COMPATIBILITY STUDY IN THE AEROMACS FREQUENCY BAND

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Abstract

This paper contains results from compatibility studies between AeroMACS and other systems operating in the same or adjacent frequency bands. These systems are RLAN, AMT, MLS and FSS feeder links. For compatibility with the terrestrial systems, the minimum distance to interferer is calculated, i.e. the minimum distance an interfering transmitter can be from a victim receiver without degrading the system performance beyond a permitted limit. For compatibility with FSS feeder links, the number of AeroMACS systems that may be installed in Europe without causing harmful interference to non-GEO satellite feeder link receivers is calculated. The results presented in this paper indicate that both MLS and AMT may cause harmful interference to AeroMACS if no precautions are made, while this is unlikely to happen when it comes to RLANs. Concerning compatibility with FSS feeder links, more than about 400 airports in Europe must be equipped with large AeroMACS installations to potentially cause harmful interference to FSS systems.

Introduction

At WRC-07, the frequency band 5091-5150 MHz was allocated to aeronautical mobile (R) services (AM(R)S) limited to surface applications at airports. This has lead to the current development of the AeroMACS system for airport surface datalink communications.

This band is however not allocated to AM(R)S systems on an exclusive basis. It is part of the 5000-5150 MHz band allocated to aeronautical mobile satellite (R) service (AMS(R)S) and to aeronautical radionavigation service (ARNS). The WRC-07 instructs the AM(R)S system not to cause harmful interference to, or claim protection from, systems operating in the ARNS band (Resolution 748). Moreover, the adjacent frequency band 5150-5350 MHz is allocated to radio local area networks (RLANs). Before AeroMACS can be implemented, it is necessary to assure that the requirements from WRC-07 are met, and also that harmful interference from RLANs will not cause a degradation of service. The purpose of this document is to summarize the results from compatibility studies between AeroMACS (at its current state of development) and other systems operating in the same or in adjacent bands.

Systems operating outside the 5000-5250 MHz band are not included in this study, as it is assumed that effects due to spurious emissions, as well as second order effects from systems operating outside this 5000 – 5250 MHz band, are insignificant.

The systems included in the study are:

- RLAN (IEEE802.11a): RLAN is a term that may include several technologies. This study is limited to IEEE802.11a systems, although IEEE802.11n and possibly future versions of the IEEE802.11 standard and IEEE802.16 systems may operate in the same band. However, the transmit requirements in this band are defined by national regulations, so that compatibility issues with AeroMACS will most likely be similar for all RLAN systems operating in this band.
- MLS: The use of MLS shall take precedence over other uses of the band 5030-5091 MHz, while the 5091-5150 MHz band is shared with FSS, AMT and AeroMACS systems.
- AMT: The 5091-5250 MHz band is allocated to mobile service for wideband aeronautical telemetry systems for flight testing.
- FSS: Fixed satellite services (Earth-to-space) limited to feeder links of non-geostationary systems may operate in the 5091-5150 MHz band. Currently, Globalstar uses this frequency band.

The compatibility studies between AeroMACS and each of these systems are provided in separate sections of this document.

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Methodology

In the studies involving terrestrial systems, minimum distance to interferer is used as a measure for compatibility. The minimum distance to interferer is a measure on how close an interfering transmitter can be to a receiver without causing degraded performance. In the study involving FSS feeder links, the increase in equivalent noise temperature at the satellite receiver due to AeroMACS installations in Europe is used.

Terrestrial Systems

The methodology used to investigate the compatibility between two technologies is as follows:

- Maximum EIRP and transmit mask of the interfering system are extracted from the relevant specifications. If the systems do not operate on the same frequency, the frequency channels closest to each other will represent the worst case due to the shape of the transmit masks.
- Maximum transmitted power P_t within the victim system's bandwidth is calculated based on the EIRP and the transmit mask of the interfering system, and the bandwidth of the victim system.
- The criterion for when an interfering signal is disturbing a communication is when the interfering signal is stronger than the interference threshold I_{th} of the victim system.
- The free space path loss model is used to estimate the propagation loss as function of distance.
- Based on the four bullet points above, the minimum separation distance d_{min} that may be tolerated without degradation of system performance beyond what is accounted for in the interference margin is derived.

The equation for minimum distance to interferer becomes:

$$d_{min} = \frac{\lambda}{4\pi} \cdot 10^{\frac{P_t + G_r - I_{th}}{20}}$$

In the equation above, G_r denotes the receive antenna gain, including the cable loss. P_t includes the transmit power, antenna gain and cable loss in the transmitter, in addition to the attenuation due to the transmit mask if the systems are operating on different frequencies.

Satellite Feeder Link

Concerning the interference from terrestrial systems to fixed satellite service feeder link receivers in the 5091-5150 MHz band, the following requirement to increased equivalent noise temperature ΔT_s applies:

- Aggregate interference from aeronautical security, aeronautical telemetry and AM(R)S should total no more than 3% $\Delta T_s / T_s$ (Resolution 748f).
- Interference of no more than 1% $\Delta T_s / T_s$ from AMT aircraft station transmission to fixed-satellite service spacecraft receivers (Resolution 418e).

Based on these two resolutions, a reasonable interference criterion for AeroMACS is that transmitters should not lead to more than 2% increase in the equivalent noise temperature at the satellite receivers. Applying this criterion, the maximum interference level allowed is then:

$$I = 10 \log_{10}(kTBC) = -157.3 \text{ dBW}$$

The following values are used:

- $k = 1.38 \cdot 10^{-23}$ (Boltzmann's constant)
- $B = 1.23$ MHz (Receiver bandwidth)
- $T = 550$ K (Noise temperature of the receiver)
- $C = 0.02$ (Interference criterion)

AeroMACS Parameters

AeroMACS is currently in the process of being specified. In this study, specifications from a draft of the AeroMACS system requirement document [1] are used to assess mutual impact between AeroMACS and other systems. If the final system requirements are different from those in [1], the results in this publication should be revised.

Aeromacs Transmitter Specifications

The EIRP values used in this study are given in Table 1. The maximum transmit power of 22 dBm is lower than power classe 2 defined in the IEEE802.16-2009 standard [2], but is considered to be realistic for future AeroMACS systems.

Table 1. AeroMACS transmit parameters

	BS	**A/C**
In band		
Maximum transmitted power from HPA	22 dBm	20 dBm
Antenna cable loss	2 dB	2 dB
Antenna gain	15 dBi	6 dBi
EIRP	*35 dBm*	*24 dBm*
Spurious domain		
Maximum spectral density at port of antenna per 1 MHz	-30 dBm	-30 dBm
Antenna gain	15 dBi	6 dBi
Maximum transmitted power per 1 MHz in spurious domain	*-15 dBm*	*-24 dBm*

Table 1 also includes maximum transmitted power per 1 MHz in the spurious domain. According to Annex 2 of [3], the maximum spurious emissions during bursts shall be less than -30 dBm at 250% of the bandwidth away from the center frequency. It is assumed that this power is delivered to the port of the antenna (see consideration k of [3]). The reference bandwidth is 1 MHz.

Furthermore, it is assumed that within the band edges, the maximum spectral density beyond 250% of the bandwidth away from the centre frequency shall not exceed the limit of the spectral mask or the limit for spurious emissions, whichever is the higher. However, beyond the band edges it is assumed that it is the limit for spurious emissions that applies, and not the spectral mask.

The same transmit spectral mask is assumed as in WirelessHUMAN (see Table 2 and Figure 1), i.e. IEEE802.16 systems operating in unlicensed bands such as the U-NII bands in the USA. As WirelessHUMAN is only defined for channel bandwidths of 10 MHz and 20 MHz, the values for 5 MHz channels are given as halves of the 10 MHz values.

Table 2. Spectral Mask Parameters

Channel bandwidth [MHz]	A [MHz]	B [MHz]	C [MHz]	D [MHz]
5	2.375	2.725	4.875	7.375
10	4.75	5.45	9.75	14.75

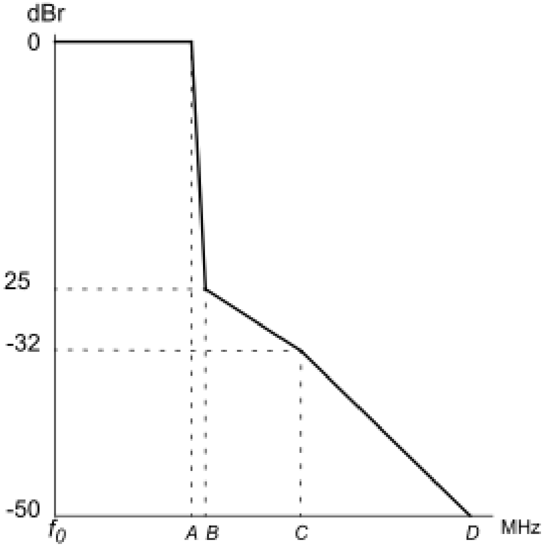

Figure 1. AeroMACS Spectral Mask

Antenna characteristics for AeroMACS systems are not specified in [1]. Therefore parameters from similar point-to-multipoint systems operating in other environments are used in this study.

In [4], equations are provided for radiation pattern to be used in absence of detailed information regarding the antennas involved. In this study, the antenna diagram is only used in the FSS feeder link compatibility study. Therefore the parameters provided in Sec. 3.2.1 of [4], corresponding to average side-lobe levels, have been used for the base station antenna. According to [4], these antenna parameters are to be used “to predict the aggregate interference to a geostationary or non-geostationary satellite from numerous fixed wireless stations”.

The radiation diagrams in azimuth and elevation are shown in Figure 2. The main antenna parameters are as follows:

- Horizontal beamwidth: 120 degrees
- Vertical beamwidth: 6 degrees
- Maximum gain: 15 dBi

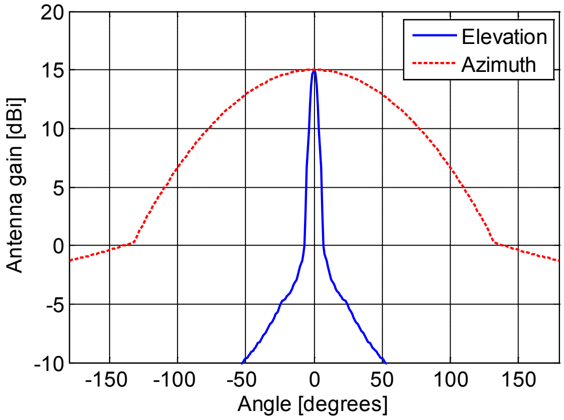

Figure 2. BS Antenna Diagram

For the A/C, it is assumed that the antenna pattern is omnidirectional in the azimuth plane. Maximum antenna gain is 6 dBi.

Receiver Specifications

The receiver specifications of AeroMACS used in this study are listed in Table 3. The channel bandwidth is either 5 MHz or 10 MHz, so both cases are included in this study. For the 5 MHz channel case, a total of eleven "non-overlapping" channels can operate simultaneously. For 10 MHz channels, the number is five.

The effective thermal noise in dBm is [1]:

$$P_N = -174 + 10\log_{10}(B)$$

Table 3. AeroMACS Receiver Parameters

	5 MHz channels	10 MHz channels
Thermal noise level P_N	-107.38 dBm	-104.37 dBm
Noise factor N_F	8 dB	8 dB
Implementation loss L_{imp}	5 dB	5 dB
Minimum SNR $(E_s/N_0)_{min}$ ($r = 1/2$ CC, QPSK, SISO)	5 dB	5 dB
Receiver sensitivity *S*	**-89.38 dBm**	**-86.37 dBm**

Using the bandwidth definitions of the IEEE802.16-2009 standard, the effective thermal noise becomes:

5 MHz channels: $P_N = -107.36$ dBm

10 MHz channels: $P_N = -104.37$ dBm

The receiver sensitivity (i.e. the minimum allowed received power required to decode the signal with a specified bit error rate (BER)) is given by:

$$S = P_N + N_F + L_{Imp} + \left(\frac{E_s}{N_0}\right)_{min}$$

P_N is the receiver noise power, N_F is the noise figure, L_{Imp} is the implementation loss, and E_s/N_0 is the minimum signal-to-noise ration (SNR) required for guaranteeing a BER less that the specified maximum BER. Values for N_F (measured at the antenna connector) and L_{imp} are taken from the IEEE802.16-2009 standard (Sec. 8.4.14.1). It must be noted that the E_s/N_0 values are obtained in an AWGN environment.

It should also be noted that the receiver sensitivity in Table 3 corresponds to the lowest data rate (QPSK, rate 0.5 coding). If higher data rates are required, the minimum SNR requirement will increase, leading to higher sensitivity figure. According to Table 545 in [2], minimum SNR for 64QAM rate 0.75 coding is 20 dB, leading to an increase in 13 dB in sensitivity with respect to the numbers in Table 3.

The interference margin used in different studies varies. In [5], a protection criterion of I/N of -6 dB, corresponding to an interference margin of $10\log 1.25 \approx 1$ dB is used for an AMT-AeroMACS compatibility study, leading to a range reduction of about 10% in free space. In [6], an interference margin of 3 dB (or I/N=0 dB) in forward link and 2 dB (or I/N=-2.3 dB) in return link is assumed in an FSS-AeroMACS compatibility study, corresponding to 30% and 20% reduction in range in free space, respectively.

In this study, the interference margin for AeroMACS is set to 3 dB, which means that the receiver must tolerate interference power equal to the thermal noise. The maximum interference level P_I can then be expressed in linear scale as:

$$P_I = kT_eB = kT_0(N_F - 1)B$$

T_e is the equivalent noise temperature and T_0 is set to 290 K.

The interference threshold is defined as the maximum tolerated interference power. For the two bandwidths it is given by:

5 MHz: $I_{th} = -100.1$ dBm

10 MHz: $I_{th} = -97.1$ dBm

RLAN Compatibility

The 5150-5350 MHz and 5470-5725 MHz bands are allocated to RLANs for mobile services, except for aeronautical mobile services, on a primary basis. The dominant RLAN standard designed to operate in these frequency bands today is IEEE802.11a. The recent standard IEEE802.11n may operate in the same band.

The 5150-5350 MHz band is only for indoor use [7]. Indoor use means herein the use inside of a permanent domestic or commercial building which will typically provide the necessary attenuation to facilitate coexistence with other systems operating outdoors in the same frequency band.

Interference from RLAN to AeroMACS

The parameters used in the calculation of minimum acceptable separation are provided in Table 4.

The lowest IEEE802.11a channel has centre frequency 5180 MHz. The transmit mask for IEEE802.11a is defined within +/- 30 MHz from the centre frequency. Hence, even the highest AeroMACS channel is located within the spurious domain of the lowest IEEE802.11a channel.

Table 4. Parameters Used in Calculations

IEEE802.11a transmitter	
EIRP	23 dBm
Maximum transmitted power in AeroMACS band $P_t = -30 + 10\log(B)$ dBm	-23 dBm (5 MHz) -20 dBm (10 MHz)
AeroMACS receiver	
Antenna gain BS	15 dBi
Antenna gain A/C	6 dBi
Cable loss (BS and A/C)	2 dB
Interference threshold (I_{th})	-100.1 dBm (5 MHz) -97.1 dBm (10 MHz)
Propagation channel parameters	
Path loss model	Free space
Propagation loss through walls (L_{wall})	6 dB and 10 dB

The propagation loss through walls needs to be taken into account when calculating the minimum separation distance between a RLAN transmitter and an AeroMACS receiver:

$$d_{min} = \frac{\lambda}{4\pi} \cdot 10^{\frac{P_t + G_r - L_{wall} - I_{th}}{20}}$$

Figure 3 shows calculated received power as function of distance for base stations and mobile stations, and for wall attenuations equal to 6 dB and 10 dB.

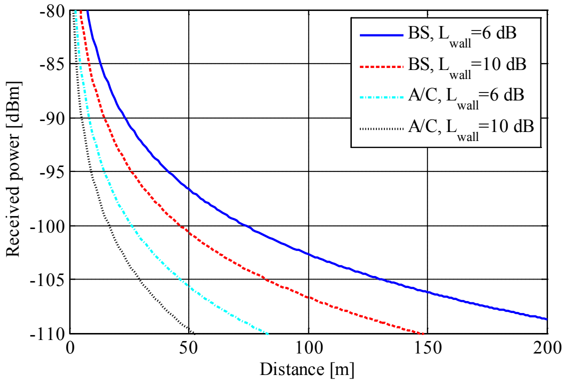

Figure 3. Received Power

Inserting the parameters of Table 4 into the equation of the minimum distance to interferer provides the numbers in Table 5.

Table 5. Minimum Distance to Interferer

Type of receiver	Wall attenuation [dB]	Minimum distance to interferer [m]
BS	6	74
BS	10	47
A/C	6	26
A/C	10	17

The results indicate that both A/C and base stations may be affected by IEEE802.11a networks located at quite a substantial distance, provided that the interference enter through the main lobe of the AeroMACS antenna. The worst case is when relatively little attenuation from walls is combined with the high gain AeroMACS base station antenna.

Interference from AeroMACS to IEEE802.11a

IEEE802.11a equipment will operate in the spurious domain of even the highest AeroMACS channel. Table 6 summarizes the parameters used in calculation of the minimum distance between a AeroMACS transmitter and a victim IEEE802.11a receiver.

Table 6. Parameters Used in Calculation

AeroMACS transmitter	
Maximum transmitted power in RLAN band $P_t = -15 + 10\log(B)$ dBm	-2 dBm (BS) -11 dBm (A/C)
IEEE802.11a receiver	
Antenna gain (G_r)	6 dBi
Cable loss (L_{cable})	0 dB
Interference threshold (I_{th})	-93.7 dBm
Propagation channel parameters	
Path loss model	Free space
Propagation loss through walls (L_{wall})	6 dB and 10 dB

The resulting received power as function of distance is shown in Figure 4, and the minimum distance requirements are given in Table 7.

Table 7. Minimum Distance Requirements

Wall attenuation [dB]	Minimum distance to interferer [m]	
	BS	A/C
6	137	48
10	86	30

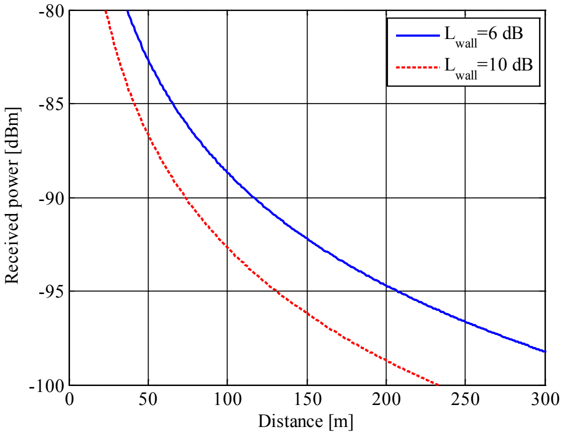

Figure 4. Received Power

The results indicate that interference from AeroMACS, and particularly from AeroMACS base stations, may cause a problem for IEEE802.11a equipment operating in the 5150-5250 MHz band within the airport area.

Conclusions on RLAN Compatibility

IEEE802.11a systems may in the worst case scenarios disturb AeroMACS communications if IEEE802.11a STAs or APs are located closer than 50-100 meters to an AeroMACS BS or 20-30 meter from an A/C. In practical situations this seems very unlikely to occur.

AeroMACS systems may represent a problem to IEEE802.11a systems if the distance between AeroMACS BS transmitters and IEEE802.11a receivers is less than about 100-150 meters, and less than 30-50 meters for A/C transmitters. For AeroMACS BS transmitters the main beam is narrow so that its RLAN radios rarely will enter the main beam, and for AeroMACS A/C transmitters the minimum distance is quite small. Moreover, IEEE802.11a will not be used for safety critical services, so that if the rare situation that an AeroMACS transmitter interferers with IEEE802.11a equipment occurs, it will not be critical.

As a conclusion of this section, compatibility between AeroMACS and IEEE802.11a systems is considered not to be a negligible threat.

AMT Compatibility

Resolution 418 of WRC-07 allocates the 5091-5250 MHz band to aeronautical mobile service for telemetry (AMT) applications. The AMT applications are limited to no-commercial flights for the purpose of development, evaluation and/or certification of aircraft in airspace designated by administrations for test purposes. Only communication from the aircraft to the ground will occur.

There is not much available information of the system characteristics of AMT systems. Information used in this section is taken from references [8][9].

Table 8. AMT Airborne Transmitter Characteristics

Expected typical transmitter power	20W
Number of transmitters per aircraft	2
Airborne transmit antenna gain	3 dBi
Bandwidth	10 MHz

Each aircraft will contain two transmitters and two transmit antennas. One antenna is located under the aircraft cockpit and one mounted on top of the tail. The two transmitters do not radiate identical signals. In the case where a receiver has clear view of both antennas, the total EIRP will therefore be 49 dBm for 10 MHz bandwidth (and 46 dBm over a 5 MHz band width).

Interference from AMT to AeroMACS

The parameters used to calculate the minimum separation distance are provided in Table 9.

If the AMT system is transmitting at the same frequency as the AeroMACS system, the minimum separation distance becomes:

- For AeroMACS BS: 418 km
- For AeroMACS A/C: 148 km

No information is provided regarding transmit mask of AMT transmitters. If a spectral mask identical to the AeroMACS spectral mask is assumed, the transmit power at a frequency more than 14.75 MHz away from the AMT center frequency would be attenuated by 50 dB. Provided that the separation between the center frequencies of the two systems is above about 20 MHz (for 10 MHz AeroMACS), the minimum separation distance becomes:

- For AeroMACS BS: 1322 m
- For AeroMACS A/C: 469 m

Table 9. Parameters Used in Calculations

AMT airborne transmitter	
EIRP	49 dBm (10 MHz) 46 dBm (5 MHz)
AeroMACS receiver	
Antenna gain BS	15 dBi
Antenna gain A/C	6 dBi
Cable loss BS and A/C	2 dB
Interference threshold (I_{th})	-100.1 dBm (5 MHz) -97.1 dBm (10 MHz)

Interference from AeroMACS to AMT

Interference from AeroMACS to AMT ground receivers is not considered to pose any problem. The AMT ground antenna is typically a parabolic disc antenna tracking the aircraft with a gain of about 40 dBi. The beam width will be about 2.2 degrees, so that interference entering through the main lobe is unlikely to occur. Moreover, if it should occur, it can be tolerated [8].

Conclusions on AMT compatibility

AMT systems will only operate in the 5091-5150 MHz band for test purposes. Hence, it is not a system operating on permanent basis such as e.g.

AeroMACS. Still, it is important that safety critical AeroMACS services are not interrupted by AMT transmissions. The high EIRP of airborne AMT transmitters may therefore prevent AMT and AeroMACS to operate on the same frequency within the same area. More information regarding the spectral mask of AMT signals is required to estimate the minimum distance in frequency between AMT transmitters and AeroMACS receivers to avoid harmful interference.

MLS Compatibility

The band 5030-5091 MHz is allocated for the operation of MLS for precision approach and landing. The requirements of this system shall take precedence over other uses of this band. The extended MLS band is located at 5091-5150 MHz, i.e. the band used by AeroMACS. 200 channels with 300 kHz spacing are located in the 5031-5091 MHz band, while 198 channels with 300 kHz spacing are located in the 5091-5150 MHz extension band.

Interference from MLS to AeroMACS

Interference problems from MLS to AeroMACS systems may arise when aircraft are located on the runways and taxiways where they will be within the main beam of MLS transmitters. The MLS signal may then interfere with the forward link communications from the AeroMACS base station to the aircraft.

Table 10. MLS DPSK Transmit Parameters

Transmit power	43 dBm
Transmit antenna gain	2 dBi to 8 dBi in coverage, 0 dBi outside
Antenna gain drop for 0 degree elevation	6 dB
EIRP for 0 degree elevation	45 dBm

It is assumed that MLS and AeroMACS systems do not operate in overlapping frequency bands. The MLS signal contains continuous wave signals with DPSK preambles. Out-of-band emission of the DPSK signal is then the only source of interference from MLS to AeroMACS.

Worst case out-of-band power at frequency offset Δf from the MLS centre frequency and measured over a bandwidth B can be analytically modeled as follows [10]:

$$L(\Delta f) \approx \frac{1}{2\pi^2}\frac{f_d\, B}{\Delta f^2}$$

The MLS DPSK bandwidth (or modulation rate) f_d is 15.625 kHz. The bandwidth is defined as $B = f_2 - f_1$, where f_1 , f_2 and B all are much larger than f_d. The minimum distance to interferer is then given by:

$$d_{min}(\Delta f) = \frac{\lambda}{4\pi} \cdot 10^{\frac{EIRP + G_r - I_{th} + L(\Delta f)}{20}}$$

The following parameters are inserted in the equation:

- EIRP=45 dBm
- $G_r = 4$ dBi (including 2 dB cable loss)
- $I_{th} = -100.1$ dBm (5 MHz channel)
- $B = 4.59$ MHz (for calculation of $L(\Delta f)$)

The same results are obtained for 10 MHz AeroMACS channels, as 3 dB increase in the interference level is counteracted by 3 dB decrease in the interference threshold.

The resulting minimum distance to interferer as function of frequency offset is provided in Figure 5. The frequency offset must be in the order of tens of MHz in order to reduce the minimum distance to interferer to 100-200 meters.

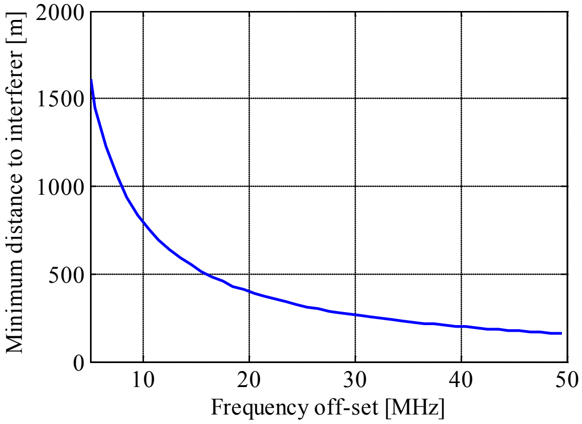

Figure 5. Minimum Distance to Interferer

Interference from AeroMACS to MLS

Assuming that the frequency offset between the MLS system and the AeroMACS system is large enough for the MLS system to operate in the spurious domain of the AeroMACS system, the power spectral density of an AeroMACS BS in the MLS band is ≤ 15 dBm/MHz. This implies that there is at least 10 MHz guard band between the systems for 5 MHz AeroMACS channels and 20 MHz guard band for 10 MHz AeroMACS channels. For 150 kHz bandwidth this corresponds to −23.2 dBm/150 kHz.

Assuming an interference threshold of -130 dBm and, receiver antenna gain $G_r = 0$ dBi, the minimum distance to interferer becomes 1014 meters (sdee Figure 6). For narrower guard bands, the minimum distance to interferer may be considerably higher.

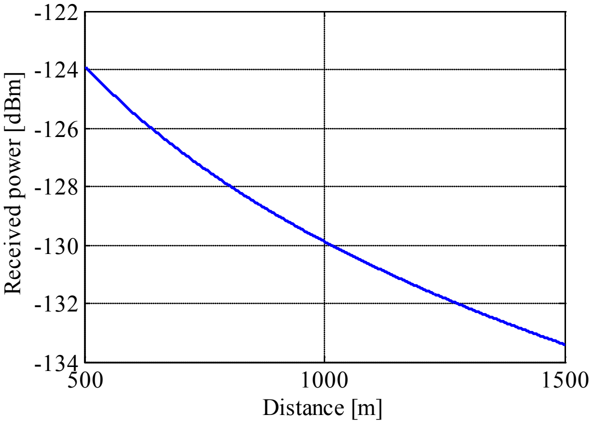

Figure 6. Interference Level as Function of Distance

Conclusions on MLS compatibility

Results demonstrated in this section indicate that interference from MLS to AeroMACS may constitute a serious problem for the aircraft which is on or close to the runway. Without a guard band, the minimum distance to interferer is over half a km. For 40 MHz guard band, the minimum distance is still about 130 meters. The implication of this is that AeroMACS may have problems to operate close to MLS transmit antennas.

Interference from AeroMACS to MLS may also be critical, even with guard bands of at least 10 MHz for 5 MHz AeroMACS systems and 20 MHz for 10 MHz AeroMACS systems. However, MLS is used during approach, and in a controlled airport environment it seems easier to combat AeroMACS interference on the MLS systems than the other way around.

FSS Compatibility

The FSS compatibility study consists of an assessment of the maximum total interference level from all AeroMACS equipped airports in Europe perceived from a satellite. As mentioned on page 2, the increase in the equivalent noise temperature is not allowed to be more than 2%, corresponding to an interference threshold of -157.3 dBW.

In Figure 7, the hundred busiest airports in Europe are illustrated. They are scattered relatively uniformly over the continent, from the Canary Islands in the south to Trondheim in the north, and from Dublin in the west to Moscow in the east.

Figure 7. Hundred Busiest Airports in Europe

Airport Characteristics

In order to be able to estimate the maximum total interference level, some assumptions must be made regarding the AeroMACS installations at the airports. In this study, all airports are assumed to fall into one of two groups (see Figure 8):

- Large airports: A total of 10 cells are covering the airport, and each cell has 3 sectors. Hence, a total of 30 sectors cover the airport. As eleven 5 MHz frequency channels are available, each frequency channel is used three times (except for 3 frequency channels that are only used twice). The frequency planning of the airport is so that three sectors operating on the same frequency are oriented with 120 degrees separation. How the cell planning is done, will of course depend on the actual airport. For airports like Charles de Gaulle and Barajas, two cells could cover the runways, and the remaining eight cells could cover the gates and parking areas where there is a high demand for AOC data traffic.

- Small airports: A total of 3 cells are covering the airport, and each cell has 3 sectors. Hence, a total of 9 sectors cover the airport. As eleven 5 MHz frequency channels are available, each frequency channel is only used one time at each airport (except for 2 frequency channels that are not used at all).

Further discussions may prove that other cell topologies than the two considered in this study are more relevant. However, keeping the assumptions relatively simple at this stage permits to draw some general conclusions on what the criteria are for AeroMACS not to cause harmful interference to FSS systems.

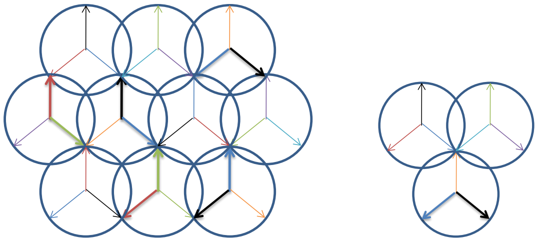

Figure 8. Schematic Illustrations of Cell Patterns

Satellite Characteristics

Table 11 shows the satellite parameters included in the study.

Table 11. Satellite Receiver Parameters

Antenna gain G_{sat}	4 dBi
Antenna feeder loss $L_{feedsat}$	2.9 dB
Polarisation loss L_p	1 dB
Bandwidth B	1.23 MHz
Height above ground	1414 km

As the bandwidth of AeroMACS is larger than the bandwidth of the satellite feeder link, only a part of the transmitted energy will enter into the satellite receiver chain. The AeroMACS channel bandwidth is 5 MHz, equivalent to a loss of:

$$B_f = 10\log(B_{sat}/B_{AeroMACS}) = -6.1 \text{ dB}$$

If the AeroMACS bandwidth is twice as large (10 MHz), the loss is 3 dB higher ($B_f = -9.1$ dB).

Received Power Level at Satellite

The received power P_r at the satellite from one AeroMACS transmitter can be estimated as:

$$P_r = P_t + G_{MIMO} + (G_t(\varphi,\theta) - L_c) + G_{sat} - L_{free}(d) - L_{feedsat} - L_p + B_f - 30 \text{ dBW}$$

The parameters involved in the equation (in addition to those provided in Table 11) are:

- $P_t = 22$ dBm
- $G_{MIMO} = 3$ dB (Assuming two BS transmit antennas)
- $G_t(\varphi,\theta)$ antenna diagram as function of azimuth and elevation angles.
- L_c cable loss in the transmitter
- $L_{free}(d)$ free space path loss

The antenna parameters provided in [4] for a 120 degree sector antenna with average side-lobe level is used.

The characteristics of the transmitted signals are close to Gaussian, and they are independent. The total power level can therefore be computed as the sum of the individual power levels.

The total power level for a number of scenarios has been calculated for a grid of sub-satellite point positions. The results of the simulations including the hundred busiest airports in Europe, and assuming that they all belong to the large airport class, are shown in Figure 9. In this case, the maximum power level is calculated to be -162.5 dBW, which is well below the threshold of -157.3 dBW. The result therefore indicate that FSS compatibility will not pose any problem over Europe, provided that maximum hundred airports are equipped with AeroMACS, and that each airport does not have more than ten cells and 2 sectors per cell.

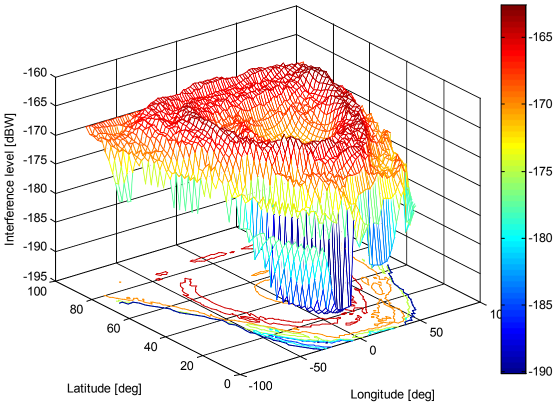

Figure 9. Interference Level for 100 Large Airports

This result assumes 5 MHz AeroMACS channels, BS to A/C communication, and that the relative orientation of BS antennas between airports are independent. Simulations have been done for other cases.

In the case where 10 MHz channels are used instead of 5 MHz channels, the number of co-frequency sectors per large airport is doubled from three to six. Simulations with only large airports provide the same result as for 5 MHz channels. The explanation for this is quite simple. When the signal bandwidth is doubled and the transmit power kept constant, the interference power from one base station entering the satellite receive filter is divided by two. This reduction is however balanced by the fact that twice as many base stations transmit at that frequency. If, on the other hand, there are only small AeroMACS installations, so that the frequency reuse does not increase when doubling the channel bandwidth, then the interference level will increase by 3 dB.

In the case where uplink communication is assumed instead of downlink communication, the total interference level is reduced to -164.5 dBW. This corresponds to the reduction in transmit power from each A/C (transmit power is 22 dBm for BS and 20 dBm for A/C – see Table 1). Hence, the reduced antenna gain of A/C transmitter antennas does not have any impact. This is also quite logical for a large number of airports, where the antennas point in arbitrary directions. The average antenna gain over all directions will be the same for both base station and A/C antennas. For a small number of airports, uplink communication will however give lower maximum interference level than downlink communications due to the reduced antenna gain.

In the case where all base station antennas point towards the satellite, there is a moderate increase in interference (0.5-0.6 dB) for hundred large airports. The reason why the increase is so moderate is that at the large airports, there are always three sectors with 120 degree separation in orientation operating on the same frequency. Together, these three antennas form a close to omnidirectional antenna. In the small airport case, where each frequency channel is used in only one 120 degree sector, the increase in interference is about 3.5 dB when all antennas is pointed towards the satellite.

In all cases described above, the resulting interference level is well below the threshold defined for FSS receivers. It is of interest to estimate how many airports that may operate AeroMACS systems before the threshold is exceeded. This was done by adding airport locations to the hundred busiest airports until the threshold was reached. However, only the locations of the hundred busiest airports are easily available. Therefore simulated airport locations were added to the hundred busiest airports. The simulated locations were selected randomly between 0 and 30 degrees in longitude and between 40 and 60 degrees in latitude.

In Figure 10, an example of 400 airport locations added to the 100 busiest airports is shown, and in Figure 11 the corresponding interference level as function of sub-satellite plot is provided. The maximum interference level is -156.8 dBW.

Figure 12 shows the maximum total interference level as function of the number of AeroMACS installations in Europe. For the large airport model, about 400 airports can be equipped with AeroMACS before the maximum total interference level at the satellite receivers exceeds the threshold. For small airports, the number is well above 1000 airports.

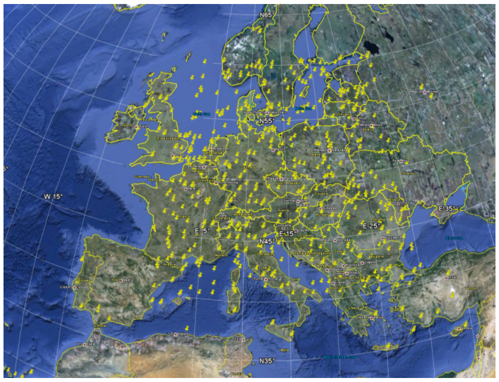

Figure 10. Example of 400 Simulated Airport Locations Added to the 100 Busiest Airports

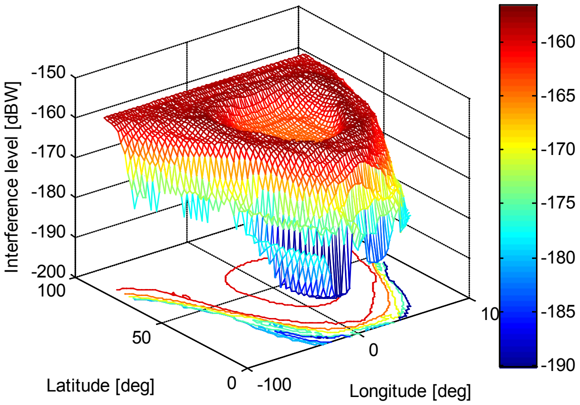

Figure 11. Interference Level for 500 Large Airports

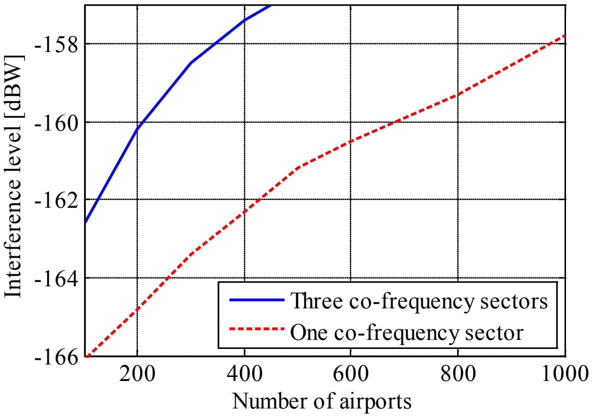

Figure 12. Interference Level for Large Airports

Conclusions on FSS Compatibility

Based on the simulation results in this report, it seems that AeroMACS in Europe will not cause harmful interference to Globalstar satellites unless 480 or more large installations (10 cells with 3 sectors per cell) are in operation. With smaller installations, the number will be even higher.

The simulated airport locations are scattered randomly over a large area. This leads to a lower maximum interference level than if the airports are clustered within small areas, in which case high peaks of interference may be observed in some satellite positions. Hence, the number of permitted AeroMACS equipped airports may be reduced if large concentration of independent AeroMACS systems within small areas occurs.

These results have been compared with similar studies in the US. The US results seem to provide about 3-4 dB higher maximum interference level than the results presented in this paper, given the same conditions. In the U.S., however, real airport locations have been used for all airports. It is believed that this difference between the results is due to the high concentration of airports in the eastern U.S. compared to in Europe, and in particular in out simulated case. An increase in interference of 3 dB in our results would lead to a maximum of only about 200 AeroMACS permitted installations instead of 400.

In both the U.S. and European studies, the required number of installations to cause harmful interference will most probably be higher then the numbers provided in this section due to several reasons:

- In the simulations, it is assumed that all base stations (or mobile stations) at all airports operating on a given frequency channel transmit at maximum power level at the same time. This will very rarely happen in practice. If e.g. half of the base stations transmit simultaneously, the resulting maximum interference level will be about 3 dB lower.
- In the case where base stations are located in between gates and terminal buildings, blockage towards the satellites at low elevations will often occur and reduce the total interference level considerably. If base stations are located on top of control towers and tall buildings, it is likely that the antennas will be tilted downwards. This will also cause reduced total

interference level if directions above the horizon fall outside the main lobe.

- If a very large number of airports (e.g. 500-1000 airports) install AeroMACS, it is likely that the majority of them will install small AeroMACS network. If e.g. only one cell with three sectors is installed, not all available channels will be used. By distributing the available channels between such airports, the number of installations may be further increased without causing harmful interference.

The results of this study are based on a number of assumptions. The results should be revised in the cases where:

- The actual AeroMACS transmitter parameters prove to be different than those assumed in this study. In particular the transmit power, the cable loss, and the number of transmit antennas at the base stations are of importance for the resulting interference level.
- The criterion for harmful interference or satellite parameters such as antenna gain and feeder loss is different than what is assumed in this study.
- AeroMACS installations with more than 10 cells are deployed, e.g. to provide very high data rate communication at the gate area.

Conclusions

This publication provides results from compatibility studies between AeroMACS and other systems operating in the 5000-5250 MHz band. The main conclusions are as follows:

- MLS signals may cause harmful interference for AeroMACS receivers, even in the case where the two systems are separated in frequency by tens of MHz. Possible mitigation techniques include placing AeroMACS base stations away from the main beam of MLS transmitters. However, the MLS azimuth sub-system transmitter will cover the runways and consequently interfere with the AeroMACS receivers of arriving aircraft if the distance is too short. As the interference level decreases with increased frequency separation, the two systems should, if possible, also be separated as much as possible in frequency. Any installed MLS system should therefore be included in the frequency planning of an AeroMACS system.
- AMT signals from aircraft to ground may cause harmful interference to AeroMACS receivers due to their high transmit power. AMT systems do however only use the frequency band for test flights, and the use of frequencies should be coordinated with the AeroMACS system.
- Out-of-band interference from RLAN systems will not cause a problem for AeroMACS. This conclusion is based on the assumption that RLAN transmitters operating in the 5150-5250 MHz band do not operate within the airport area close to AeroMACS equipment.
- Interference from AeroMACS systems will not constitute a problem for FSS systems over Europe, provided that the number of airports equipped with AeroMACS is not above about 400, and provided that the total interference from each airport is not substantially higher than that assumed in this study.

It is important to note that all conclusions drawn above are based on theoretical analyses. As most theoretical work involving wireless communications, they should be validated through real measurements. Also, if the assumptions made in this work regarding the parameters of the systems involved prove to be different than those of future deployed systems, the results should be revised.

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