, downlinked weather-radar data, and redundant backup required for the control link, as described in Report ITU-R M.2171.

6.3.2.3 Small UAS hardware requirements

The required small UAS equipment would include only one transceiver with a 12.5 kHz bandwidth. As with medium/large UAS, an arrangement that minimizes ground station hardware may be possible if the signal modulation is OFDM. Using orthogonal frequency-division multiple access (OFDMA) it would be possible to assemble all 20 channels into a single 250-kHz-wide channel comprising 20M subcarriers. Each user pair would be assigned M subcarriers. (The value of M would be chosen based on the characteristics of the communications channel.) If this method is feasible, then each UA would still require just one transceiver (using M subcarriers). A centralized ground station servicing a fully loaded net also would need only one OFDM transceiver (utilizing 20M subcarriers). Note that if M = 1 is found to be a suitable value, the transceiver for small UAS could be a very simple, single-carrier system.

6.3.2.4 Small UAS link budget

A budget for an small UAS link is shown in Table 1-14 for a link range of 46 km (25 nautical miles), a UA altitude of 300 m (1 000 feet), and a ground station with its antenna at the top of a 30-metre (100-foot) tower. Since the OFDM waveform requires a relatively linear transceiver system in which the amplifier gain is backed off, thereby reducing amplifier efficiency, the postulated one watt of transmitter power might need to be generated by a transmitter amplifier rated at about 4 dB higher, i.e., 2.5 W.

TABLE 1-14

Link budget for small UAS channel along 46-km (25-nmi) path

Parameter	Uplink	Downlink
Transmitter power (dBm) (1 W)	30	30
Transmitting antenna gain (dBi)	8	5
Transmitter cable loss (dB)	1	1
Transmitter e.i.r.p. (dBm)	37	34
Free-space path loss (970 MHz, 46 km (25 nmi)) (dB)	125	125
Receiving antenna gain (dBi)	5	8
Receiver cable loss (dB)	1	1(1)
Received signal power (dBm)	–84	–84
Thermal noise at 290 K (dBm/Hz)	–174	–174
Receiver noise figure (dB)	2	2
Receiver bandwidth (dBHz) (12.5 kHz)	41	41
Receiver noise power (dBm)	–131	–131
Signal-to-noise ratio (SNR) (dB)	47	47
Theoretical SNR for BER = 10^{-6} (dB)(2)	4	4
Implementation loss margin (dB)	2	2

TABLE 1-14 (*end*)

Parameter	Uplink	Downlink
Required SNR (dB)	6	6
Aviation safety margin (dB)	6	6
Margin (dB)(3)	35	35

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

(2) QPSK with 1/2 – rate coding (concatenated Reed-Solomon and convolutional).

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

7 Conclusion

1. The results of studies conducted in ITU-R show that sharing between ARNS and UAS CNPC systems operating in the 960-1 164 MHz frequency band is only feasible where geographical and frequency separation is used, due to the fact that the shared operation could only be implemented beyond LoS.
2. Geographical separation of ARNS and AM(R)S systems are limited in certain areas, particularly in those with high densities of ARNS stations.
3. In some countries, another sub-band, 1 151-1 156 MHz, may also be usable but has EIRP limits that could restrict its CNPC use to short-range links.
4. A communications system capable of meeting all non-backup CNPC requirements of medium and large UAS except for downlinking of video and airborne weather-radar data can be implemented within 9 MHz in the 960-1 164 MHz band in some countries.
5. The non-backup CNPC requirements of small UAS would require an additional 1.4 MHz in the 960-1 164 MHz band.
6. Because of the lack of available spectrum in the 960-1 164 MHz band, requirements for backup links, video, and airborne weather-radar data downlinking cannot be met in this band alone, the spectrum requirement needed for terrestrial component will therefore need to be addressed in several different bands.
7. Restrictions on the usage of the band 960-1 164 MHz have to be taken into account in particular in the lower adjacent band with the mobile service which is not studied in this report and in the upper adjacent band with regard of RNSS
8. In the 960-1 164 MHz band compatibility of UAS CNPC with non-ICAO ARNS systems operating in some countries, including countries listed in RR No. 5.312 is hardly feasible. In most cases separation distances beyond line-of-sight are required in order to provide compatibility between those systems.

Annex 2

Sharing in the band 5 030-5 091 MHz between the international standard microwave landing system (MLS) and a satellite system of the aeronautical mobile-satellite (route) service (AMS(R)S)

1 Introduction

The band 5 030-5 091 MHz is proposed, under WRC-12 Agenda item 1.3, as a candidate band for satellite systems providing UAS with safety communications as required for their integration in non segregated airspaces.

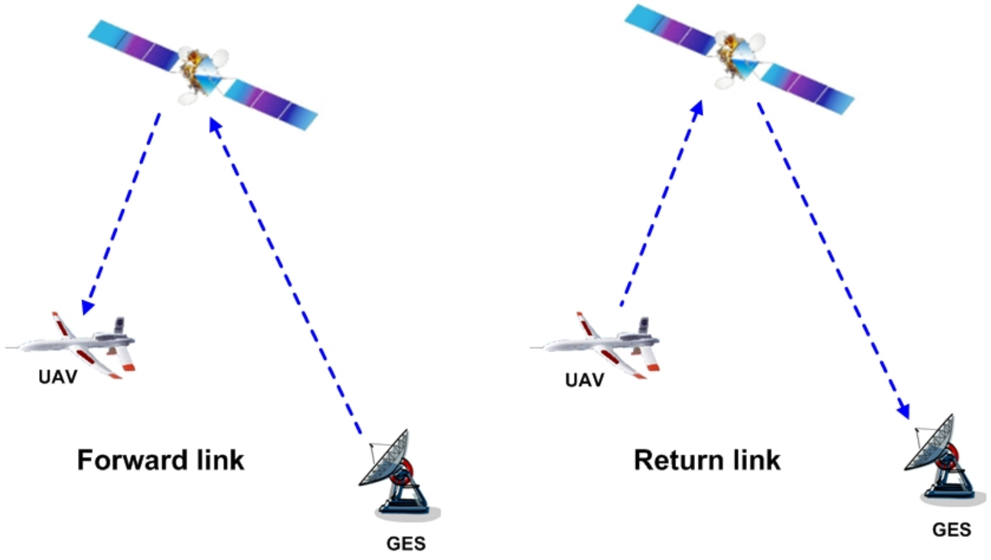
However, due to MLS precedence in that band, this could be achieved only if AMS(R)S systems are appropriately designed in order to ensure compatibility with foreseen MLS deployment.

The aim of this document is to provide material for analysis of the sharing situation between AMS(R)S systems and MLS in the band 5 030-5 091 MHz.

2 Definition

FIGURE 2-1

Definition – forward link and return link



3 Microwave landing system

3.1 General architecture

The microwave landing system (MLS) is a precision approach and landing guidance system, which provides position information and various ground-to-air data. It was originally designed to replace or supplement the instrument landing system (ILS). Following figures present the general architecture. Azimuth and elevation signals are transmitted preceded by a DPSK modulated preamble. MLS transmitters are installed on runways while MLS receivers are on board aircrafts.

FIGURE 2-2

MLS principle (1/2)

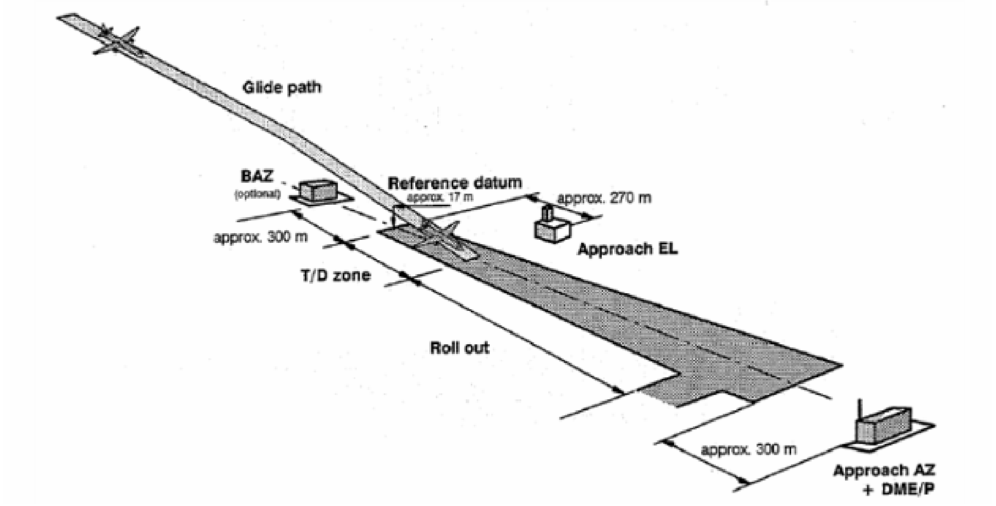
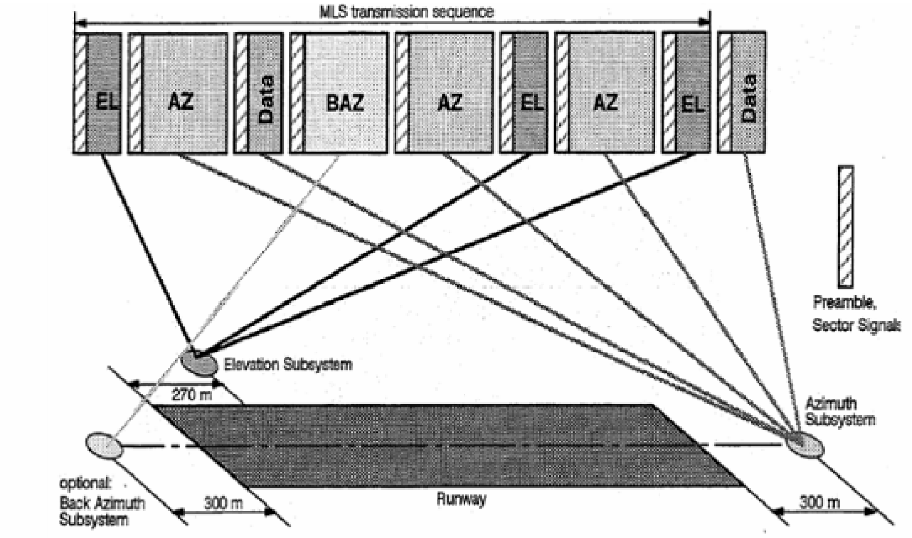


FIGURE 2-3

MLS principle (2/2)



MLS system provides coverage within an azimuth (+40°, –40°, possible extension to +60°, –60°) and an elevation (0.9°, 15°). Moreover, the MLS AZ coverage area is limited longitudinally to 41.7 km (22.5 nmi) and vertically to 6 000 m (20 000 ft). The back azimuth coverage is limited longitudinally to 18.5 km (10 nmi) from the opposite threshold and vertically to 3 000 m (10 000 ft). This is illustrated on following figures, which give a horizontal view and a vertical view of the MLS coverage area.

FIGURE 2-4

MLS coverage area (horizontal view)

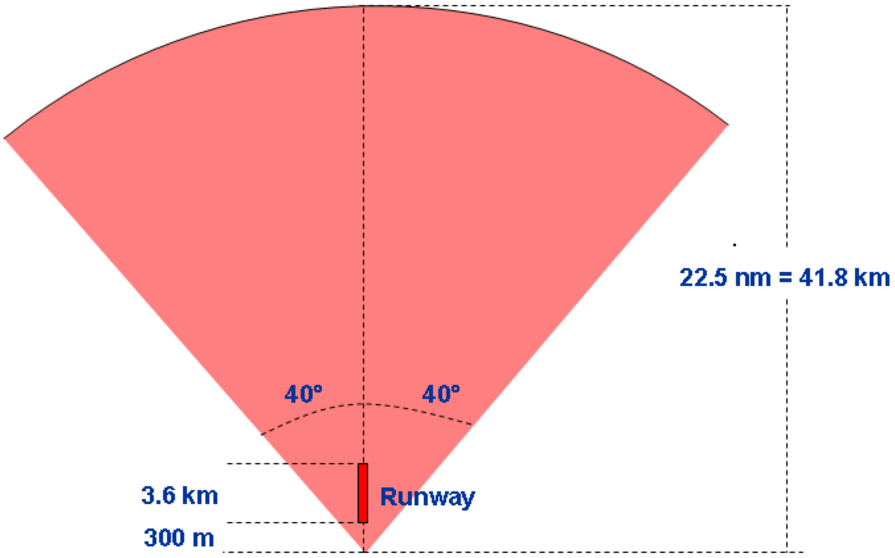
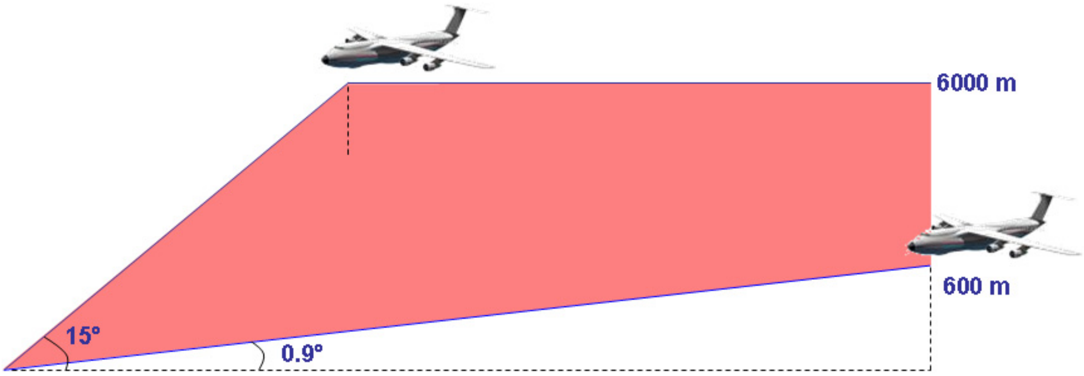


FIGURE 2-5

MLS coverage area (vertical view)



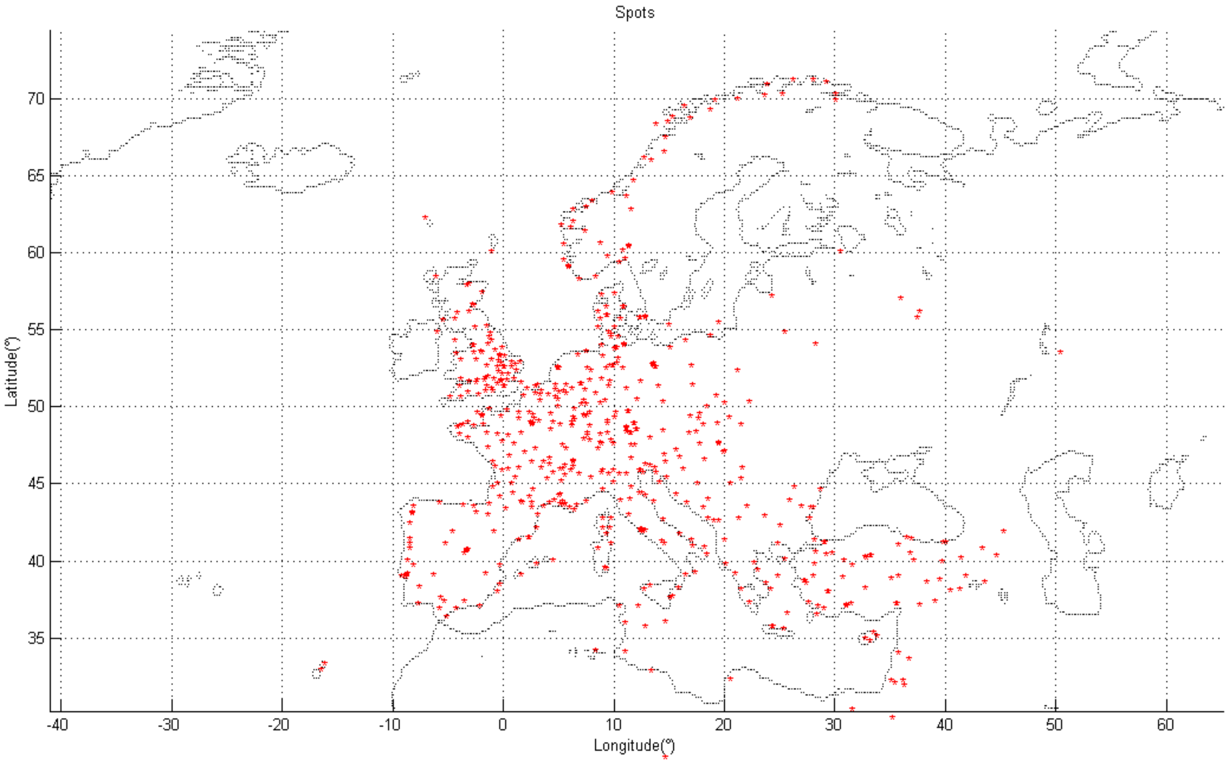
As of today, MLS system is operational on one airport in one European country. Four runways directions are equipped, two being used simultaneously.

The ICAO database gives a frequency plan for about 800 MLS assignments over Europe. It should be noted that NSP SSG indicated that the consideration of these 800 assignments may pose an overly restrictive assumption in MLS sharing studies, since the latest responses to a state-letter by the ICAO Paris office indicates that there is a lower need for MLS stations in Europe (around 400).

However, as no frequency plan is available for these requirements, for the time being sharing studies are based on this worst-case scenario. Let us note finally that each MLS channel is paired with a DME channel and for a limited amount of channels with an ILS/VOR VHF frequency.

FIGURE 2-6

MLS transmitters (ICAO database)

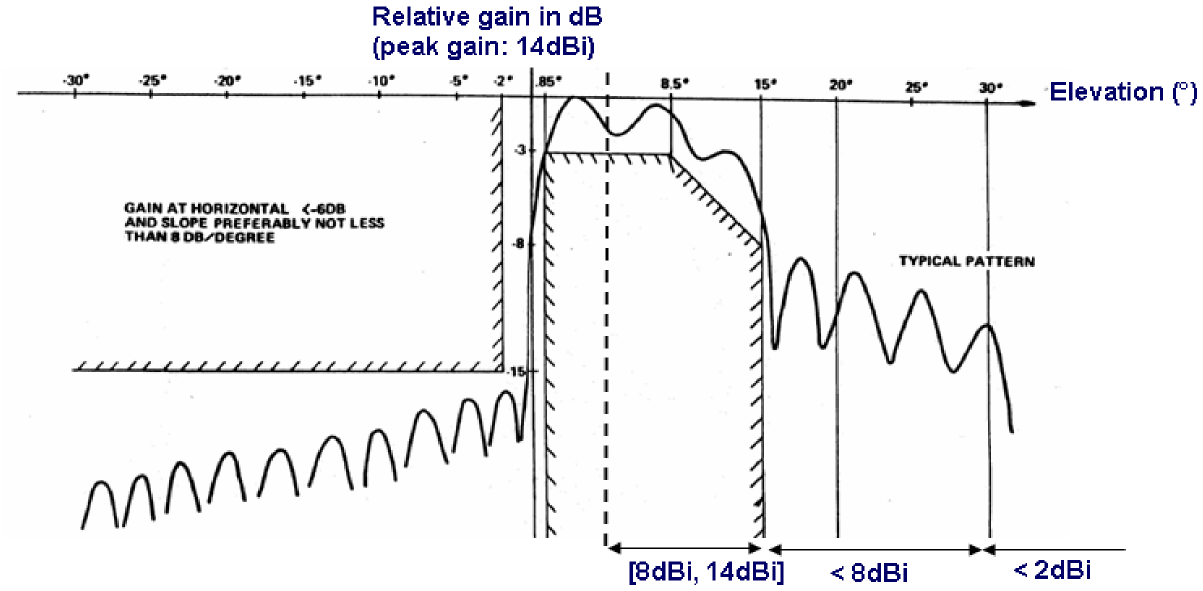


3.2 MLS transmitter

As in ICAO SARPs Annex 10 [1], MLS transmitter output power is considered to be 43 dBm (20W). The elevation antenna is depicted below. The maximum gain is 14 dBi and gets down to 8 dBi for a 15° elevation. Let us note finally that a vertical polarization is used.

FIGURE 2-7

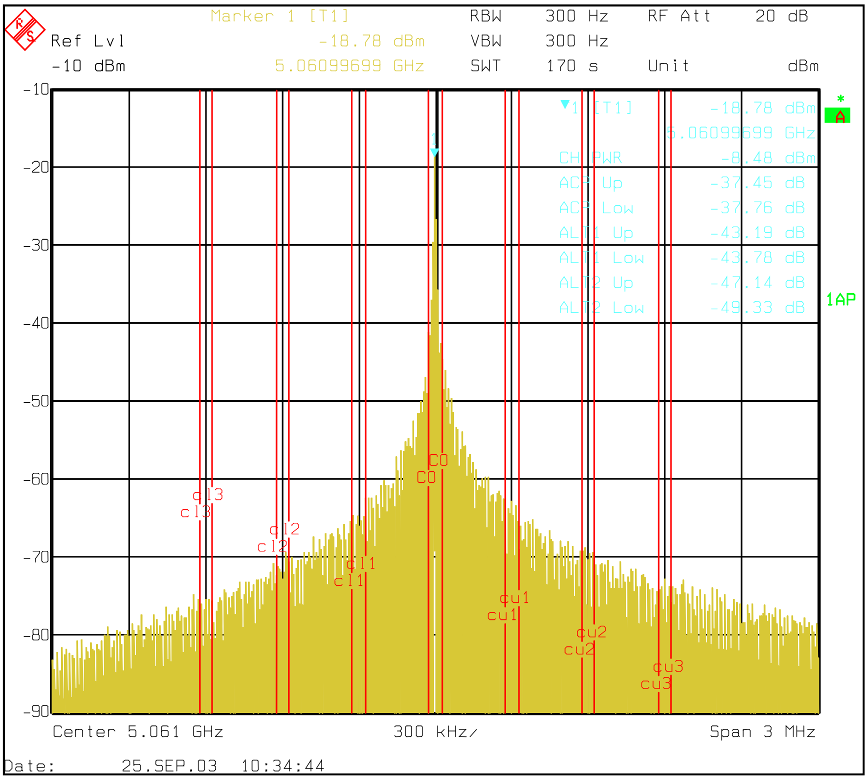
MLS Tx antenna pattern



MLS transmitters generate out-of-band (OoB) emissions. This is illustrated on Fig. 2-8, which presents the measurements carried out on a typical MLS transmitter by a European civil aviation authority (300 Hz resolution bandwidth).

FIGURE 2-8

MLS emission spectrum



From recent ICAO documentation, the MLS out-of-band power at f_Δ kHz from the MLS centre frequency and measured over a bandwidth BW can be analytically modelled as follows:

$$P(f_\Delta, Bw) = P_{Total} \times Rolloff\,(f_\Delta, Bw) \approx P_{Total} \times \frac{1}{2\pi^2} \frac{f_d \cdot Bw}{f_\Delta^2}$$

with:

P_{Total}: total MLS power, typically 43 dBm;

Bw: bandwidth of interest;

f_d: MLS DPSK carrier bandwidth, i.e., modulation rate (15.625 kHz);

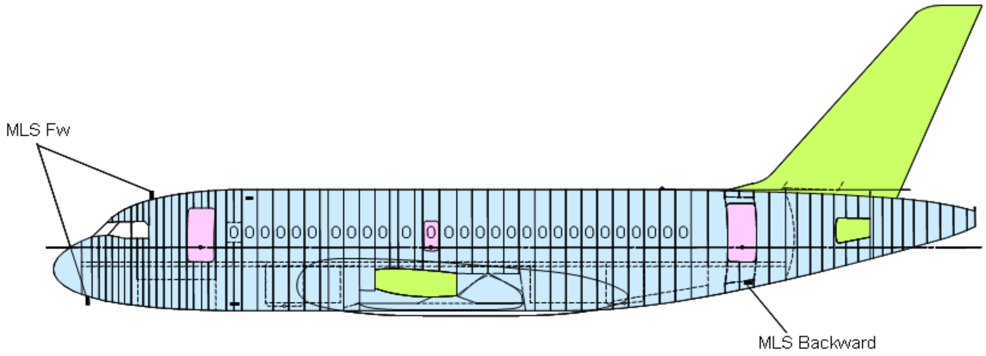
f_Δ: frequency offset from the MLS centre frequency.

3.3 MLS receiver

Figure 2-9 represents the MLS antennas installed on board an actual aircraft. Let us note that, several MLS antennas may be embarked. This has to be considered when assessing interactions between a UA and an MLS receiver.

FIGURE 2-9

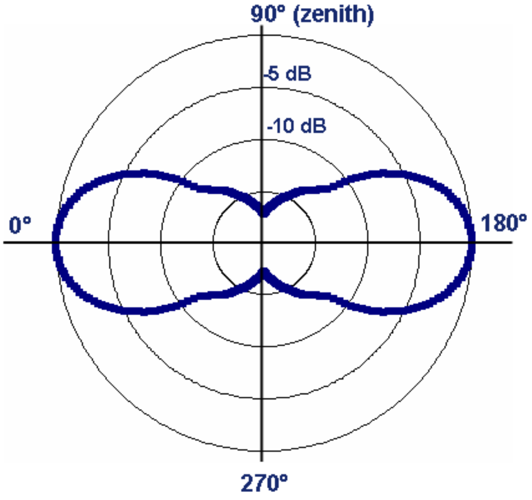
MLS antenna positions



The azimuth antenna pattern of the MLS receiver is supposed to be omnidirectional, which is a worst case approach. The elevation antenna pattern that is considered is depicted below. It is based on generic Recommendation ITU-R F.1336-2 and on typical MLS Rx antennas characteristics (e.g., a 40° elevation beamwidth is considered). Let us note as well that a vertical polarization is used.

FIGURE 2-10

MLS Rx antenna pattern



As specified in reference [1], MLS receiver minimum required sensitivity is –100 dBm for DPSK signals (at receiver input). Actual MLS receiver designs achieve a sensitivity of –107 dBm. This sensitivity is computed as follows:

TABLE 2-1

MLS receiver sensitivity

Noise power in 150 kHz (dBm)	–122.0
Noise figure (dB)	11.0
Minimum SNR (dB)	5.0
Aeronautical margin (dB)	6.0
Receiver minimum sensitivity at receiver input (dBm)	–100.0

3.4 Protection criteria

In order not to cause harmful interference to the MLS operating in the band 5 030-5 091 MHz, the aggregate power flux-density received over 150 kHz by a MLS receiver in a MLS coverage area at its antenna input and at its centre frequency shall not exceed –124.5 dBW/m^2.

This requirement translates into −130 dBm/150 kHz, using the conversion rule given in reference [1] (Attachment G, § 2.6.2.1): Power into isotropic antenna (dBm) = Power density (dBW/m^2) – 5.5 dB. This power level is afterwards referenced as the in-band power level.

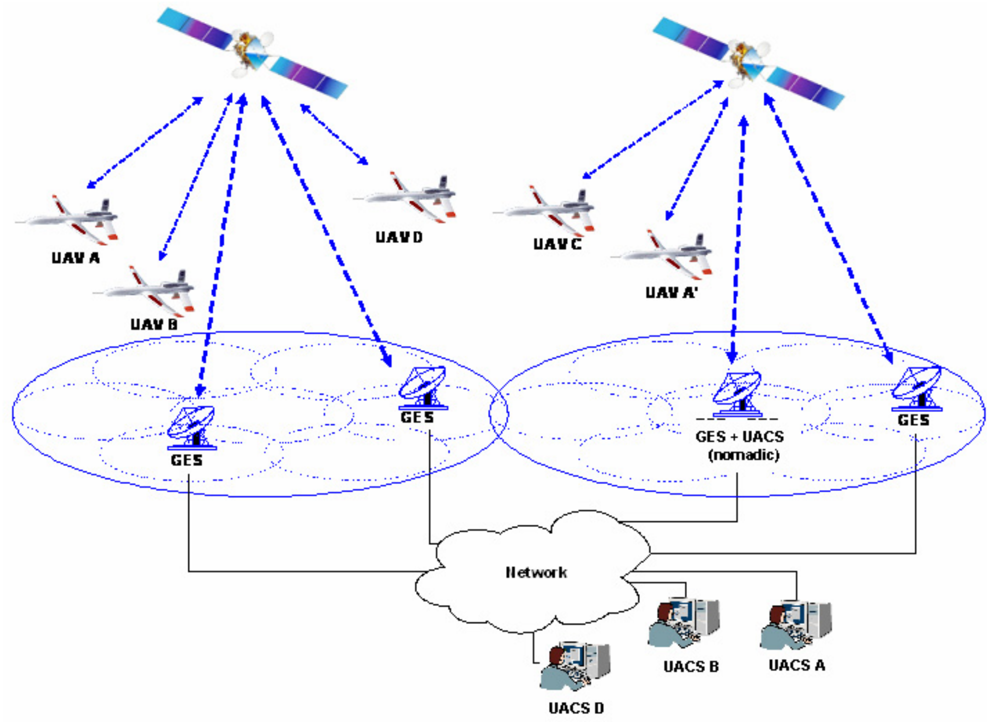
4 Possible AMS(R)S system

4.1 General architecture

Figure 2-11 presents the high-level architecture of a possible AMS(R)S system. UA control stations (UACS) can be collocated with a dedicated ground earth station (GES) or connected to a centralized GES through a terrestrial network. As a baseline, the link between the GES and the satellite, i.e., the feeder link, also uses the 5 030-5 091 GHz band.

FIGURE 2-11

AMS(R)S architecture



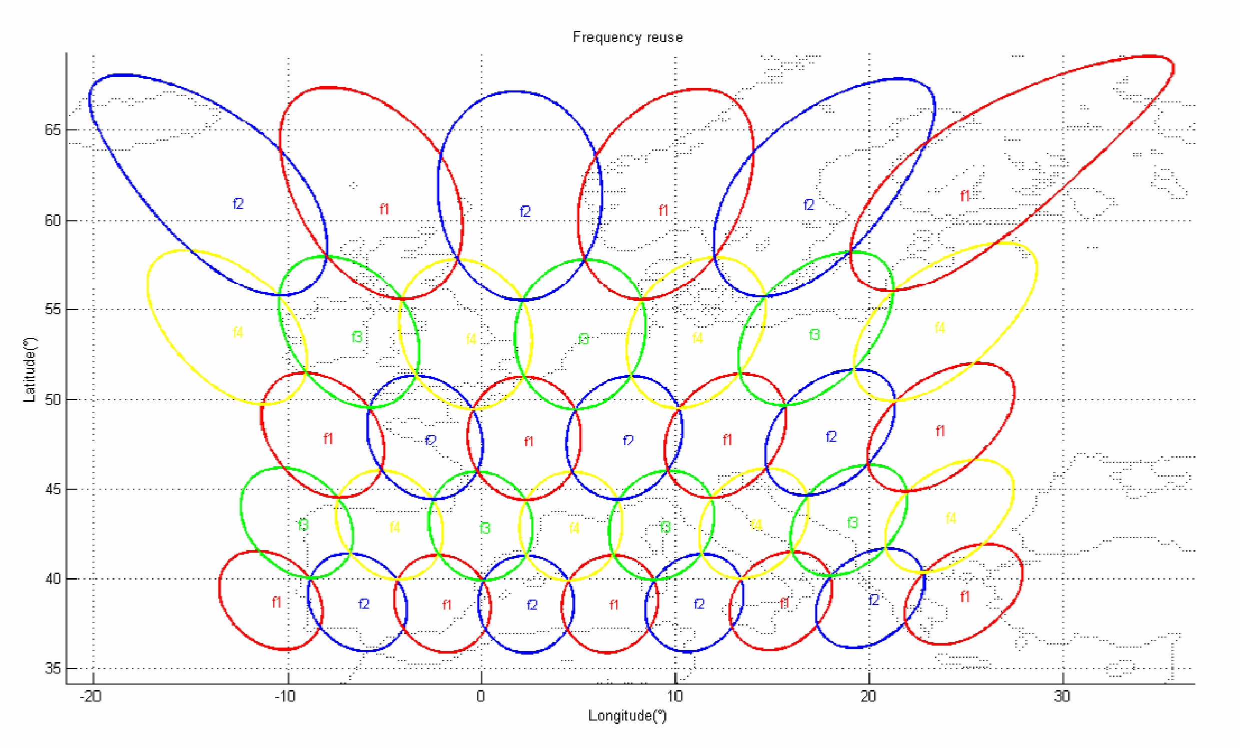
4.2 Space segment

The satellite segment is made of a constellation of several geostationary satellites in order to offer a global coverage of the part of the Earth visible from the geostationary orbit. As an example, the satellite serving the European area is located at a distance between 37 000 km and 40 000 km depending on the latitude that is considered (e.g., 38 000 km in Toulouse). The corresponding elevation is between 15° and 50° (e.g., 39° in Toulouse).

Each satellite will create several narrow spot beams. For each satellite, spot beams can be activated dynamically within the satellite coverage. As a baseline, a frequency reuse 4 is considered. Such a pattern is illustrated on Fig. 2-12 for a 6-metre satellite antenna, which is the required size to close the link budget with sufficient margins.

FIGURE 2-12

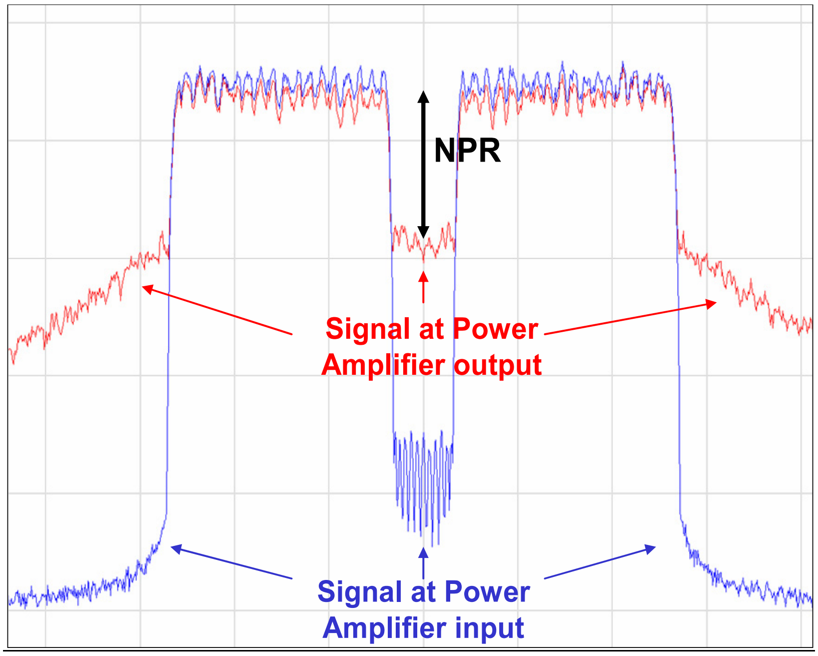
Illustrative state-of-the-art spot beam satellite antenna and frequency re-use pattern



Satellite OoB emissions are driven by its NPR (noise power ratio) performance. As depicted below, the NPR is the ratio between the carrier signal power and the noise level brought by multi-carrier amplifier nonlinearities. A NPR equal to 17 dB is considered for the analysis. Such a value is a typical value for a state-of-the-art satellite and a 3-4 dB output back-off (OBO), which is the difference between the effective amplifier output power and the maximum amplifier output power.

FIGURE 2-13

Satellite noise power ratio (NPR)



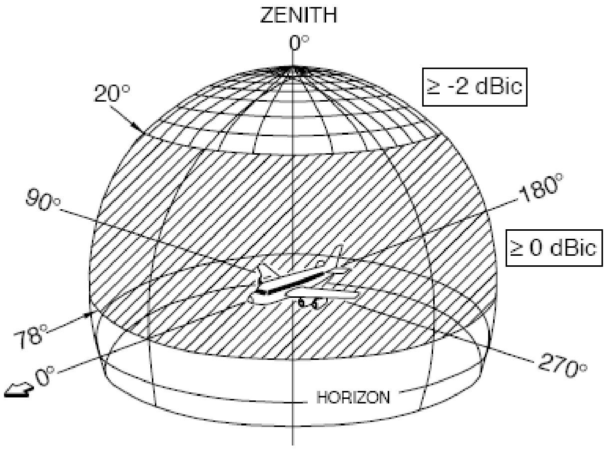
4.3 UA terminal segment

As far as the UA terminal segment is concerned, a low-gain omnidirectional terminal is considered. Possibly, several antennas may be used to ensure the availability of the link whatever the attitude of the UA is.

A 3 dBi antenna gain is assumed. The antenna pattern is supposed to be omnidirectional for the azimuth and partially omnidirectional above the horizon for the elevation. For information, an example of a 1-GHz band airborne antenna pattern is presented below (higher gains can be reached at 5 GHz). Let us note that the antenna gain decreases when reaching the zenith.

FIGURE 2-14

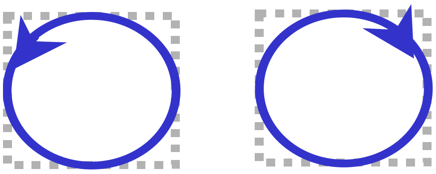
Example of 1-GHz band airborne antenna pattern



A circular polarization is used, either RHCP (Right hand circular polarization) or LHCP (Left hand circular polarization).

FIGURE 2-15

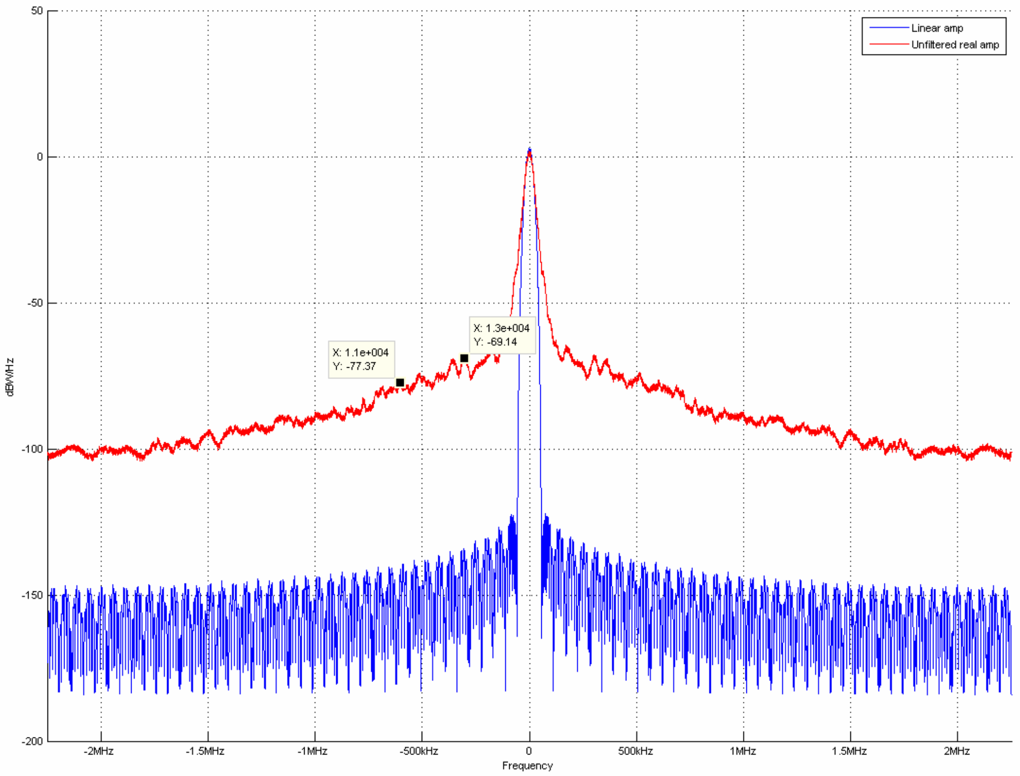
LHCP and RHCP



A power amplifier providing at maximum a 20 W radio output power is considered. The emission spectrum has been modelled though simulations and is depicted on Fig. 2-16. The blue curve represents the ideal amplifier while the red curve represents the real amplifier.

FIGURE 2-16

UA emission spectrum



Finally, in order to ease the feasibility of the UA terminal diplexer, a half duplex FDD (frequency duplex division) design is considered, meaning that the UA terminal does not transmit and receive at the same time. It must thus transmit or receive twice as faster, that's why the required bandwidth is twice as wider. Let us note that such a design does not impact the overall system capacity given that two users can be multiplexed in time on a single carrier.

4.4 Carrier bandwidth and frequency plan

Table 2-2 presents the computation leading to the carrier bandwidth. In the return link, 2 carriers, i.e., 4 UA, are multiplexed on a 300 kHz channel. In the forward link, 8 carriers, i.e., 16 UA, are multiplexed on a 300 kHz channel.

TABLE 2-2

Carrier bandwidth

	Forward	**Return**
User throughput per carrier (kbit/s)	7.0	44.0
Physical layer efficiency (bit/s/Hz)	0.85	0.85
Duplex ratio	0.5	0.5
No. of UAV per carrier	2	2
Symbol rate per carrier (kHz)	16.5	103.5
Roll-off	1.35	1.35
Minimum bandwidth per carrier (kHz)	22.2	139.8
Canalization (kHz)	37.5	150.0
No. of carriers over 300 kHz	8	2

The AMS(R)S system will operate in the 5 030-5 091 MHz band. This frequency band is split into three separate parts:

- 5 030-5 050 MHz: satellite to UA (forward) and satellite to GES (return) paths;
- 5 050-5 071 MHz: frequency separation to ensure a sufficient isolation between both paths (20 MHz is the foreseen separation so that the satellite diplexer can provide a sufficient isolation). This section of the band is thus not used and a part of it could be reserved for tactical MLS stations (provided that the corresponding MLS frequency allocation is validated at ICAO level). Indeed, tactical MLS stations can be used anywhere and, as a consequence, require MLS channels that are never used by the AMS(R)S system. As a baseline, it is assumed that 10% of the overall band, i.e., 6 MHz, is reserved in the section 5 050-5 071 MHz for tactical MLS stations (knowing that around 30 tactical MLS stations are included in the ICAO database, which contained around 800 MLS stations).
- 5 071-5 091 MHz: UA to satellite (return) and GES to satellite (forward) paths.

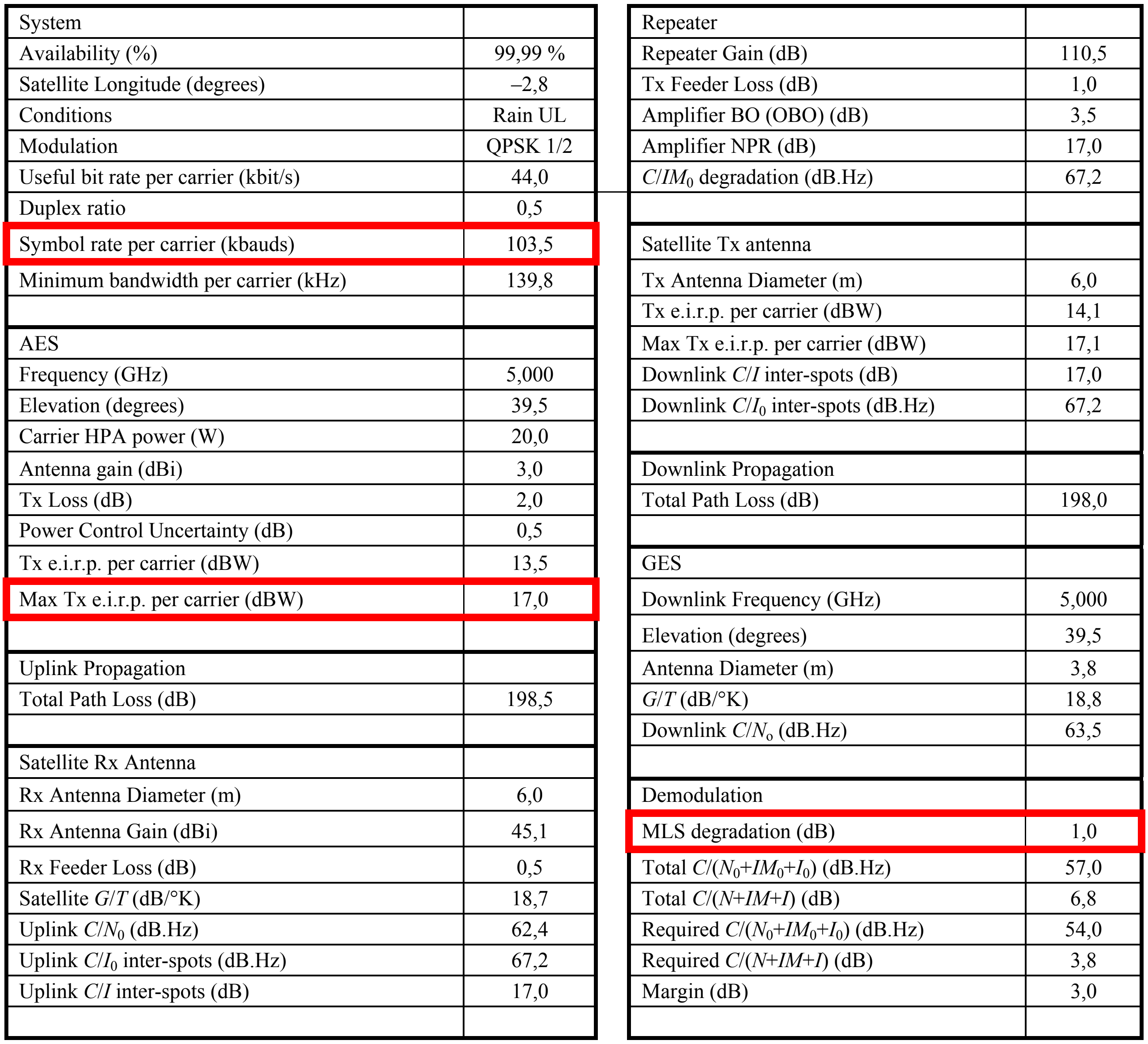
4.5 Link budgets

Link budgets for the return link and the forward link are presented hereafter. The feeder link is assumed to be in 5 030-5 091 MHz band, this case being the most restrictive one. A QPSK 1/2 DVB-RCS type waveform is considered. Parameters that are of prime interest for sharing studies are highlighted in red:

- Max e.i.r.p.
- Used bandwidth (i.e., symbol rate).
- Tolerated degradation caused by MLS stations.

FIGURE 2-17

AMS(R)S return link budget

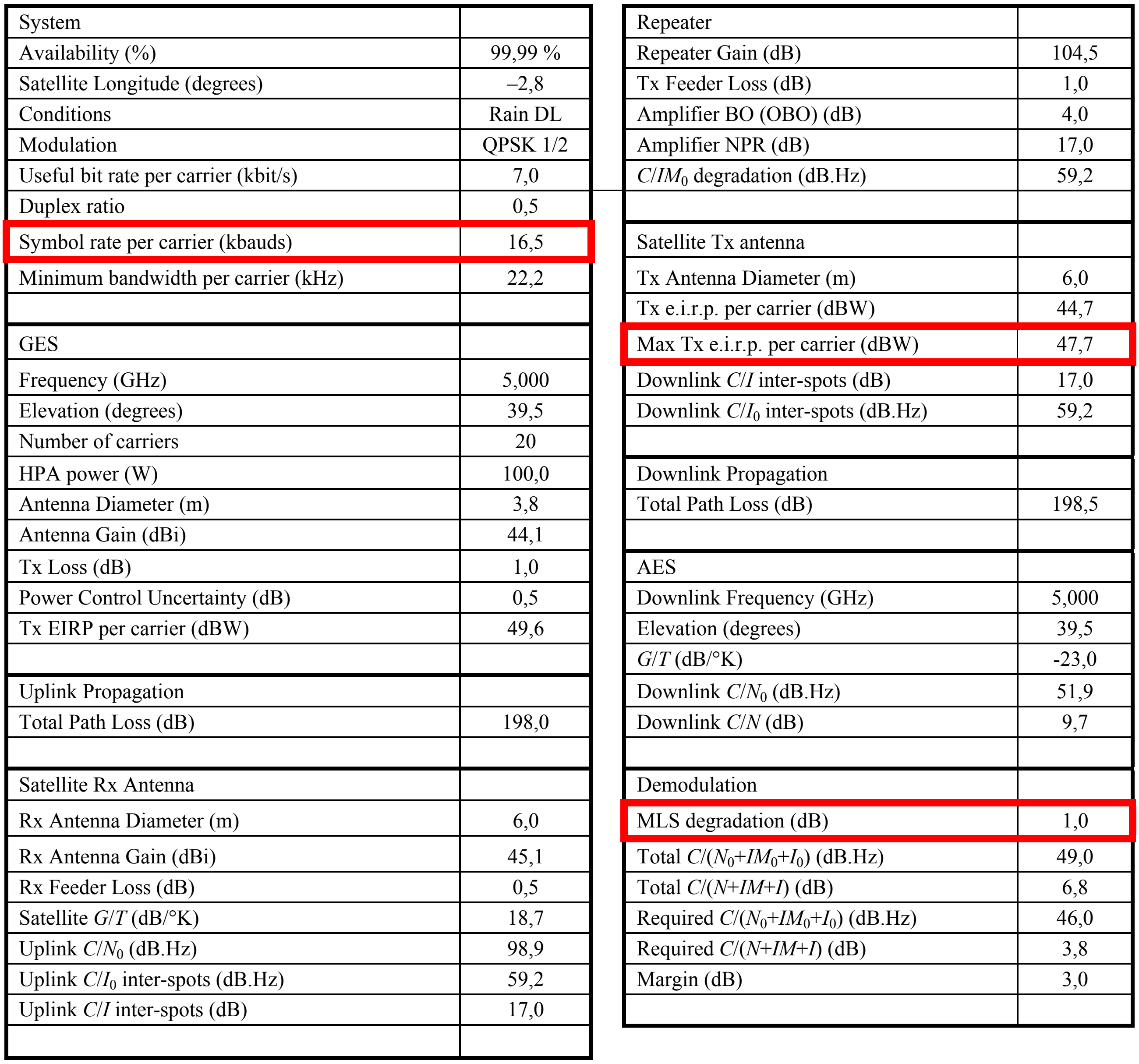


System	
Availability (%)	99,99 %
Satellite Longitude (degrees)	–2,8
Conditions	Rain UL
Modulation	QPSK 1/2
Useful bit rate per carrier (kbit/s)	44,0
Duplex ratio	0,5
Symbol rate per carrier (kbauds)	103,5
Minimum bandwidth per carrier (kHz)	139,8
AES	
Frequency (GHz)	5,000
Elevation (degrees)	39,5
Carrier HPA power (W)	20,0
Antenna gain (dBi)	3,0
Tx Loss (dB)	2,0
Power Control Uncertainty (dB)	0,5
Tx e.i.r.p. per carrier (dBW)	13,5
Max Tx e.i.r.p. per carrier (dBW)	17,0
Uplink Propagation	
Total Path Loss (dB)	198,5
Satellite Rx Antenna	
Rx Antenna Diameter (m)	6,0
Rx Antenna Gain (dBi)	45,1
Rx Feeder Loss (dB)	0,5
Satellite G/T (dB/°K)	18,7
Uplink C/N_0 (dB.Hz)	62,4
Uplink C/I_0 inter-spots (dB.Hz)	67,2
Uplink C/I inter-spots (dB)	17,0

Repeater	
Repeater Gain (dB)	110,5
Tx Feeder Loss (dB)	1,0
Amplifier BO (OBO) (dB)	3,5
Amplifier NPR (dB)	17,0
C/IM_0 degradation (dB.Hz)	67,2
Satellite Tx antenna	
Tx Antenna Diameter (m)	6,0
Tx e.i.r.p. per carrier (dBW)	14,1
Max Tx e.i.r.p. per carrier (dBW)	17,1
Downlink C/I inter-spots (dB)	17,0
Downlink C/I_0 inter-spots (dB.Hz)	67,2
Downlink Propagation	
Total Path Loss (dB)	198,0
GES	
Downlink Frequency (GHz)	5,000
Elevation (degrees)	39,5
Antenna Diameter (m)	3,8
G/T (dB/°K)	18,8
Downlink C/N_o (dB.Hz)	63,5
Demodulation	
MLS degradation (dB)	1,0
Total $C/(N_0+IM_0+I_0)$ (dB.Hz)	57,0
Total $C/(N+IM+I)$ (dB)	6,8
Required $C/(N_0+IM_0+I_0)$ (dB.Hz)	54,0
Required $C/(N+IM+I)$ (dB)	3,8
Margin (dB)	3,0

FIGURE 2-18

AMS(R)S forward link budget



System	
Availability (%)	99,99 %
Satellite Longitude (degrees)	–2,8
Conditions	Rain DL
Modulation	QPSK 1/2
Useful bit rate per carrier (kbit/s)	7,0
Duplex ratio	0,5
Symbol rate per carrier (kbauds)	16,5
Minimum bandwidth per carrier (kHz)	22,2
GES	
Frequency (GHz)	5,000
Elevation (degrees)	39,5
Number of carriers	20
HPA power (W)	100,0
Antenna Diameter (m)	3,8
Antenna Gain (dBi)	44,1
Tx Loss (dB)	1,0
Power Control Uncertainty (dB)	0,5
Tx EIRP per carrier (dBW)	49,6
Uplink Propagation	
Total Path Loss (dB)	198,0
Satellite Rx Antenna	
Rx Antenna Diameter (m)	6,0
Rx Antenna Gain (dBi)	45,1
Rx Feeder Loss (dB)	0,5
Satellite G/T (dB/°K)	18,7
Uplink C/N_0 (dB.Hz)	98,9
Uplink C/I_0 inter-spots (dB.Hz)	59,2
Uplink C/I inter-spots (dB)	17,0

Repeater	
Repeater Gain (dB)	104,5
Tx Feeder Loss (dB)	1,0
Amplifier BO (OBO) (dB)	4,0
Amplifier NPR (dB)	17,0
C/IM_0 degradation (dB.Hz)	59,2
Satellite Tx antenna	
Tx Antenna Diameter (m)	6,0
Tx e.i.r.p. per carrier (dBW)	44,7
Max Tx e.i.r.p. per carrier (dBW)	47,7
Downlink C/I inter-spots (dB)	17,0
Downlink C/I_0 inter-spots (dB.Hz)	59,2
Downlink Propagation	
Total Path Loss (dB)	198,5
AES	
Downlink Frequency (GHz)	5,000
Elevation (degrees)	39,5
G/T (dB/°K)	-23,0
Downlink C/N_0 (dB.Hz)	51,9
Downlink C/N (dB)	9,7
Demodulation	
MLS degradation (dB)	1,0
Total $C/(N_0+IM_0+I_0)$ (dB.Hz)	49,0
Total $C/(N+IM+I)$ (dB)	6,8
Required $C/(N_0+IM_0+I_0)$ (dB.Hz)	46,0
Required $C/(N+IM+I)$ (dB)	3,8
Margin (dB)	3,0

5 Coexistence studies

5.1 Introduction

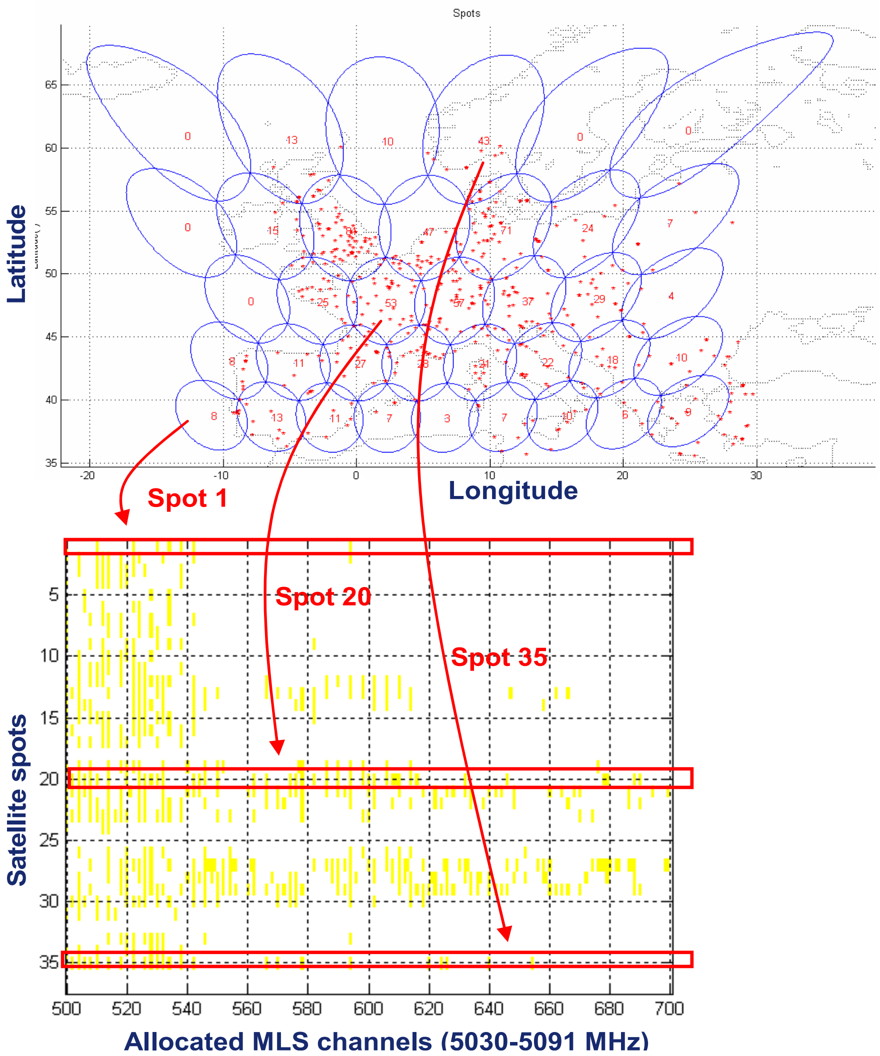
The coexistence study aims at assessing whether:

1. The sharing of the band between MLS and the AMS(R)S system is feasible (considering the criteria defined in § 3.4).
2. The AMS(R)S system can provide the required capacity, as defined in Report ITU-R M.2171 of which assumptions in terms of UA density and bit rate per UA have been retained. It is to be noted that spot beams considered here are smaller than those in Report ITU-R M.2171. This leads to 16 UA per spot and to satellite spectrum requirement smaller than the 49 MHz concluded in this Report.

For the sake of illustration of interactions between MLS and the AMS(R)S system, MLS transmitters (red signs) and AMS(R)S spots are represented on Fig. 2-19, along with the number of MLS transmitters in each AMS(R)S spot.

FIGURE 2-19

Satellite spots and MLS transmitters in satellite coverage



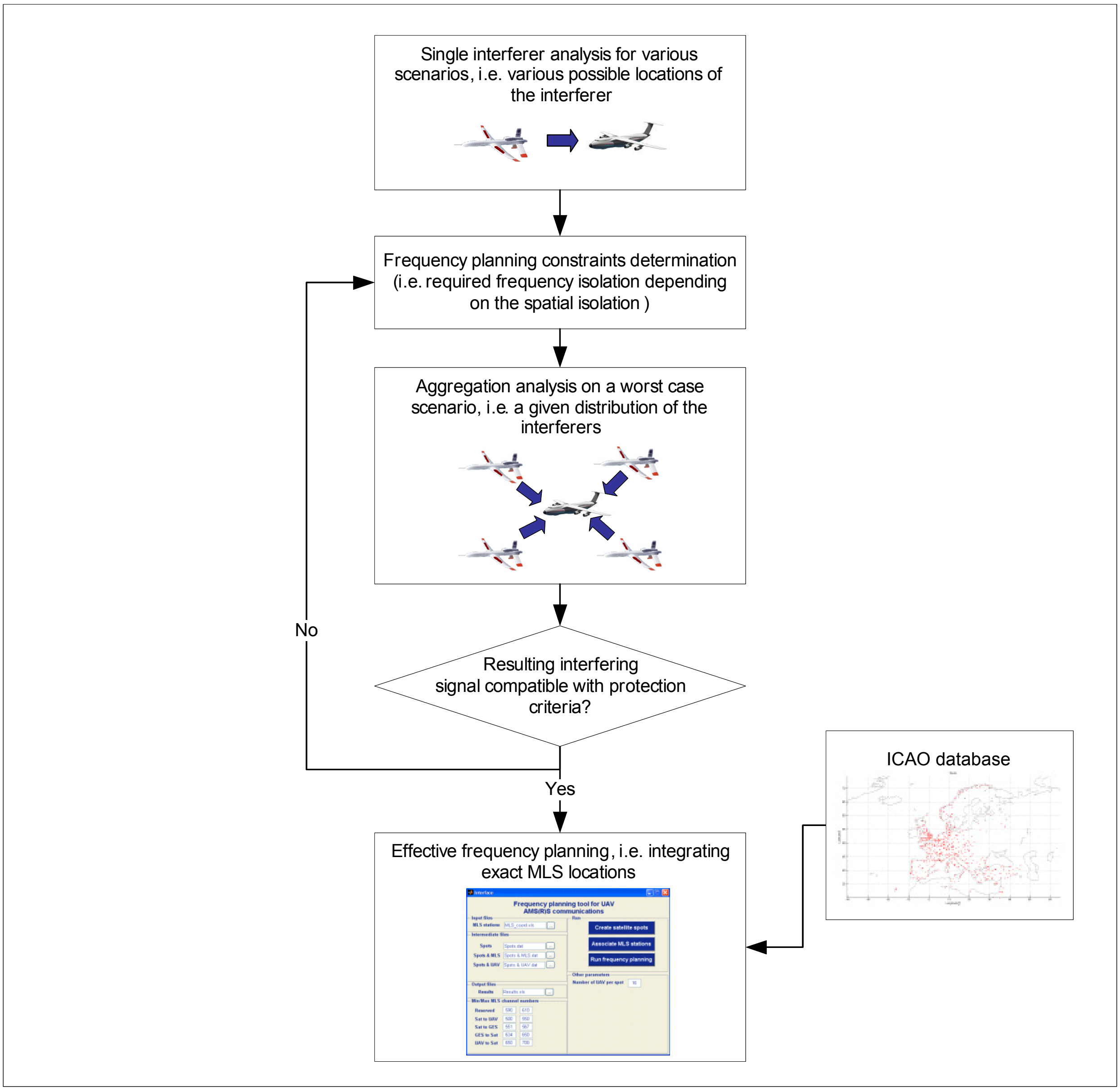
5.2 General methodology

The general methodology, which is presented on Fig. 2-20, is organized in 4 steps:

1. Single interferer analysis: for each case (e.g., UA creating potential interferences towards MLS), all possible scenarios, i.e., all possible locations of the interferer, are studied to determine what the interference level is as a function of the frequency isolation.
2. Frequency planning constraints determination: based on the single interferer analysis, an initial set of constraints, i.e., required frequency isolation as a function of the spatial isolation, is derived. These constraints can be refined after the aggregation analysis.
3. Aggregation analysis: all potential AMS(R)S interferers are considered to compute the aggregated interference level. A worst-case scenario is considered.
4. Effective frequency planning: the exact locations of MLS transmitters and their corresponding channel number (based on ICAO database) are taken into account to derive an effective frequency planning over Europe.

FIGURE 2-20

General methodology



MLS stations: MLS_coord.xls

Spots: Spots.dat

Spots & MLS: Spots & MLS.dat

Spots & UAV: Spots & UAV.dat

Results: Results.xls

Reserved: 590 610

Sat to UAV: 500 550

Sat to GES: 551 567

GES to Sat: 634 650

UAV to Sat: 680 700

Number of UAV per spot: 10

5.3 Single interferer analysis

5.3.1 Satellite to MLS (satellite to UA link, forward)

The general scenario for the potential interferences created by the satellite towards the MLS receiver is described hereafter. In this example, the UA is served by the satellite spot in which is located the MLS receiver. Scenarios in which the UA is served by other satellite spots are as well considered. These other spots are represented in Fig. 2-22.

FIGURE 2-21

Interferences from satellite to MLS receiver – Single interferer scenario

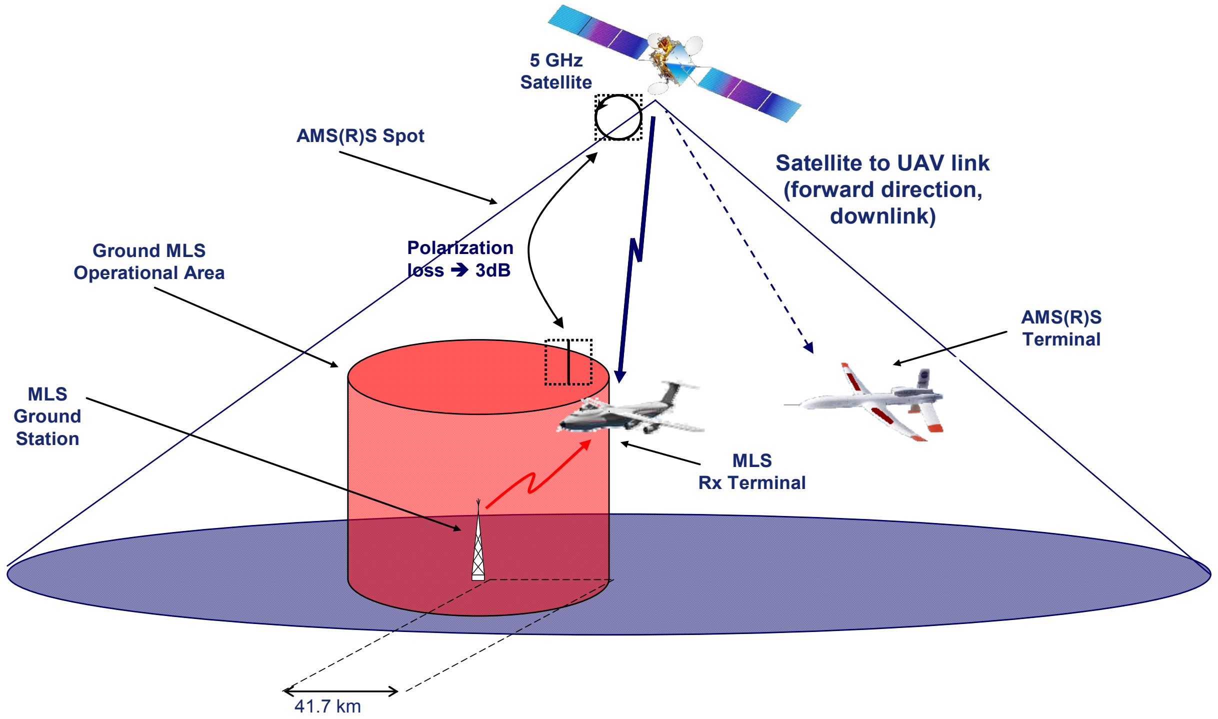
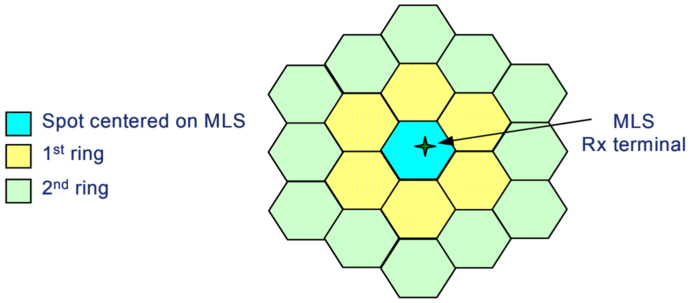


FIGURE 2-22

Satellite spots creating potential interferences towards the MLS receiver



Results are presented in the Table 2-3, each combination of spatial and frequency isolations being studied. Combinations that are flagged “NOK” do not meet criteria defined in § 3.4, meaning that they cannot be used. As an example, the same 300 kHz channel as the one used by a MLS station cannot be used neither in the spot covering the MLS coverage area corresponding to this MLS station or in the spots surrounding this spot (1st ring spots).

TABLE 2-3

Interferences from satellite to MLS receiver – Single interferer – Results

			Co-channel	1st 300kHz ajd channel	2nd 300kHz ajd channel	3rd 300kHz ajd channel	4th 300kHz ajd channel	5th 300kHz ajd channel	6th 300kHz ajd channel
Max in-band Rx level @ MLS Rx antenna input		dBm	-130	-130	-130	-130	-130	-130	-130
Satellite signal attenuation		dB	0	-17	-17	-17	-17	-17	-17
MLS spot	Spot isolation	dB	0	0	0	0	0	0	0
	In-band Rx level from Sat @ MLS Rx antenna input / 150 kHz	dBm	-120,3	-133,7	-133,7	-133,7	-133,7	-133,7	-133,7
			NOK	OK	OK	OK	OK	OK	OK
1st ring	Spot isolation	dB	3	3	3	3	3	3	3
	In-band Rx level from Sat @ MLS Rx antenna input / 150 kHz	dBm	-123,3	-136,7	-136,7	-136,7	-136,7	-136,7	-136,7
			NOK	OK	OK	OK	OK	OK	OK
2nd ring	Spot isolation	dB	25	25	25	25	25	25	25
	In-band Rx level from Sat @ MLS Rx antenna input / 150 kHz	dBm	-145,3	-158,7	-158,7	-158,7	-158,7	-158,7	-158,7
			OK	OK	OK	OK	OK	OK	OK

5.3.2 MLS to UA (satellite to UA link, forward)

The general scenario for the potential interferences created by a MLS transmitter towards the UA is described hereafter.

FIGURE 2-23

Interferences from MLS transmitter to UA receiver – Single interferer scenario

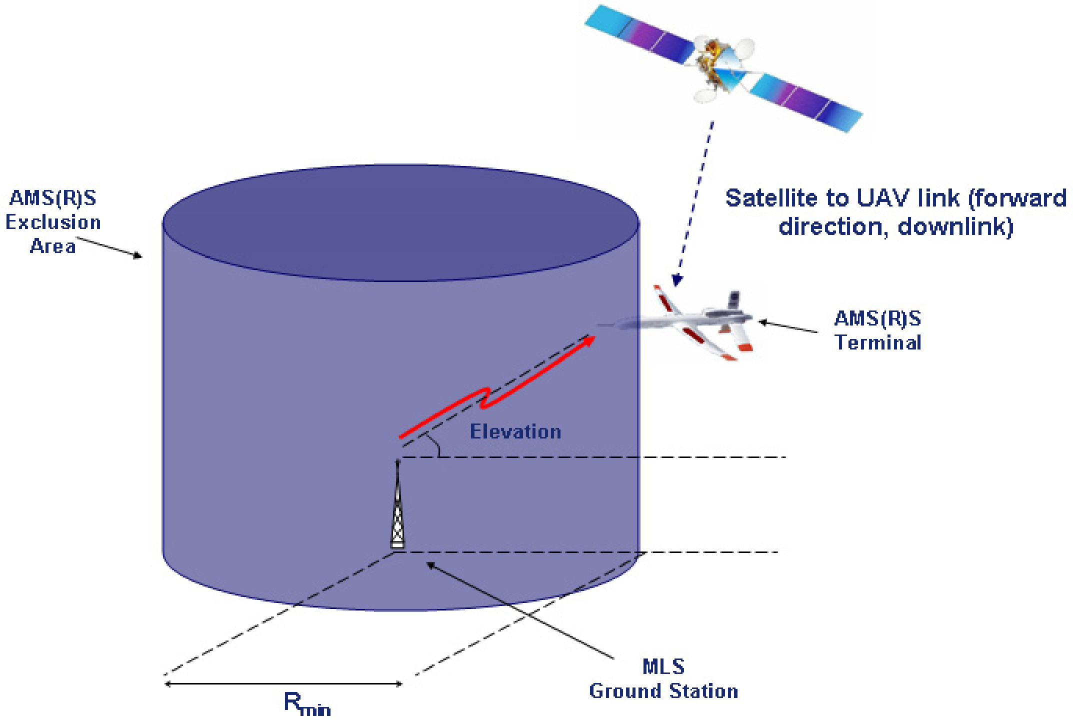
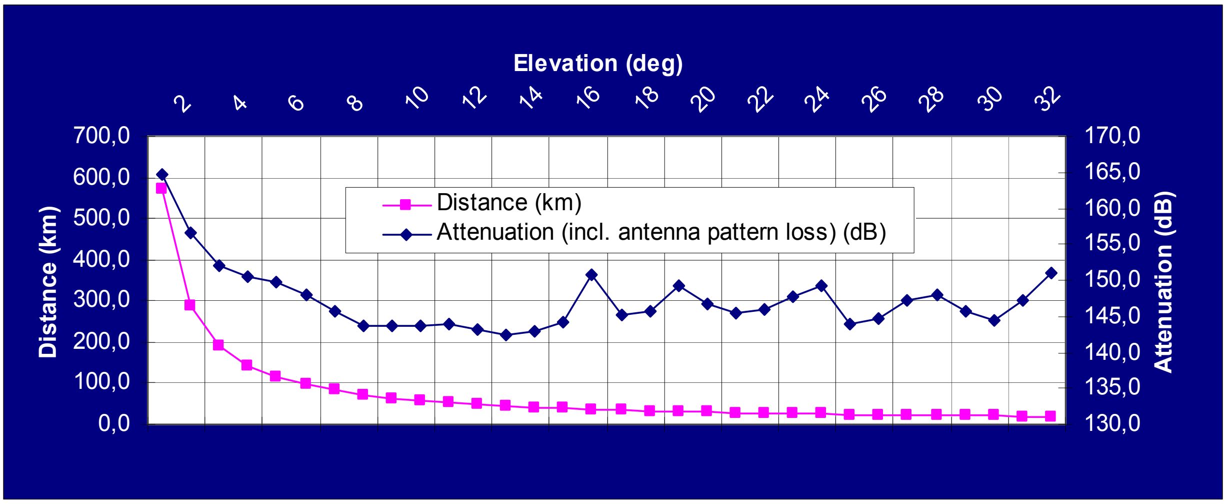


Figure 2-24 presents the path loss variation between the MLS transmitter and the UA depending on the elevation for a given UA altitude (10 km). Indeed, due to variation of the MLS Tx antenna pattern, the path loss varies as the UA is approaching the MLS transmitter. Thus, the minimum path loss, i.e., the worst case for the interferences towards the UA, is reached when the MLS transmitter sees the UA with a 13° elevation, corresponding then to a distance equal to 44.5 km (respectively 4.4 km) for a UA flying with a 10 km (respectively 1 km) altitude. This worst case is considered for the analysis.

FIGURE 2-24

MLS to UA path loss variation depending on the elevation



Results are presented in the Table 2-4, each combination of spatial and frequency isolations being studied. Combinations that are coloured red do not make it possible to sufficiently protect the AMS(R)S system, meaning that they cannot be used. The considered UA altitude is 10 km.

TABLE 2-4

Interferences from MLS transmitter to UA receiver – Single interferer – Results

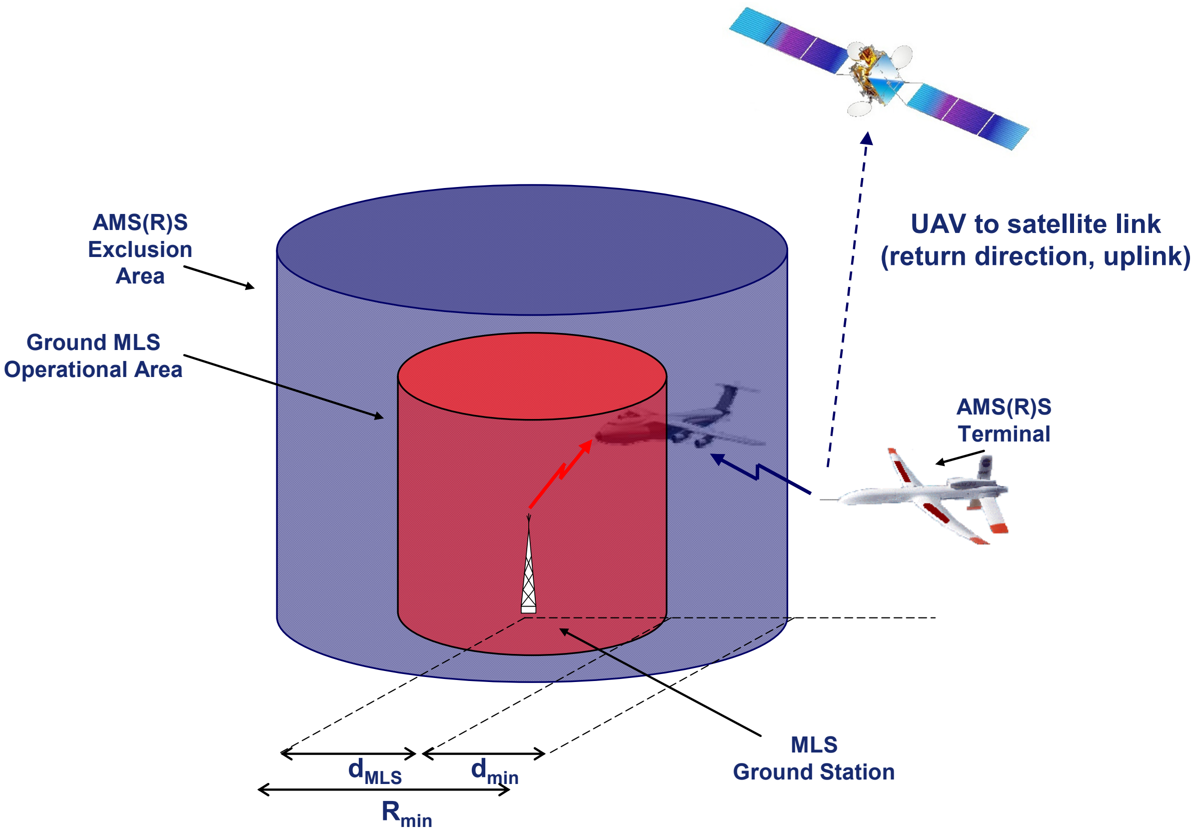
			Co-channel	1st 300kHz ajd channel	2nd 300kHz ajd channel	3rd 300kHz ajd channel	4th 300kHz ajd channel	5th 300kHz ajd channel	6th 300kHz ajd channel
Max in-band Rx level		dBm	-127.4	-127.4	-127.4	-127.4	-127.4	-127.4	-127.4
MLS signal roll-off over AMSRS bandwidth		dB	0.0	-32.4	-41.9	-46.3	-49.3	-51.4	-53.2
Co-spot	MLS transmitter to UAV distance (path loss worst case: 13° elevation)	km	44.5	44.5	44.5	44.5	44.5	44.5	44.5
	In-band Rx level from MLS	dBm	-98.1	-130.5	-140.0	-144.5	-147.4	-149.6	-151.3
1st ring	MLS transmitter to UAV distance (path loss worst case)	km	44.5	44.5	44.5	44.5	44.5	44.5	44.5
	In-band Rx level from MLS	dBm	-98.1	-130.5	-140.0	-144.5	-147.4	-149.6	-151.3
2nd ring	MLS transmitter to UAV distance (path loss worst case)	km	441.7	441.7	441.7	441.7	441.7	441.7	441.7
	In-band Rx level from MLS	dBm	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon

5.3.3 UA to MLS (UA to satellite link, return)

The general scenario for the potential interferences created by the UA towards the MLS receiver is described hereafter.

FIGURE 2-25

Interferences from UA transmitter to MLS receiver – Single interferer scenario

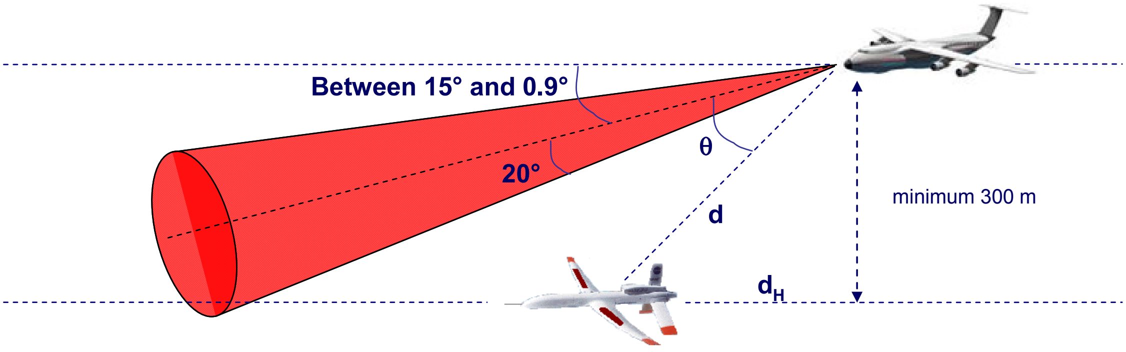


This scenario can be divided into 3 sub scenarios:

– Scenario A: the UA is in the MLS operational area and is at the minimum vertical separation from MLS receiver, as per ICAO regulation that gives the minimum vertical separation between two aircraft in controlled airspace (i.e., 300 m (1 000 ft)). A minimum frequency isolation is required.

FIGURE 2-26

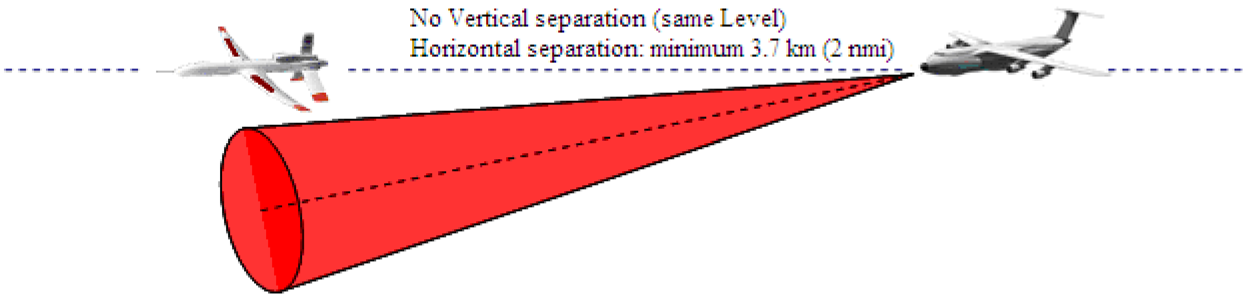
Interferences from UA transmitter to MLS receiver – Scenario A



– Scenario B: the UA is in the MLS operational area and is at the minimum horizontal separation from MLS receiver, as per ICAO regulation that gives the minimum horizontal separation between two aircrafts in controlled airspace (i.e., 3.7 km (2 NM). A minimum frequency isolation is required.

FIGURE 2-27

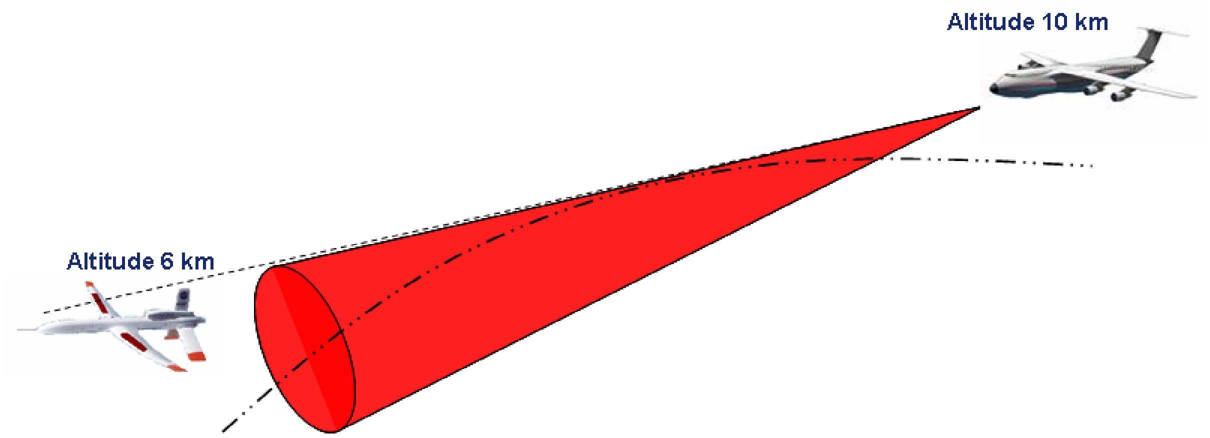
Interferences from UA transmitter to MLS receiver – Scenario B



– Scenario C: the UA is outside the MLS operational area and possibly beyond the radio horizon. The required spatial isolation depends on the frequency offset.

FIGURE 2-28

Interferences from UA transmitter to MLS receiver – Scenario C



Results are presented in the Table 2-5, each combination of spatial and frequency isolations being studied. Combinations that are flagged "NOK" do not meet criteria defined in § 3.4, meaning that they cannot be used. Assuming that the MLS receiver is at the edge of two spots of the 1st ring, two cases are studied for 1st ring spots: firstly, a 1st ring spot being close to the MLS Rx (adjacent spot) and, secondly, a 1st ring spot being on the other side (non adjacent spots). This illustrated on Fig. 2-32, which presents the aggregation scenario.

TABLE 2-5

Interferences from UA transmitter to MLS receiver – Single interferer – Results

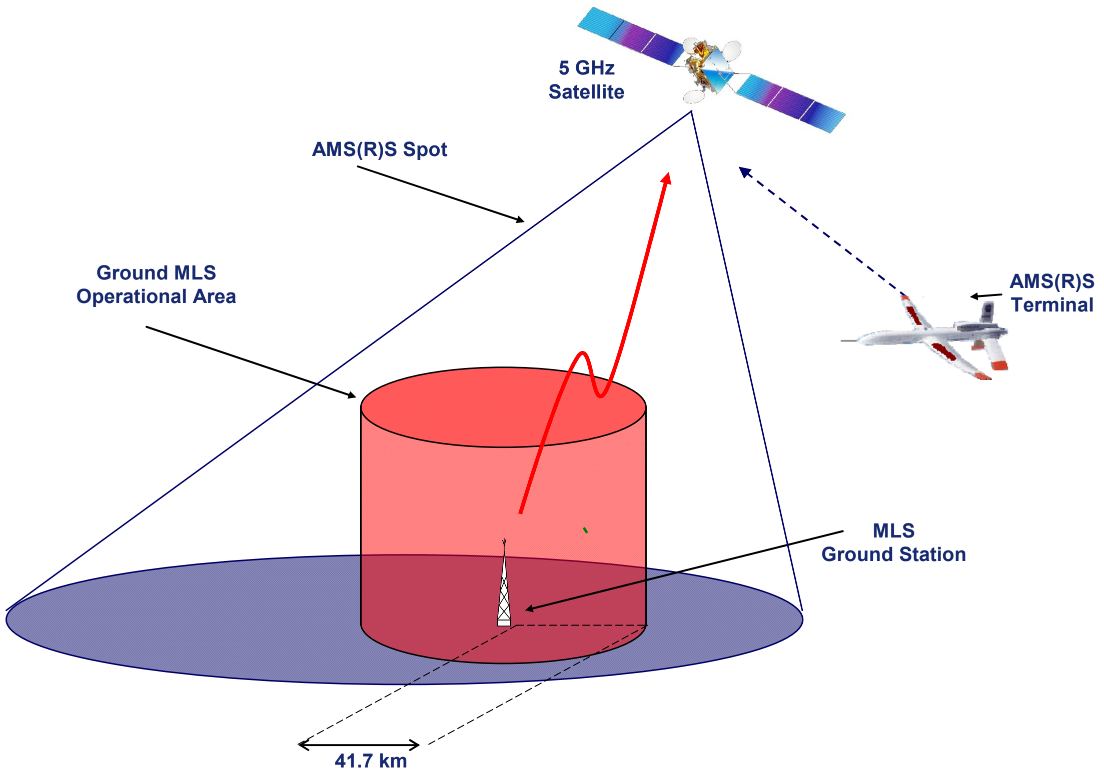
			Co-channel	1st 300kHz ajd channel	2nd 300kHz ajd channel	3rd 300kHz ajd channel	4th 300kHz ajd channel	5th 300kHz ajd channel	6th 300kHz ajd channel
	Max in-band Rx level @ MLS Rx antenna input	dBm	-130.0	-130.0	-130.0	-130.0	-130.0	-130.0	-130.0
	UA signal roll-off in the band over 150 kHz	dBc	0.0	-38.2	-67.2	-73.2	-80.0	-80.0	-80.0
	Required distance to verify the Rx level criterion (dmin)	km	731.12	29.34	1.04	0.52	0.24	0.24	0.24
Co-spot	UAV to MLS receiver distance (worst case: scenario A)	km	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	In-band Rx level from UA @ MLS Rx antenna input / 150 kHz	dBm	-52.0	-90.2	-119.2	-125.2	-132.0	-132.0	-132.0
			NOK	NOK	NOK	NOK	OK	OK	OK
1st ring (adjacent spot)	UAV to MLS receiver distance (worst case: 5nm)	km	9.3	9.3	9.3	9.3	9.3	9.3	9.3
	In-band Rx level from UA @ MLS Rx antenna input / 150 kHz	dBm	-81.8	-120.0	-149.0	-155.0	-161.8	-161.8	-161.8
			NOK	NOK	OK	OK	OK	OK	OK
1st ring (non adjacent spot)	UAV to MLS receiver distance (worst case: 200 km))	km	200.0	200.0	200.0	200.0	200.0	200.0	200.0
	In-band Rx level from UA @ MLS Rx antenna input / 150 kHz	dBm	-108.5	-146.7	-175.7	-181.7	-188.5	-188.5	-188.5
			NOK	OK	OK	OK	OK	OK	OK
2nd ring	UAV to MLS receiver distance (worst case)	km	400.0	400.0	400.0	400.0	400.0	400.0	400.0
	In-band Rx level from UA @ MLS Rx antenna input / 150 kHz	dBm	-114.5	-152.7	-181.7	-187.7	-194.5	-194.5	-194.5
			NOK	OK	OK	OK	OK	OK	OK

5.3.4 MLS to satellite (UA to satellite link, return)

The general scenario for the potential interferences created by a MLS transmitter towards a UA receiver is described hereafter.

FIGURE 2-29

Interferences from MLS transmitter to satellite – Single interferer scenario



Results are presented in the Table 2-6, each combination of spatial and frequency isolations being studied. Combinations that are coloured red do not make it possible to sufficiently protect the AMS(R)S system, meaning that they cannot be used.

TABLE 2-6

Interferences from MLS transmitter to satellite – Single interferer – Results

			Co-channel	1st 300kHz ajd channel	2nd 300kHz ajd channel	3rd 300kHz ajd channel	4th 300kHz ajd channel	5th 300kHz ajd channel	6th 300kHz ajd channel
	Max in-band Rx level	dBm	-127.4	-127.4	-127.4	-127.4	-127.4	-127.4	-127.4
	MLS signal roll-off over AMSRS bandwidth	dB	0.0	-32.4	-41.9	-46.3	-49.3	-51.4	-53.2
Co-spot	MLS transmitter to UAV distance (path loss worst case: 13° elevation)	km	44.5	44.5	44.5	44.5	44.5	44.5	44.5
	In-band Rx level from MLS	dBm	-98.1	-130.5	-140.0	-144.5	-147.4	-149.6	-151.3
1st ring	MLS transmitter to UAV distance (path loss worst case)	km	44.5	44.5	44.5	44.5	44.5	44.5	44.5
	In-band Rx level from MLS	dBm	-98.1	-130.5	-140.0	-144.5	-147.4	-149.6	-151.3
2nd ring	MLS transmitter to UAV distance (path loss worst case)	km	441.7	441.7	441.7	441.7	441.7	441.7	441.7
	In-band Rx level from MLS	dBm	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon	Beyond radio horizon

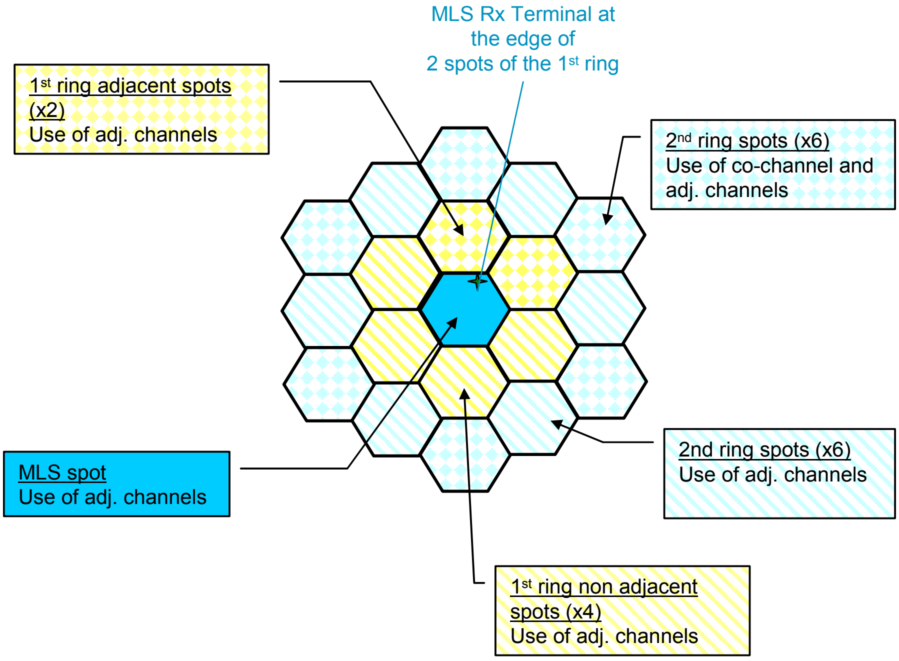
5.4 Aggregation analysis

5.4.1 Satellite to MLS (satellite to UA link, forward)

The aggregation scenario is described hereafter. It integrates frequency planning constraints that stems from the sharing with MLS as well as frequency reuse constraints. The MLS receiver is assumed to be at the edge of 3 spots, which is a worst case.

FIGURE 2-30

Interferences from satellite to MLS receiver – Aggregation scenario



Results of the aggregation analysis are presented in the Table 2-7, presenting the intermediate aggregated levels as well as the total aggregated level, which is below the maximum level received at MLS receiver antenna input. The MLS receiver being located at the border of the central spot (the so-called MLS spot in the table), a 3dB attenuation is considered when computing the received power in this central spot.

TABLE 2-7

Interferences from satellite to MLS receiver – Aggregation – Results

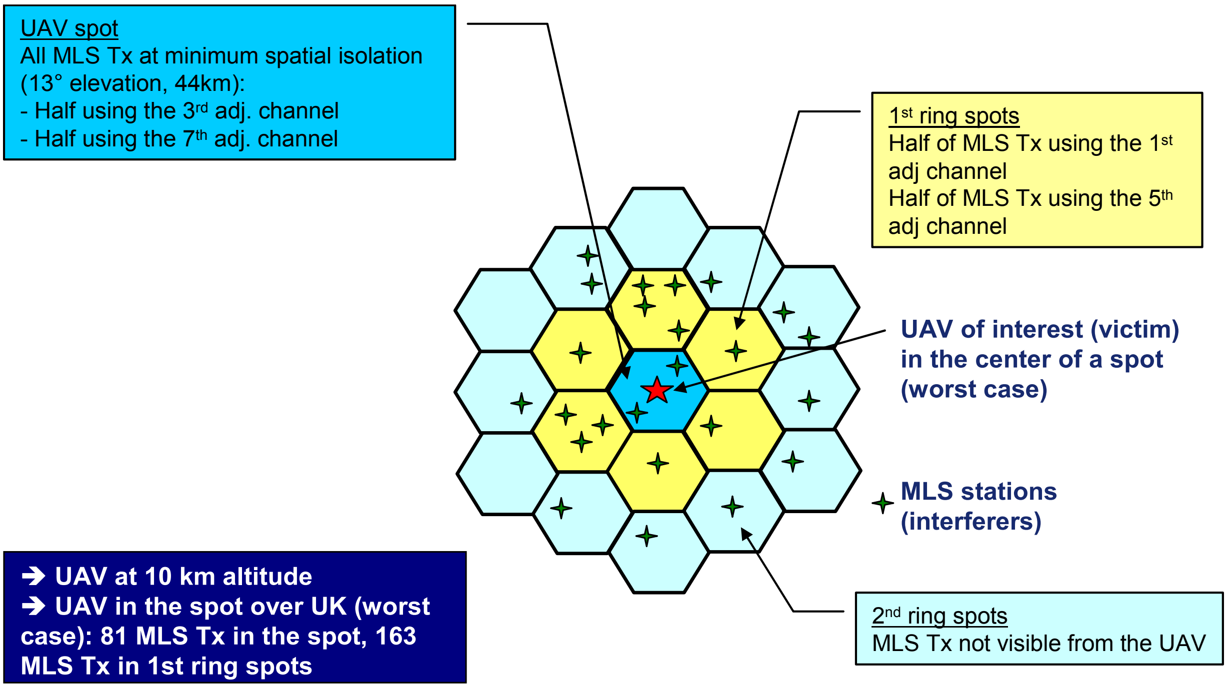
			#UAV
MLS spot	1 x MLS spot (using adjacent channels)		
	Rx level from Sat	-136.7 dBm/150 kHz	16
1st ring spots (x6)	2 x adjacent spots (using adjacent channels)		
	Rx level from Sat per spot	-136.7 dBm/150 kHz	16
	Rx level from Sat for all spots	-133.7 dBm/150 kHz	32
	4 x non adjacent spots (using adjacent channels)		
	Rx level from Sat per spot	-158.7 dBm/150 kHz	16
	Rx level from Sat for all spots	-152.7 dBm/150 kHz	64
	All spots		
	Rx level from Sat for all spots	-133.7 dBm/150 kHz	96
2nd ring spots (x12)	6 x spots using the MLS channel		
	Rx level from Sat per spot	-145.3 dBm/150 kHz	16
	Rx level from Sat for all spots	-137.5 dBm/150 kHz	96
	6 x spots using adjacent channels		
	Rx level from Sat per spot	-158.7 dBm/150 kHz	16
	Rx level from Sat for all spots	-150.9 dBm/150 kHz	96
	All spots		
	Rx level from Sat for all spots	-137.3 dBm/150 kHz	192
	Total	**-130.8 dBm/150 kHz**	**304**

5.4.2 MLS to UA (satellite to UA link, forward)

The aggregation scenario for the MLS to UA case is presented hereafter. In order to sufficiently protect the UA, frequency planning constraints that are considered are more stringent than the ones resulting from the single interferer analysis. Moreover, the fact that MLS transmitters cannot all use the same channel is integrated in the analysis.

FIGURE 2-31

Interferences from MLS transmitter to UA receiver – Aggregation scenario



Results of the aggregation analysis are presented in the Table 2-8, presenting the intermediate aggregated levels as well as the total aggregated level, which is below the maximum level received at UA antenna input.

TABLE 2-8

Interferences from MLS transmitter to UA receiver – Aggregation – Results

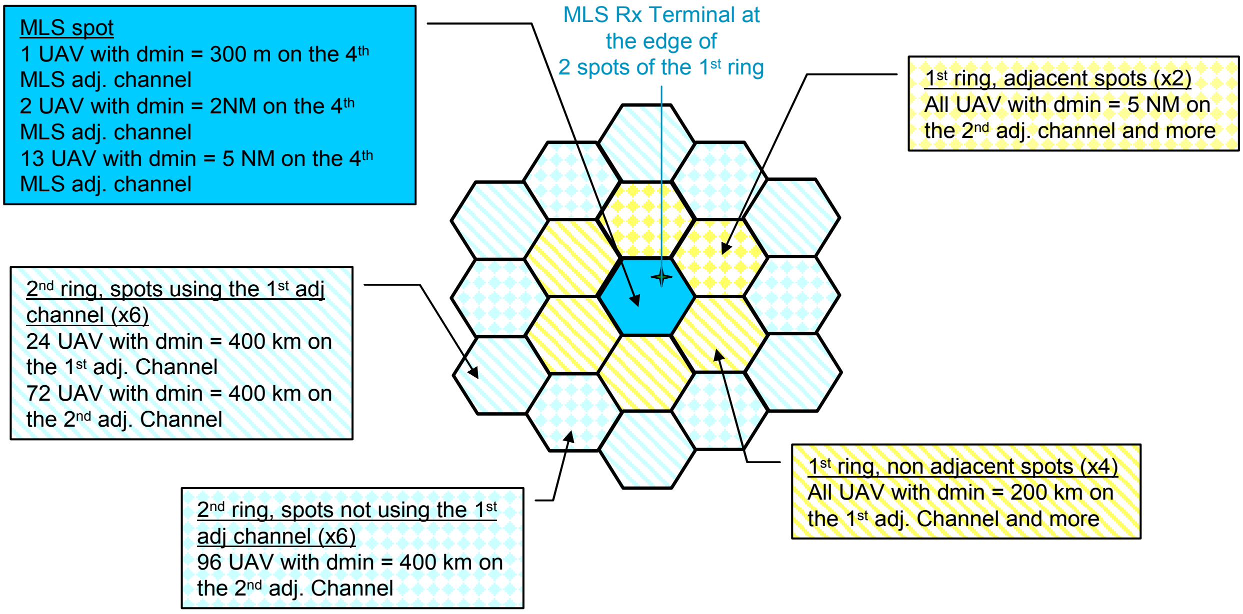
UAV spot	MLS at minimum distance using at least the 3rd adjacent channel	
	#visible MLS stations oriented towards the UAV	11
	Rx level from 1 MLS	-144.5 dBm
	Rx level from all MLS	-134.1 dBm
	MLS at minimum distance using at least the 7th adjacent channel	
	#visible MLS stations oriented towards the UAV	10
	Rx level from 1 MLS	-152.8 dBm
	Rx level from all MLS	-142.8 dBm
	All MLS	
	Rx level from all MLS	-133.5 dBm
1st ring spots	MLS using at least the 1st adjacent channel	
	#visible MLS stations / spot oriented towards the UAV	21
	Rx level from 1 MLS	-142.2 dBm
	Rx level from all MLS in all spots	-129.0 dBm
	MLS using at least the 5th adjacent channel	
	#visible MLS stations / spot oriented towards the UAV	21
	Rx level from 1 MLS	-161.3 dBm
	Rx level from all MLS in all spots	-148.1 dBm
	All MLS	
	Rx level from all MLS	-128.9 dBm
2nd ring spots		▨
	Total	**-127.6 dBm**

5.4.3 UA to MLS study (UA to satellite link, return)

The aggregation scenario is described hereafter. Similarly to the aggregation scenario for interferences from satellite to MLS receiver, it integrates frequency planning constraints that stems from the sharing with MLS as well as frequency reuse constraints. Moreover, 16 UA per spot are considered, meaning that the interference created by 19 * 16 = 304 UA is aggregated at the MLS receiver (UA at a higher distance are beyond radio LoS).

FIGURE 2-32

Interferences from UA transmitter to MLS receiver – Aggregation scenario



Results of the aggregation analysis are presented in the Table 2-9, presenting the intermediate aggregated levels as well as the total aggregated level, which is below the maximum level received at MLS receiver antenna input. Let us note that, for the sake of clarity, not all frequency planning constraints have been integrated, overestimating then slightly the resulting aggregated level. Nevertheless, it is worth highlighting anyway that this aggregated level is mainly driven by the interference created by the closest UA, i.e., the one located at 300 m (minimum vertical separation) from the MLS receiver.

TABLE 2-9

Interferences from UA transmitter to MLS receiver – Aggregation – Results

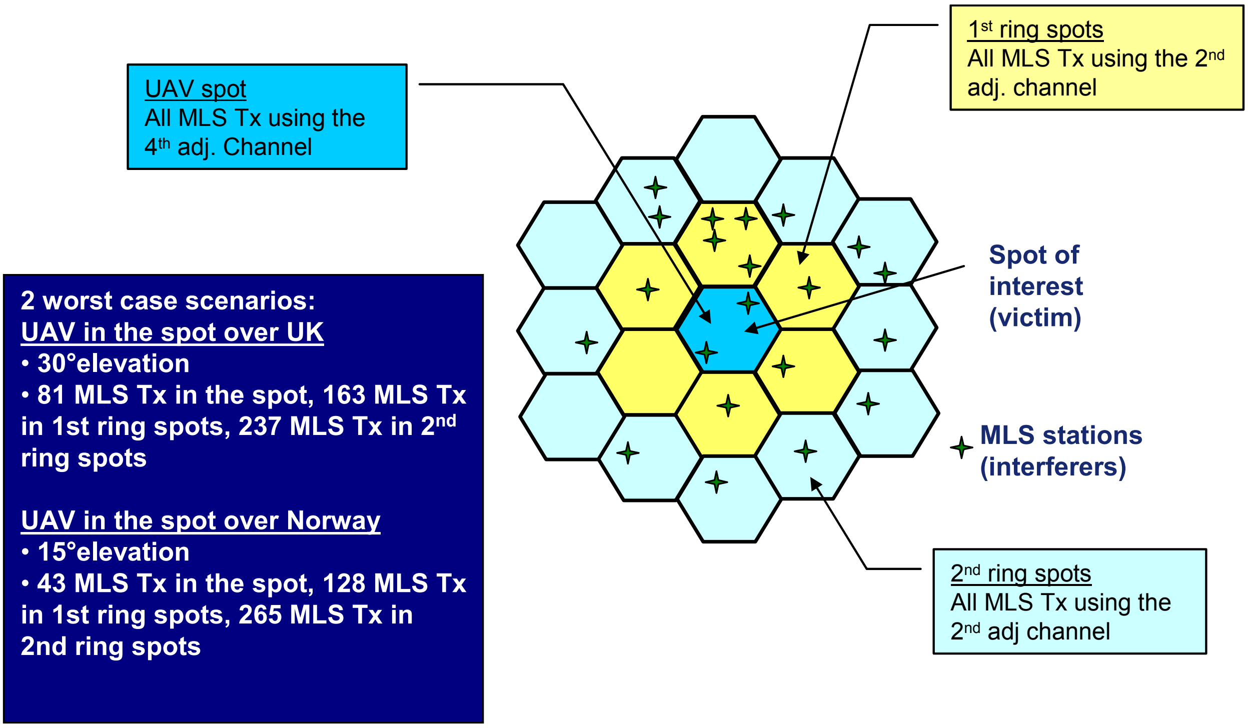
				#Carriers	#UAV
MLS spot	1 x UAV at min vertical distance (using the 4th adj channel)				
	Rx level from 1 UAV	-133.2	dBm/150 kHz	1	1
	2 x UAV at min horizontal distance (using the 4th adj channel)				
	Rx level from 1 UAV	-155.0	dBm/150 kHz	1	1
	Rx level from all UAV	-152.0	dBm/150 kHz	2	2
	13 x other UAV in the MLS spot (using the 4th adj channel)			1	1
	Rx level from 1 UAV	-163.0	dBm/150 kHz	1	1
	Rx level from all UAV	-156.0	dBm/150 kHz	5	13
	Total	**-133.1**	**dBm/150 kHz**	8	16
1st ring spots	8 x UAV in adjacent spots (using the 2nd adj channel)				
	Rx level from 1 UAV	-149.0	dBm/150 kHz	1	1
	Rx level from all UAV	-143.0	dBm/150 kHz	4	8
	24 x UAV in adjacent spots (using the 3rd adj channel)				
	Rx level from 1 UAV	-155.0	dBm/150 kHz	1	1
	Rx level from all UAV	-144.2	dBm/150 kHz	12	24
	8 x UAV in non adjacent spots (using the 1st adj channel)				
	Rx level from 1 UAV	-146.7	dBm/150 kHz	1	1
	Rx level from all UAV	-140.7	dBm/150 kHz	4	8
	56 x UAV in non adjacent spots (using the 2nd adj channel)				
	Rx level from 1 UAV	-175.7	dBm/150 kHz	1	1
	Rx level from all UAV	-161.2	dBm/150 kHz	28	56
	Total	**-137.6**	**dBm/150 kHz**	20	40
2nd ring spots	48 x UAV in adjacent spots (using the 1st adj channel)				
	Rx level from 1 UAV	-152.7	dBm/150 kHz	1	1
	Rx level from all UAV	-138.9	dBm/150 kHz	24	48
	168 x UAV in adjacent spots (using the 2nd adj channel)				
	Rx level from 1 UAV	-181.7	dBm/150 kHz	1	1
	Rx level from all UAV	-163.1	dBm/150 kHz	72	144
	Total	**-138.9**	**dBm/150 kHz**	96	192
	Total	**-131.0**	**dBm/150 kHz**	**124**	**248**

5.4.4 MLS to satellite (UA to satellite link, return)

The aggregation scenario for the MLS to satellite case is presented hereafter.

FIGURE 2-33

Interferences from MLS transmitter to satellite – Aggregation scenario



UAV spot
All MLS Tx using the 4th adj. Channel

1st ring spots
All MLS Tx using the 2nd adj. channel

2nd ring spots
All MLS Tx using the 2nd adj channel

2 worst case scenarios:
UAV in the spot over UK
- **30°elevation**
- **81 MLS Tx in the spot, 163 MLS Tx in 1st ring spots, 237 MLS Tx in 2nd ring spots**

UAV in the spot over Norway
- **15°elevation**
- **43 MLS Tx in the spot, 128 MLS Tx in 1st ring spots, 265 MLS Tx in 2nd ring spots**

Results of the aggregation analysis are presented in the Table 2-10, presenting the intermediate aggregated levels as well as the total aggregated level, which is below the maximum level received at satellite antenna input.

TABLE 2-10

Interferences from MLS transmitter to satellite – Aggregation – Results

		#Spots	**Scenario 1**	**Scenario 2**
	Satellite elevation		30 deg	16 deg
	Orientation ratio		4	4
	MLS Tx antenna pattern loss		12 dB	8 dB
UAV spot	MLS using at least the 4th adjacent channel			
	Rx level from 1 MLS	1	-197.0 dBm	-193.0 dBm
	#MLS stations / spot		81	43
	#MLS stations / spot oriented towards the satellite		21	11
	Rx level from all MLS	1	-183.8 dBm	-182.6 dBm
1st ring spots	MLS using at least the 2nd adjacent channel			
	Rx level from 1 MLS	1	-192.6 dBm	-188.6 dBm
	#MLS stations on the 1st ring		163	128
	#MLS stations on the 1st ring oriented towards the satellite		41	32
	Rx level from all MLS in all spots	6	-176.5 dBm	-173.6 dBm
2nd ring spots	MLS using at least the 2nd adjacent channel			
	Rx level from 1 MLS	1	-214.6 dBm	-210.6 dBm
	#MLS stations on the 2nd ring		237	265
	#MLS stations on the 2nd ring oriented towards the satellite		60	67
	Rx level from all MLS in all spots	12	-196.9 dBm	-192.4 dBm
	All MLS			
	Rx level from all MLS in all spots		-196.9 dBm	-192.4 dBm
	Total	**19**	**-175.7 dBm**	**-173.0 dBm**

5.5 Frequency planning constraints determination

Following graphs present the frequency planning constraints resulting from the single interferer analysis and the aggregation analysis. These constraints are used as inputs for the frequency planning process. Let us note that, although the frequency planning constraints for the return link are given in terms of distance, from an operational point of view, the frequency will not be changed when approaching an MLS coverage area but when entering a satellite spot in which the UA may interfere with an MLS coverage area.

FIGURE 2-34

Frequency planning constraints for the forward link (satellite to UA)

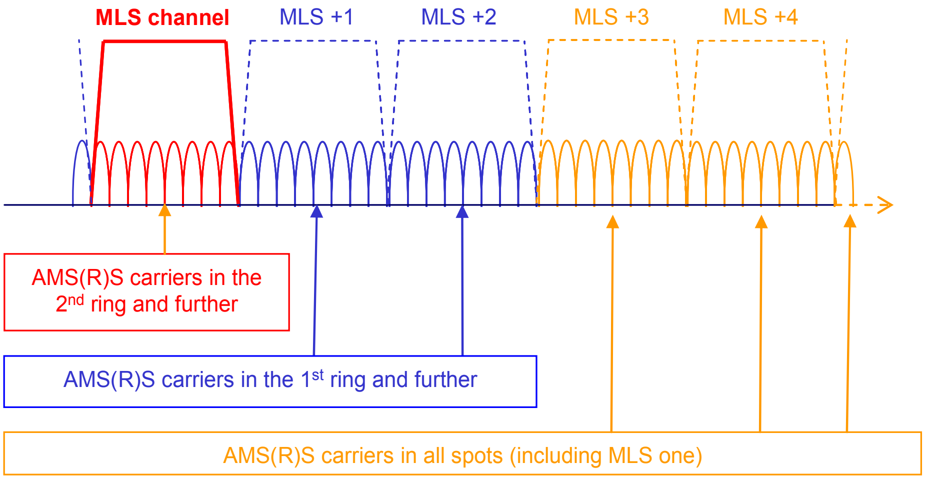
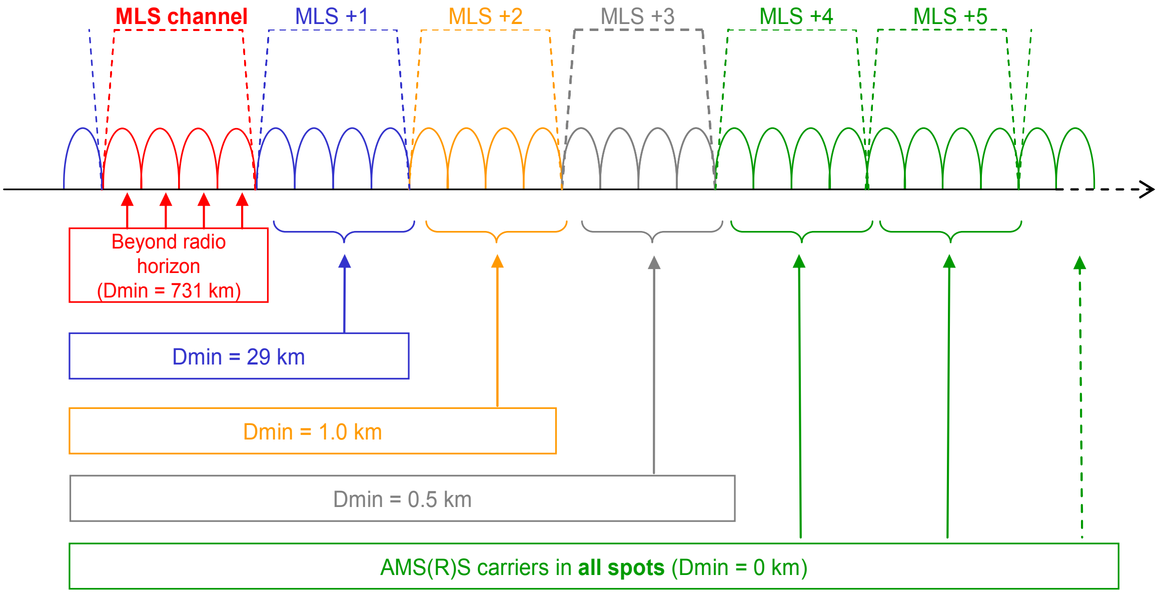


FIGURE 2-35

Frequency planning constraints for the return link (UA to satellite)



A similar study can be performed for the feeder link, if operated as well the 5 030-5 090 MHz band. Resulting frequency planning constraints are significantly relaxed due to:

– the much lower satellite EIRP for the satellite to GES link;

– the high directivity of the GES antenna.

Moreover, contrarily to UA, GES can be located so that interferences with MLS receivers are minimized.

5.6 Frequency planning

The following graph depicts the resulting frequency plan for the complete band and all links (the colour code is explained hereafter):

- Satellite to UA (forward): channels 500 to 550.
- Satellite to GES (return): channels 551 to 567.
- GES to satellite (forward): channels 634 to 650.
- UA to satellite (return): channels 651 to 700.
- Tactical MLS: channels 590 to 610 (see §4.4).

Several GES, distributed over several spots, are considered. This is illustrated in Fig. 2-37.

This frequency plan makes it possible to serve the required number of UA, as derived from Report ITU-R M.2171.

FIGURE 2-36

Resulting frequency plan

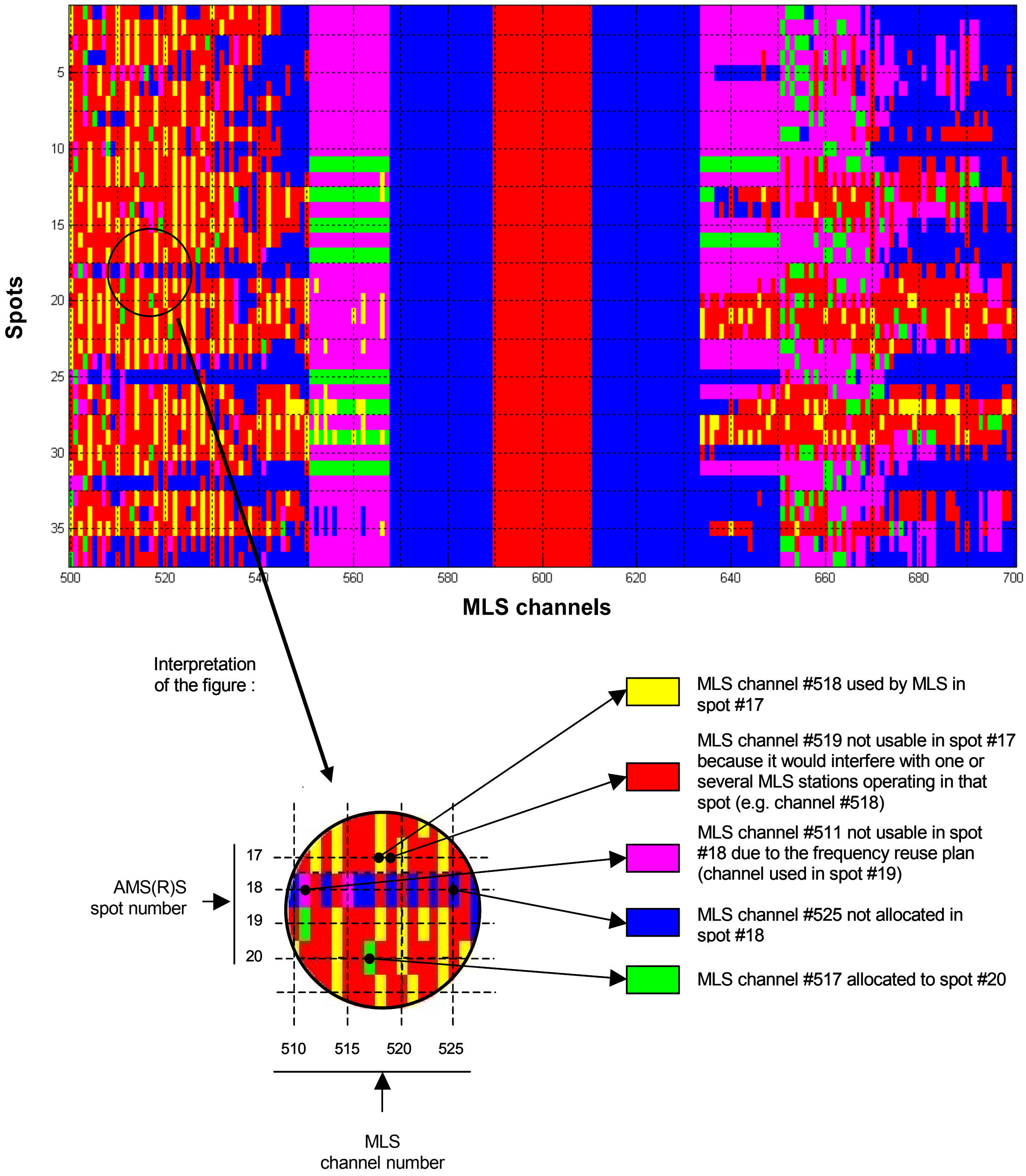
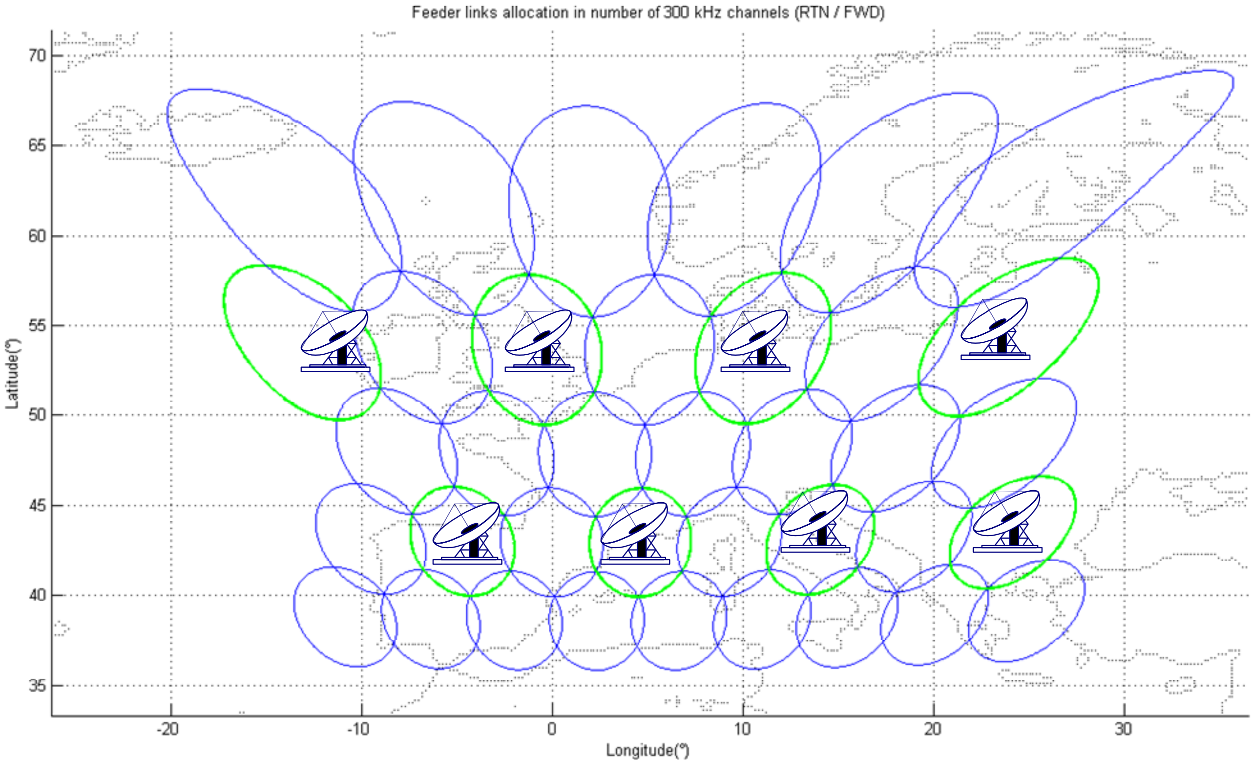


FIGURE 2-37

GES allocation



6 Conclusion

The above studies show that it is possible to design an AMS(R)S system sharing the 5 030-5 091 MHz band with the MLS, even when considering worst-case assumptions.

Indeed, in particular, studies assume a massive MLS deployment in Europe (i.e., approximately 800 MLS stations), which, as considered by ICAO, is a very conservative approach considering latest MLS requirements expressed by ICAO State Members, which are much below 800 stations.

However, even when using these worst case assumptions, studies show that i) the protection criteria for MLS (in-band level below –130 dBm/150 kHz) is met for all interference scenarios and ii) UA spectrum requirements as derived from Report ITU-R M.2171 can be accommodated in the band 5 030-5 091 MHz.

Hence, carefully designed AMS(R)S system in the band 5 030-5 091 MHz safeguards the long-term access to the band for MLS, while enabling additional aeronautical use of the band, which will increase spectrum efficiency.

Reference

[1] International Standards and Recommended Practices (SARPs), Annex 10, Volume 1 (Radio Navigation Aids), ICAO, 6th edition, July 2006.

Annex 3

Glossary

ACI	Adjacent channel interference
ACP	Aeronautical communications panel
ADS	Automatic dependent surveillance
ADS-B	Automatic dependent surveillance – broadcast
ADS-R	Automatic dependent surveillance – rebroadcast
AGL	Above ground level
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
AZ	Azimuth
BAZ	Back azimuth
BER	Bit error ratio
BLoS	Beyond line-of-sight
BW	Bandwidth
CNPC	Control and non-payload communications
CPM	Conference preparatory meeting
DL	Downlink
DME	Distance measuring equipment
DME/P	Precision distance measuring equipment
DME/N	Narrow-spectrum distance measuring equipment
DPSK	Differential phase shift keying
E_b/N_0	Ratio of energy per bit to noise power spectral density
ECC	Electronic Communications Committee
e.i.r.p.	Equivalent isotropically radiated power
EL	Elevation
ES	Earth station
FDD	Frequency-division duplex

FDR	Frequency-dependent rejection
FEC	Forward error correction
FIS-B	Flight Information Service – Broadcast
FSS	Fixed-satellite service
GES	Ground Earth Station
GMSK	Gaussian minimum-shift keying
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System (U.S.)
G/T	Ratio of receiving-antenna gain to receiver thermal noise temperature in kelvins
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronics Engineers
IEEE 802.16e	IEEE standard for mobile broadband wireless access systems
IFF	Identification friend or foe
ILS	Instrument landing system
IPF	Interference protection function
JTIDS	Joint Tactical Information Distribution System
kHz	Kilohertz
L-DACS	L-band digital aeronautical communications system
L-DACS1	L-band digital aeronautical communications system 1 (FDD-based)
L-DACS2	L-band digital aeronautical communications system 2 (TDD-based)
LHCP	Left hand circular polarization
LOS	Line-of-sight
MHz	Megahertz
MIDS	Multifunctional information distribution system
MLS	Microwave landing system
MOPS	Minimum operational performance standards
MS	Mobile service
MSS	Mobile-satellite service
NF	Noise figure
NPR	Noise power ratio
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access
pps	Pulses per second
PRF	Pulse repetition frequency
PW	Pulse width
QAM	Quadrature amplitude modulation

QPSK	Quadrature phase-shift keying
RF	Radio frequency
RHCP	Right hand circular polarization
RNSS	Radionavigation-satellite service
RR	Radio Regulations
RTCA	Radio Technical Commission for Aeronautics
Rx	Receiver
S&A	Sense and avoid
SARPs	Standards and recommended practices
SAT	Satellite
SIR	Signal-to-interference ratio
SNR	Signal-to-noise ratio
SSPA	Solid state power amplifier
SSR	Secondary surveillance radar
small UAS	Small UA system
SV	Service volume
SWAP	Size, weight, and power
TACAN	Tactical air navigation
TCAS	Traffic alert and collision avoidance system
TDD	Time-division duplex
TIS-B	Traffic information services – broadcast
Tx	Transmitter
UA	Unmanned aircraft
UACS	UA control station
UAS	UA system(s)
UAT	Universal access transceiver
UL	Uplink
VHF	Very high frequency
VOR	VHF omnidirectional range