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Compatibility analysis between wireless avionic intra-communication systems and systems in the existing services in the frequency band 4 200-4 400 MHz

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REPORT ITU-R M.2319-0

Compatibility analysis between wireless avionics intra-communication systems and systems in the existing services in the frequency band 4 200-4 400 MHz

(2014)

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Scope

This Report provides compatibility and sharing studies performed between wireless avionics intra-communication (WAIC) systems and existing systems in the aeronautical radionavigation service, the Earth exploration-satellite service (passive) and the fixed service in the frequency band 4 200-4 400 MHz as well as a summary of corresponding results in response to Resolution 423 (WRC-12).The studies are contained in the Annexes to this Report.

1 Introduction

This Report contains compatibility and sharing studies for wireless avionics intra-communication (WAIC) systems in the frequency band 4 200-4 400 MHz. The frequency band is allocated to the aeronautical radionavigation service (ARNS) for radio altimeters installed on board aircraft and for the associated transponders on the ground by Radio Regulations (RR) footnote No. **5.438**. It may further be used by passive sensors in the Earth exploration-satellite service (EESS) and the space research service (SRS) on a secondary basis. It is also allocated to the fixed service (FS) on a secondary basis in one administration per RR footnote No. **5.439**. Furthermore, the standard frequency and time signal-satellite service may be authorized to use the frequency 4 202 MHz for space-to-Earth transmissions. Such transmissions shall be confined within the frequency band 4 200-4 204 MHz, subject to agreement obtained under RR No. **9.21**.

Studies involving the ARNS, focus on scenarios between different aircraft. Analyses involving compatibility between aeronautical systems installed on the same aircraft are under the purview of aircraft certification authorities.

As systems in the standard frequency and time signal-satellite service are authorised on a case by case basis in accordance with RR No. **9.21** coordination will be completed by individual Administrations. A general compatibility analysis is not required.

2 Compatibility between wireless avionics intra-communication systems and radio altimeters

Three studies from different administrations were performed independently using different analysis techniques.

2.1 Description of studies performed

Three studies were performed analyzing the potential interference impact from WAIC systems into radio altimeters, as well as the potential interference impact from radio altimeters into WAIC systems. Annex 1 provides a summary of relevant WAIC technical characteristics used for Studies 1, 2, and 3 which were taken from Report ITU-R-M.2283. The characteristics for radio altimeters were taken from Recommendation ITU-R M.2059.

Study 1 assesses a mainbeam-to-mainbeam as well as mainbeam-to-sidebeam coupling scenarios between an aircraft equipped with WAIC systems and another aircraft equipped with a radio altimeter. Study 2 and Study 3 assess the worst-case interference scenarios that could occur during typical aircraft operations. In addition both, Study 2 and Study 3 apply directional antennas for outside WAIC systems for reducing the radiated power towards the incumbent systems.

2.1.1 Description of Study 1 (Annex 2)

Study 1, attached as Annex 2, analyzes compatibility between outside WAIC systems and radio altimeters. In both cases (interference to WAIC and interference from WAIC) it was assumed that interference was caused by a single source. It was also assumed that outside WAIC systems use omni-directional antennas.

2.1.2 Description of Study 2 (Annex 3)

Study 2, attached as Annex 3, assesses the potential mutual impact between radio altimeters and WAIC systems in the frequency band 4 200-4 400 MHz. These assessments address two worst-case scenarios, the in-flight and the airport scenarios.

The in-flight scenario consists of two aircraft vertically separated by 300 m, the minimum separation distance permitted by ICAO. In this case it is assumed, that a WAIC equipped aircraft is in the mainbeam of the radio altimeter antenna of another aircraft. Consequently, mainbeam-to-mainbeam coupling was assumed, which represents the worst-case coupling that can occur between both systems.

The airport scenario, found in § A-3.2.3, depicts the situation when an aircraft approaches the runway for landing while WAIC-equipped aircraft are taxiing on a taxiway adjacent to that runway. The airport scenario is further subdivided into the airport taxiway and the airport holding bay scenarios. The scenarios differ in the way the taxiing and the approaching aircraft are mutually oriented and separated from the landing aircraft.

The assessments of all of the above scenarios consider both, the potential impact of WAIC systems onto radio altimeters as well as the potential impact of radio altimeters onto WAIC systems. The results are presented separately for each combination of WAIC system category and radio altimeter type. For outside WAIC systems the directional antenna concept, found in § A-1.4, is applied to reduce the radiated power towards the incumbent pulse and FMCW type radio altimeters.

2.1.3 Description of Study 3 (Annex 4)

Study 3, attached as Annex 4, addresses interference scenarios between WAIC systems and radio altimeters on different: landing and taxiing aircraft; aircraft in flight; and, taxiing aircraft to taxiing aircraft.

In this study, WAIC transceiver nodes are distributed throughout the aircraft in a possible operational configuration. The study investigates the interference from a single aircraft as well as from five aircraft aligned on the taxiway. In both cases the aggregate interference from all WAIC systems into the radio altimeter is analyzed. Interference from radio altimeters to WAIC systems are also studied, the minimum vertical separation is determined if a radio altimeter were located directly over a WAIC equipped aircraft, and scenarios where interference from a single radio altimeter on an adjacent taxiway as well as the aggregate interference from a group of three aircraft, each equipped with one radio altimeter, on an adjacent taxiway to WAIC systems is analyzed.

2.2 Summary of results

2.2.1 Results of Study 1

Study 1 shows that for outside WAIC systems using omni-directional antennas, separation distances of up to 15.8 km are necessary to ensure compatibility between WAIC systems and radio altimeters. The study suggests that additional measures, such as the use of directional antennas and reduced power levels are necessary to achieve compatibility. These measures are analyzed in studies 2 and 3.

Results of study 1 can be found in Annex 2, § A-2.5.

2.2.2 Results of Study 2

Study 2 shows that inside low and high data rate WAIC systems are compatible with all types of radio altimeters.

Furthermore, outside low and high data rate WAIC systems using directive antennas and power level lower than the maximum specified, as described in § A-1.4, are compatible with all types of radio altimeters.

Results of study 2 can be found in Annex 3, §§ A-3.2.2.1, A-3.2.2.2, A-3.2.3.3 and A-3.2.3.4.

2.2.3 Results of Study 3

Study 3 shows that inside low and high data rate WAIC systems are compatible with radio altimeters.

This study also concludes that outside low and high data rate WAIC systems using suitable techniques such as reduced power and directional antennas are compatible with radio altimeters.

Results of study 3 can be found in Annex 4, §§ A-4.3 and A-4.4.

3 Sharing between systems in the fixed service and Wireless Avionics Intra-Communication systems

3.1 Description of Study 4 (Annex 5)

In one administration the frequency band 4 200-4 400 MHz is allocated to the FS on a secondary basis by RR footnote No. **5.439**.

Characteristics for the FS in the frequency band 4 200-4 400 MHz are not available, therefore characteristics of systems in the FS in frequency bands adjacent to the frequency band 4 200-4 400 MHz were used for the analysis (see Recommendation ITU-R F.758-5).

The impact of WAIC systems into the FS is studied considering a single FS station receiving potential interference from aircraft in the range of vision of that FS station. These aircraft are assumed to be randomly deployed on actual air routes.

The impact of FS systems into WAIC systems is analyzed by considering a deployment of 100 FS stations in a bandwidth of 1 MHz. The aggregate interference from all stations into a WAIC receiver on board an aircraft flying over a given path over the territory around the FS station is analyzed.

The studies can be found in Annex 5.

3.2 Results of Study 4

The study results presented in Annex 5 show that both the short-term and long-term FS protection criteria are met for low data rate and high data rate inside WAIC systems as well as for low data rate and high data rate outside WAIC systems.

The study results also show that no harmful interference of inside or outside WAIC systems caused by the FS will occur.

The analysis assumes that directional antennas, as described in Annex 1 § A-1.4 are utilized for WAIC systems outside the aircraft structure.

Results of Study 4 can be found in Annex 5, §§ A-5.2.2, A-5.2.4 and A-5.3.3.4.

4 Sharing between systems in the Earth exploration-satellite service (passive) and Wireless Avionics Intra-Communication systems

4.1 Description of Study 5 (Annex 6)

Passive sensing in the Earth exploration-satellite service (EESS) may be authorized on a secondary basis in the frequency band 4 200-4 400 MHz (see Radio Regulations footnote No. **5.438**). Until the time of writing of this Report the frequency band however has never been used by EESS (passive) sensors. Furthermore, characteristics for EESS (passive) sensors for the frequency band 4 200-4 400 MHz are not available in Recommendation ITU-R RS.1861. The studies described in

Annex 6 are based on the characteristics which were defined and approved in Recommendation ITU-R RS.1624 containing a sharing study between radio altimeters and the EESS (passive) in the frequency band 4 200-4 400 MHz.

The study considers a worldwide deployment of 50 000 WAIC equipped aircraft moving on actual air routes over a time period of one day. Aircraft located at airports prior to departure as well as after landing are also considered. The aggregate interference power into a rotating EESS (passive) sensor on board a low Earth orbiting satellite is then computed.

The studies can be found in Annex 6.

4.2 Results of Study 5

WAIC systems internal to the aircraft (high data rate inside and low data rate inside) can be introduced in the frequency band while still allowing EESS (passive) sensors authorized in RR footnote No. **5.438** on a secondary basis to operate in the frequency band 4 200-4 400 MHz.

With regard to WAIC applications external to the aircraft (high data rate outside and low data rate outside), the use of the directive antenna concept introduced in Annex 1 § A-1.4 of this Report would also permit EESS (passive) sensors to operate in the frequency band 4 200-4 400 MHz.

Results of study 5 can be found in Annex 6, § A-6.3.1.

5 Conclusions

The studies show that WAIC systems located inside the aircraft can share the frequency band 4 200-4 400 MHz with the aeronautical radionavigation service, the Earth exploration-satellite service (passive) and the fixed service. Studies also show that WAIC systems located outside the aircraft using measures such as directional antennas and reduced transmit power can also share the frequency band 4 200-4 400 MHz with the aeronautical radionavigation service, the Earth exploration-satellite service (passive) and the fixed service.

Annex 1

Wireless avionics intra-communication systems

A-1.1 Wireless avionics intra-communication technical characteristics used in the studies

Report ITU-R-M.2283 provides detailed characteristics for WAIC systems and their potential use. WAIC systems provide radiocommunication over short distances between two or more stations onboard a single aircraft. WAIC will not provide communication, in any direction, between stations installed on one aircraft and those on another aircraft, terrestrial systems, or satellites. Providing sensor information wirelessly is an example of an application of WAIC systems. These sensors will be installed at various locations both within and outside the aircraft and will be used to monitor the health of the aircraft structure and it's critical systems and to communicate this information within the aircraft to a central onboard entity which can make the best use of such information. WAIC systems are also intended to support data, voice and safety related video surveillance applications such as taxiing cameras and may also include communication systems used by the crew for safe operation of the aircraft.

Points of communication will include avionics components with integrated wireless capabilities and dedicated components of the WAIC system. In all cases communication between two or more stations installed on a single aircraft is assumed to be part of an exclusive network required for the aircraft's safe operation. WAIC systems are not intended to provide communication with consumer devices, such as radio local area network (RLAN) devices that are brought onboard the aircraft by passengers or for in-flight entertainment applications. The scope of WAIC applications is limited to applications that relate to the safe, reliable and efficient operation of the aircraft as specified by the International Civil Aviation Organization (ICAO). WAIC systems are envisioned to offer aircraft designers and operators many opportunities to improve flight safety and operational efficiency while reducing costs to the aviation industry and the flying public.

There are two types of WAIC systems, low data rate and high data rate. Additionally, either of these two system types may be installed outside or inside of the aircraft structure; creating four types of WAIC application categories as shown in Fig. A-1.1.

FIGURE A-1.1

Wireless avionics intra-communication system categorization

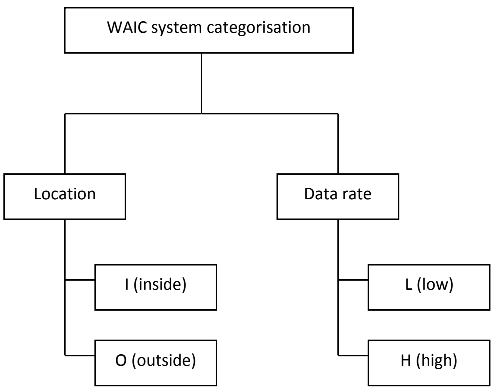


Table A-1.1 summarizes all WAIC system characteristics used for studies contained in this Report.

TABLE A-1.1

Technical characteristics for wireless avionics intra-communication low and high data rate systems

	Units	**Low data rate systems**	**High data rate systems**
Aggregate net average data rates for inside applications (D_{LI}, D_{HI})	Kbps	394	18 385
Aggregate net average data rates for outside applications (D_{LO}, D_{HO})	Kbps	856	12 300
Total aggregate net average data rates ($D_{T,L}$, $D_{T,H}$)	Kbps	1 250	30 685
Channelization overhead factor (β_L, β_H)	–	1.92	1.20
Spectrum requirements per aircraft[1]($S_{AC,L}$, $S_{AC,H}$)	MHz	35	53
number and location of simultaneously active transmitters per channel	–	1	1
Antenna gain (RX and TX)[2]	dBi	0	0
Max. transmission power[3]	mW	10	50
3-dB emission bandwidth (B_L, B_H)	MHz	2.6	16.6
Receiver IF-bandwidth	MHz	2.6	20
Receiver noise floor	dBm	–100	–91
Required signal-to-noise ratio	dB	9	14
Receiver sensitivity	dBm	–91	–77
Protection criterion (I/S)	dB	–9	–14
Maximum distance between WAIC transmitter and receiver[3]	meter	15	15

[1] Values reflect spectrum requirements assuming a single aircraft and no mutual interference with other WAIC system equipped aircraft.

[2] Directive antennas with gains larger than 0 dBi in the mainbeam direction and consequential negative gains outside the mainbeam may be applied. In these cases, the antenna mainbeams are pointed towards the center of the aircraft. This will enable the reduction of the overall emissions of the aircraft.

[3] These values are technical upper limits. Lower values are generally possible at the cost of cell size and increased number of required cells to appropriately cover the aircraft.

A-1.2 Definition of channel gain/loss models for various areas of the aircraft

The protection criterion for WAIC systems is based on interference-to-signal power at the WAIC receiver. For determining the signal power it is necessary to take the aircraft-specific propagation conditions into account. Annex 3 of Report ITU-R-M.2283 provides information on radio-frequency (RF) signal propagation within and around a typical commercial passenger aircraft. Based on analysis of various sets of RF propagation measurements taken in different areas of this aircraft, the grouping of sets of test locations into six groups as summarized in Table A-1.2 below was defined. Each of the groups A to F contains measurements obtained at locations (test points) with similar propagation conditions, e.g. similar shadowing situation. For each of these groups a corresponding channel model was derived.

TABLE A-1.2

Combining datasets into groups with similar propagation characteristics

Group	Group name	Description
A	Intra-Cabin &Intra-Flight Deck	Includes test pairs where both points are in the same cabin area (e.g. business class), or both are in the flight deck
B	Inter-Cabin	Includes test pairs where each point is in a different cabin area. Points are generally separated by cabin monuments (lavatories, galleys, etc.)
C	Inter-Cabin-to-Lower Lobe & Inter-Cabin-to-Flight Deck	Includes test pairs where one point is in the cabin and one is in a lower-lobe area (Electronic Equipment Bay or Cargo area), separated by the main deck floor. Also includes test pairs where one point is in the cabin and one point is in the flight deck, separated by the forward cabin monuments and flight deck door/bulkhead.
D	Inter-Cabin-to-Exterior (points on wing)	Includes test pairs where one point is in the cabin and one point is on the wing or engine, separated by the fuselage. Note there is some expected LOS or near-LOS component expected through the cabin windows.
E	Inter-Cabin-to-Landing Gear & Inter-Lower-Lobe to Exterior	Includes test pairs where one point is in the cabin and one point is on the landing gear, or one point is in the lower-lobe and one point is outside the fuselage. In both cases the test points are separated by the fuselage with no expected LOS or NLOS through the cabin windows.
F	Inter-Exterior	Includes test pairs where both points are exterior of the aircraft fuselage.

For the gain/loss prediction a model of the functional form is used:

$$h(f,d) = C_1 d^{-n} f^{-k} \qquad \text{(A-1.1)}$$

where n and k are the distance and frequency exponents and C_1 is a constant offset. Values for the parameters k, n and C_1 are summarized in Table A-1.3 below.

TABLE A-1.3

Channel gain model parameters for each group of test points

Group	Group name	***k*** **(freq exp)**	***n*** **(dist exp)**	$C_{1,dB}$
A	Intra-Cabin & Intra-Flight Deck	2.45	2.00	189.8
B	Inter-Cabin	2.09	3.46	167.5
C	Inter-Cabin-to-Lower Lobe & Inter-Cabin-to-Flight Deck	1.86	2.49	124.5
D	Inter-Cabin-to-Exterior (points on wing)	1.86	2.12	118.2
E	Inter-Cabin-to-Landing Gear & Inter-Lower-Lobe to Exterior	1.59	1.51	77.9
F	Inter-Exterior	1.95	2.31	142.5

A-1.3 Wireless avionics intra-communication reference models

This section provides reference models which can be utilized to derive overall emissions of WAIC applications described in Report ITU-R-M.2283.

A reasonable simplification for determining the aggregate effect of the emissions of all WAIC applications onboard an aircraft is provided in Annex 4 of Report ITU-R-M.2283. In this approach first the number of WAIC transmitters required to cope with the expected data rates per aircraft compartment or area is determined. Applying a compartment-/ area-specific duty and structural shielding factor allows performing very detailed studies focusing on specific applications and aircraft compartments or areas. The resulting e.i.r.p. values per WAIC application and aircraft compartment/area are provided in Table A-1.4.

TABLE A-1.4

Wireless avionics intra-communication e.i.r.p. values per aircraft compartment/area and application

Compartment/aircraft area	NTX	Duty factor	Structural shielding	e.i.r.p. per channel	e.i.r.p. density
		%	dB	dBm	dBm/MHz
LI WAIC category					
Flight deck	1	0.5	35	–48.3	–52.4
Cabin compartment	2	55.4	35	–27.6	–31.7
Avionics compartment	1	1.2	35	–44.3	–48.4
fwd and aft cargo compartment, center tank, bilge	1	32.1	35	–29.9	–34.1
Bulk cargo compartment	1	8.5	35	–35.7	–39.8
Wing fuel tank	1	12.1	35	–34.2	–38.3
Horizontal stabilizer	1	1.1	35	–44.6	–48.7
Nacelles	1	50.9	35	–27.9	–48.7
LI WAIC total e.i.r.p.(dBm)	–21.6				
LO WAIC category					
Nose	1	36.0	0	5.6	1.4
Center (upper)	1	93.6	0	9.7	5.6
Center (lower)	2	79.3	5	4.0	–0.2
Tail	1	47.4	0	6.8	2.6
Left wing	1	68.0	5	3.3	–0.8
Right wing	1	68.0	5	3.3	–0.8
LO WAIC total e.i.r.p.(dBm)	14.3				
HI WAIC category					
Flight deck	1	37.3	35	–22.3	–34.5
Cabin compartment	1	63.8	35	–19.9	–32.2
Avionics compartment	1	48.1	35	–21.2	–33.4
fwd and aft cargo compartment. center tank. Bilge	1	80.5	35	–18.9	–31.1
Nacelles	1	22.1	35	–24.6	–36.8
HI WAIC total e.i.r.p.(dBm)	–14.0				
HO WAIC category					
Nose	1	22.7	0	10.6	–1.6
Center (upper)	1	38.9	0	12.9	0.7
Center (lower)	1	24.6	5	5.9	–6.3
Tail	1	32.6	0	12.1	–0.1
Left wing	1	25.0	5	6.0	–6.2
Right wing	1	25.0	5	6.0	–6.2
HO WAIC total e.i.r.p.(dBm)	17.7				

For compatibility studies on a WAIC application category basis, a simplified reference model described below is utilized. The model assumes that the electromagnetic radiation emitted by all inside or outside WAIC applications communicating within a low or high data rate frequency channel can be perceived as single omni-directional point source (OPS), when the aircraft is observed from a large distance. These OPSs are considered to continuously transmit at their corresponding transmit power level (either 10 dBm or 17 dBm for low or high data-rate WAIC systems, respectively). An antenna gain of G_{WAIC} = 0 dB, as listed in Table A-1.1 is further taken into account. For an OPS located inside the aircraft fuselage an additional signal attenuation of L_{Body} = 35 dB caused by the aircraft body is assumed in reference to the shielded aircraft compartment case described in Report ITU-R-M.2283.

The number of OPSs required to adequately represent all low and high data rate WAIC applications described in Annex 4 of Report ITU-R-M.2283 is given by the minimum number of radio channels $N_{\text{Channel,xy}}$ required for communication by a WAIC application category (xy → LI, LO, HI or HO). These numbers are derived from the high and low data rate WAIC spectrum requirements and the inside and outside WAIC application data-rates which are listed in Table A-1.1. The results for LI, LO, HI and HO channels given by equation (A-1.2) with respect to the parameters provided by Table A-1.1 are listed in Table A-1.5. The corresponding numbers are rounded towards the next integer value in order to provide margin for multiple simultaneous peaks in the application data rates.

$$\left\lceil \frac{D_{\text{xy}}}{D_{\text{T,x}}} \frac{S_{\text{AC,x}}}{B_{\text{x}} \beta_{\text{x}}} \right\rceil = N_{\text{Channel,xy}} \qquad \text{(A-1.2)}$$

TABLE A-1.5

Number of required channels on board a wireless avionics intra-communication aircraft per category

	Inside systems	Outside systems
Low data rate systems	$\left\lceil \frac{394 kbps\ 35 MHz}{1250 kbps\ 2.6 MHz\ 1.92} \right\rceil = 3$	$\left\lceil \frac{856 kbps\ 35 MHz}{1250 kbps\ 2.6 MHz\ 1.92} \right\rceil = 5$
High data rate system	$\left\lceil \frac{18385 kbps\ 53 MHz}{30685 kbps\ 16.6 MHz\ 1.2} \right\rceil = 2$	$\left\lceil \frac{12300 kbps\ 53 MHz}{30685 kbps\ 16.6 MHz\ 1.2} \right\rceil = 2$

Table A-1.6 summarizes all relevant parameters of the OPS model. The comparison of the total emitted e.i.r.p. values per WAIC application category (see Table A-1.4) with the OPS model (see Table A-1.6) shows that both models have e.i.r.p. levels that are closely related.

TABLE A-1.6

Omni-directional point source reference model parameters

WAIC application category	**Transmit power (dBm)**	**Aircraft body attenuation L_{Body} (dB)**	**Required number of OPS**	**Total OPS e.i.r.p. (dBm)**	**Total OPS PSD (dBm/MHz)**	**Bandwidth requirements per OPS/Channel (MHz)**
LI	10	35	3	–20.2	–24.3	5
LO	10	0	5	17.0	12.9	5
HI	17	35	2	–15.0	–28	20
HO	17	0	2	20.0	7	20

A-1.4 Maximum tolerable emission values for outside wireless avionics intra-communication systems

The use of omni-directional antennas for WAIC systems outside the aircraft structure implies that WAIC signals are radiated homogeneously into all directions. However, initial study results showed that under this assumption the RF emissions of LO and HO WAIC applications into the upward directions will exceed the protection criteria of the fixed service, the Earth exploration-satellite service (passive), and radio altimeters in the frequency band. Consequentially, to archive compatibility with the incumbent services and applications and WAIC systems installed outside the aircraft structure, the RF emissions into the critical directions have to be limited.

For that purpose an angle-dependent maximum power pattern defining the maximum tolerable RF power emissions of an aircraft expressed in e.i.r.p. is derived (see Fig. A-1.2). The pattern is defined in such a way that will exceed the protection criteria of the incumbent services and applications will never occur in the considered worst-case scenarios. The maximum tolerable RF power emission pattern shown in Fig. A-1.2 is rotationally symmetrical regarding the vertical axis. It was derived from detailed analysis of the initial study results generated under the assumption of usage of omni-directional antennas for LO and HO WAIC systems. Table A-1.7 provides a list of relevant e.i.r.p. values together with the corresponding angle dependencies which are used in the following analysis to interpolate the maximum tolerable e.i.r.p. pattern shown in Fig. A-1.2.

FIGURE A-1.2

Maximum angle-dependent tolerable RF power emissions caused by wireless avionics intra-communication systems

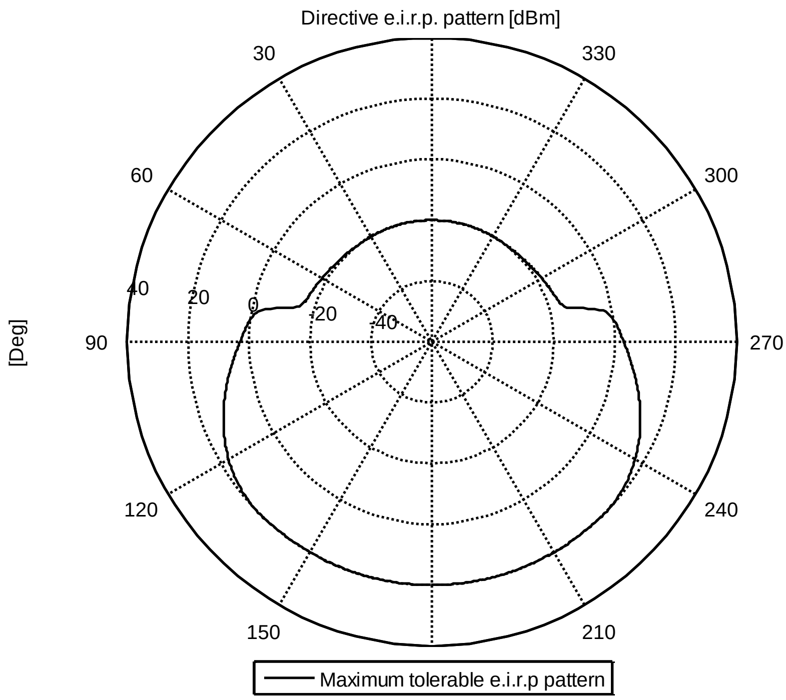


TABLE A-1.7

Angle-dependent maximum tolerable e.i.r.p. reference values

Parameter	**Values**											**Units**
Angle	>120	90	75	69	35	0	325	291	285	270	<240	degree
e.i.r.p.	20	3	–2	–15	–17	–20	–17	–15	–2	3	20	dBm

For the implementation of LO and HO WAIC systems complying with the maximum tolerable RF power emission pattern provided in Fig. A-1.2, several methods can be utilized:

– Reduction of the HO and LO WAIC system's transmit power:

  The transmit power of LO and HO WAIC systems as specified in Report ITU-R-M.2283 provides a link budget which exceeds the required SNR by 21 dB and 28 dB respectively, considering a maximum distance between WAIC transmitter and receiver of 15 m. Hence the transmit power of both, HO and LO WAIC systems can be reduced by the corresponding amount without falling short in terms of link budget.

– Reduction of the WAIC system's cell size:

  The maximum distance between a WAIC transmitter and receiver according to Report ITU-R-M.2283 is 15 m. Hence a single WAIC cell has a diameter of 30 m, which is sufficient to cover smaller aircraft almost entirely, or alternatively an entire wing of larger long-haul aircraft. Tables A-1.5 and A-2.6 show that at least two cells are required to cover the full range of WAIC LO and HO applications. Hence, it is reasonable to assume that the maximum distance between a WAIC transmitter and receiver can be reduced in many cases. For example, reducing the maximum distance from 15 m to 3 m (6 m cell diameter) will cause an increase of the link budget by approximately 14 dB.

– Utilization of directional antennas:

  Directional antennas can be used to reduce RF emissions into the upwards direction. For that purpose their mainbeams have to point into horizontal or downward directions. Additionally directional antennas can be used to provide isolation into the directions towards the incumbent systems.

– Isolation caused by the aircraft structure:

  Depending on the installation location of LI and LO WAIC system transmitters, the aircraft structure can act as isolator for RF emissions into upward directions. For example, the emissions of WAIC applications located on the bottom of the aircraft fuselage (e.g. landing gear sensors) or on the bottom side of the wings (e.g. engine sensors) will be shielded by the aircraft structure.

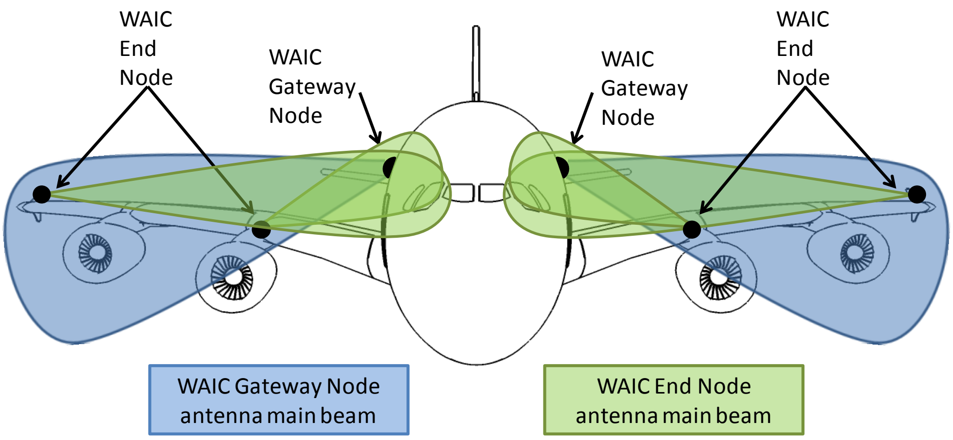
In order to comply with the described maximum tolerable RF emission power pattern the methods described above can be combined but have to be tailored to each LO and HO WAIC system and installation environment individually.

In order to show that LO and HO WAIC applications in general can comply with the introduced RF power emission constraints an example utilizing directional antennas is proposed. The application of directional antennas, described in the following, is selected because it can easily be proven that compliance with the maximum tolerable RF emission power limits can be achieved. Also it allows keeping the distance between WAIC transmitter and receiver at the maximum of 15 m as defined in Report ITU-R-M.2283. However, it is emphasized, that many other possible options to archive compliance exist.

In the concept described below, directional antennas are installed at the WAIC Gateway and End Nodes. The End Node antennas have narrow antenna beam patterns and are oriented such that they point towards the Gateway Node which is located in a central location on the aircraft fuselage. Consequently, the amount of energy emitted into other directions is small. The antennas of the Gateway Nodes have a broader opening angel in the horizontal plane since their beams have to illuminate multiple sensor node locations. For this example End Nodes are always located below or approximately on the same horizontal plane as Gateway Nodes, consequently antenna mainbeam elevation angles can be kept small and interference into the direction of a possible victim radio altimeter receiver onboard other aircraft located above the WAIC aircraft or towards EESS (passive) sensors is considerably reduced (see Fig. A-1.3).

FIGURE A-1.3

Example for the use of directional antennas at gateway and end node for providing wireless avionics intra-communication signal coverage around the wings



The RF emission power pattern of the described concept is characterized by the antenna pattern of the gateway node as well as the gateway and end nodes antenna's main-to-sidelobe ratio. The mainbeam characteristics of the End Nodes' antennas are of lesser importance, since they never point outwards. Hence, the gateway nodes mainbeam has the dominant impact on the overall RF emissions of the aircraft.

In accordance with Fig. A-1.1 it is exemplarily assumed that gateway nodes are equipped with directional antennas providing an isotropic gain of at least 10 dBi with an opening angle of 10 degrees in the vertical plane and a broad opening angle in the horizontal plane in order to cover multiple end nodes on the wings. Furthermore, the sensor nodes are assumed to be equipped with spot beam antennas which point onto the aircraft's fuselage having at least a gain of 25 dBi. As a consequence the transmit power of HO and LO WAIC applications can be reduced by 35 dB without effecting the link budget. Thus, the maximum distance between a WAIC transmitter and receiver can be kept at 15 m. Moreover, the antenna gains into directions other than the direction of the mainbeams is assumed to be –25 dBi of both type of antennas utilized in this exemplary concept.

FIGURE A-1.4

Sum emission pattern resulting from the use of directional antennas at gateway and end node

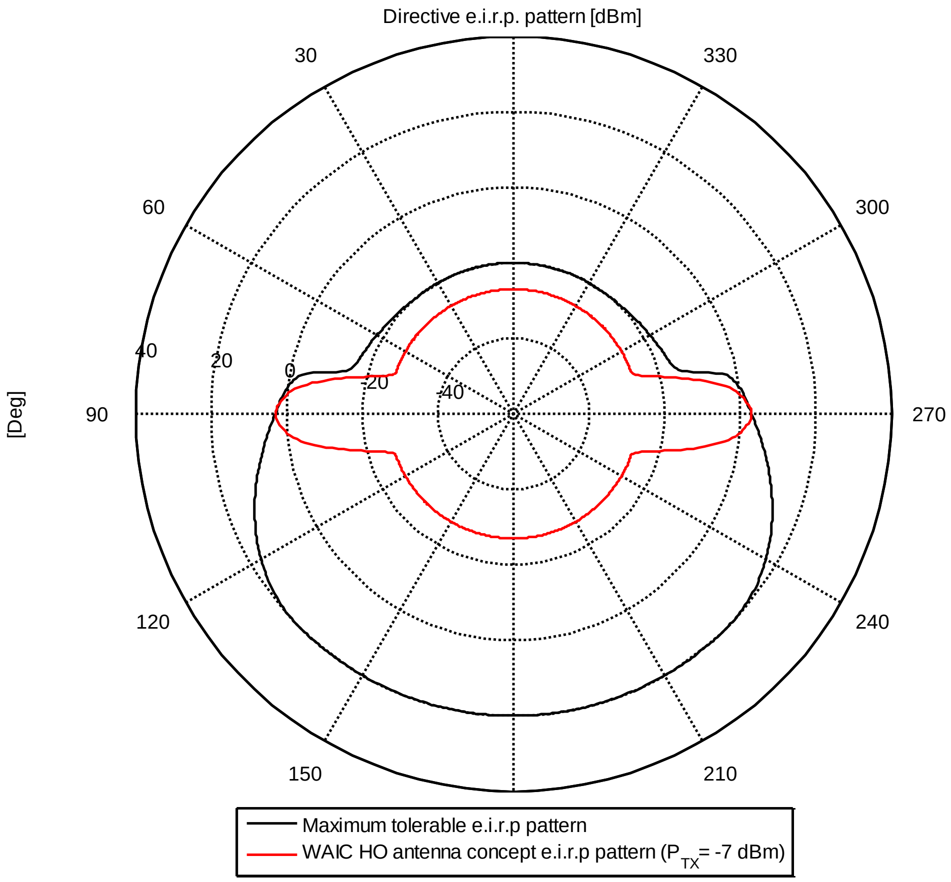


Figure A-1.4 shows the RF emission power pattern resulting from the directional antenna concept discussed above in comparison with the maximum tolerable RF emission power pattern from Fig. A-1.2. The transmission power of the HO or LO WAIC applications is assumed to be –7 dBm, because this value causes the maximum RF emission pattern to exactly coincide with the maximum tolerable e.i.r.p. pattern for 90 and 270 degrees, see equation (A-1.3) and Table A-1.7.

$$3 \text{ dBm} = -7 \text{ dBm} + 10 \text{ dBi} \tag{A-1.3}$$

Additionally, the link budget is increased due to the additional 35 dB margin obtained from the mainbeam coupling. For any other angle the RF emissions caused by the directional antenna concept are less than the allowed emission limits. Considering Fig. A-1.4, this is reflected by the fact that the red curve, representing the RF emission of the antenna concept, never exceeds the black curve of the maximum tolerable e.i.r.p. pattern. Consequently, this specific example shows that it is possible to operated HO and LO WAIC applications which fulfil the FS, EESS (passive) and the radar altimeter protections criteria.

For that reason, the maximum tolerable e.i.r.p. pattern is a suitable method to represent the total RF emissions of LO and HO WAIC systems for the analysis of the interference impact of WAIC onto the FS, EESS, and radar altimeters. However, the corresponding LO and HO WAIC applications have to utilize the emission limiting techniques described in this section to archive compliance.

Annex 2

Study 1

Compatibility analysis between wireless avionics intra-communication systems and radio altimeters in the aeronautical radionavigation service

A-2.1 Introduction

Some WAIC systems will operate outside the aircraft fuselage and data from the sensors will be transmitted to receivers around the aircraft. An example of WAIC systems operating outside the aircraft fuselage is given in Fig. A-2.1.

The main difficulty associated with WAIC systems operation outside the aircraft fuselage is that their receivers do not have additional protection provided by the aircraft fuselage and can be affected by interference from the systems operating co-frequency with WAIC systems.

The studies contained in this Annex include interference impact assessments to outside WAIC systems from radio altimeters operating in the frequency band 4 200-4 400 MHz and vice versa.

FIGURE A-2.1

Example installation locations of wireless avionics intra-communication transceivers outside the aircraft structure

A-2.2 Radio altimeter technical characteristics

The frequency band 4 200-4 400 MHz is allocated to the aeronautical radionavigation service on global primary basis. In accordance with RR footnote No. **5.438**, it is reserved exclusively for radio altimeters installed on board aircraft and for the associated transponders on the ground. Recommendation ITU-R M.2059 (which contains characteristics of 6 analog and 4 digital radio altimeters is used for the compatibility study in this Annex. These characteristics are presented in Table A-2.1.

TABLE A-2.1

Radio altimeter technical characteristics

Name	Frequency MHz	Power, dBW	Antenna gain dB	Emission bandwidth MHz	Q*	Receiving bandwidth MHz	Receiver noise ratio dB	Protection criterion *I*/*N* dB	Feeder loss dB
A1	4 300	–2.2	10	110	1	2	10.0	–6	6
A2	4 300	0.0	10	162.8	1	0.25	6.0	–6	6
A3	4 300	–6.0	10	171	1	2	6.0	–6	2
A4	4 300	20.0	13	8	0.0013	9.2	10.0	–6	6
A5	4 300	6.99	11	7	0.001	6	10.0	–6	6
A6	4 300	16.0	11	15	0.0005	16	10.0	–6	6
D1	4 300	–3.98	11	150	1	0.31	8.0	–6	6
D2	4 300	–10.0	10	177	1	1.95	9.0	–6	0
D3	4 300	0.0	11	175	1	2.00	8.0	–6	2
D4	4 300	6.99	13	31	0.006	30.00	10.0	–6	0

* Q – pulse duty factor.

A-2.3 Wireless avionics intra-communication systems technical characteristics used in compatibility assessment

In accordance with Report ITU-R-M.2283, interference-to-noise ratio (*I*/*S*) shall not exceed –9 dB (for low data rate systems) and –14 dB (for high data rate systems). Table A-2.2 presents characteristics of WAIC systems.

TABLE A-2.2

Characteristics of wireless avionics intra-communication systems

	Low data rate systems (LR)	High data rate systems (HR)
Antenna gain (Rx and Tx), dBi	0	0
Maximum Tx power, mW	10	50
3dB emission bandwidth, MHz	2.6	16.6
Required S/N, dB	9	14
Protection criterion $(I/S)_{acc}$, dB	–9	–14
Maximum distance between receiver and transmitter of outside WAIC, m	15	15

From the data in Table A-2.2, the maximum power at the input of the outside WAIC system receiver was determined. The acceptable power of interference was calculated as follows:

$$I_{acc} = P_{WAIC\,trans} + G_{WAIC\,trans} + G_{WAICrec} + 20\lg(\lambda/4\pi R) + (I/S)_{acc}$$

where:

I_{acc} : acceptable power of interference at input of outside WAIC receiver, dBW

$P_{WAIC\,trans}$: power of outside WAIC transmitter, dBW

$G_{WAIC\,trans}$, $G_{WAIC\,rec}$: Tx and Rx antenna gain of outside WAIC system, dB

λ : wavelength, m

R : maximum distance between Tx and Rx antennae of outside WAIC system, m

$(I/S)_{acc}$: protection criterion, dB.

The acceptable power of interference calculated for the frequency 4 300 MHz is equal to –97.6 dBW in the 2.6 MHz bandwidth (for LR WAIC) and –95.6 dBW in the 16.6 MHz bandwidth (for HR WAIC).

A-2.4 Assessment of mutual interference impact

The compatibility study considered both interference to outside WAIC systems from radio altimeters and interference from outside WAIC systems to radio altimeters.

In the first case (interference to WAIC) the protection distance that would meet the protection criterion (see Table A-2.2) was determined. It was assumed that interference to outside WAIC system was caused by a single radio altimeter transmitter. Then required protection distance was calculated as follows:

$$R_{WAIC} = 10^{\frac{P_{eff\ rad\,alt} + G_{T\ rad\,alt} + G_{R\,WAIC} + 20\lg(\lambda/4\pi) - I_{accWAIC}}{20}}$$

where:

R_{WAIC} : required protection distance, m

$P_{eff\ rad\ alt}$: radio altimeter effective power, dBW

$G_{T\ rad\,alt}$: radio altimeter transmitter antenna gain, dB

$G_{R\,WAIC}$: WAIC receiver antenna gain, dB

λ : wavelength, m

$I_{acc\ WAIC}$: acceptable level of interference, dBW.

The calculation took into account pulse or continuous nature of the interference, difference between bandwidths of WAIC receiver and radio altimeter transmitter, and feeder loss in interfering transmitter. Effective power of radio altimeter $P_{eff\ rad\,alt}$ used for this was determined as follows:

– if $\Delta F_{WAIC} \le \Delta F_{rad\,alt}$, then $P_{eff\ rad\,alt} = P_{rad\,alt} + 10\lg(Q) + 10\lg(\Delta F_{WAIC}/\Delta F_I) - L$,

– if $\Delta F_{WAIC} \ge \Delta F_{rad\,alt}$, then $P_{eff\ rad\,alt} = P_{rad\,alt} + 10\lg(Q) - L$,

where:

Q = t/T : pulse duty factor

t : pulse width, s

T : pulse repetition period, s

ΔF_{WAIC} : WAIC signal bandwidth, MHz

ΔF_I : interference (caused by radio altimeter) bandwidth, MHz

L : transmitter feeder loss, dB.

Analysis of characteristics in Table A-2.2 shows that WAIC systems use omnidirectional antennae. With this respect two interference scenarios were considered for assessment of protection distances:

– interference to WAIC is caused by Tx antenna pattern main lobe of radio altimeter;

– interference to WAIC is caused by Tx antenna pattern side-lobe of radio altimeter. The side lobe was assumed to be 17 dB less than the main lobe level.

To assess impact of outside WAIC systems to operation of radio altimeters installed on board other aircraft, protection distances were also calculated as follows:

$$R_{ALT} = 10^{\frac{P_{eff\ WAIC} + G_{R\,rad\,alt} + G_{T\,WAIC} + 20\lg(\lambda/4\pi) - I_{acc\,ALT} - L}{20}}$$

where:

- R_{ALT} : required protection distance for radio altimeter, m
- $P_{eff\ WAIC}$: effective power of WAIC transmitter, dBW
- $G_{R\,rad\,alt}$: radio altimeter Rx antenna gain, dB
- $G_{T\,WAIC}$: WAIC Tx antenna gain, dB
- λ : wavelength, m
- L : feeder loss in radio altimeter, dB
- $I_{acc\,ALT}$: acceptable level of interference, dBW.

Effective power of WAIC transmitter was calculated as follows:

– if $\Delta F_{WAIC} \geq \Delta F_{INT\,rad\,alt}$, then $P_{eff\ WAIC} = P_{WAICt} + 10\lg(\Delta F_{rad\,alt} / \Delta F_{WAIC})$,

– if $\Delta F_{WAIC} \leq \Delta F_{INT\,rad\,alt}$, then $P_{eff\ WAIC} = P_{WAIC}$.

Since radio altimeters use directional antennae, two interference scenarios were considered:

– interference from WAIC is received by antenna pattern main lobe of radio altimeter;

– interference from WAIC is received by antenna pattern side-lobe of radio altimeter. The side lobe was assumed to be 17 dB less than the main lobe level.

A-2.5 Analysis of results

A-2.5.1 Assessment of interference from radio altimeters to outside wireless avionics intra-communication systems

The calculation results of the minimum protection distances from interference caused by radio altimeter are given in Table A-5.3.

TABLE A-2.3

Protection distances for interference caused by radio altimeters to outside wireless avionics intra-communication systems

Type of altimeter	Required protection distance (m)			
	Main lobe interference		Side lobe interference	
	LR WAIC	HR WAIC	LR WAIC	HR WAIC
A1	80	202	11	29
A2	85	214	12	30
A3	66	166	9	23
A4	195	492	27	69
A5	32	82	5	12
A6	44	112	6	16
D1	63	158	9	22
D2	51	129	7	18
D3	145	367	21	52
D4	95	239	13	34

Analysis of results presented in Table A-2.3 shows that the maximum separation distance required to protect outside WAIC receivers does not exceed 500 m.

This distance can be reduced by application of directional antennas in the WAIC system receivers. For example application of the directional antenna with side lobe level of –14 dB allows reducing the minimum required protection distance to 98 m if interference is fallen into the WAIC antenna side lobe.

In case of interference caused by the radio altimeter transmit antenna side lobes to WAIC systems using an omni-directional antenna the required protection distance does not exceed 69 m. It can be additionally reduced by application of directional antenna in WAIC systems.

A-2.5.2 Assessment of interference from outside wireless avionics intra-communication systems to radio altimeters

To determine protection distances that ensure meeting the protection criteria in Table 2, acceptable level of interference for each of considered types of radio altimeters was calculated follows:

$$I_{acc\,ALT} = 10\lg(kT_N \Delta F_I) + (I/N),$$

where:

T_N : noise temperature of radio altimeter receiver, °K

ΔF_I : receiver IF-bandwidth, Hz.

Calculated values of acceptable interference level are presented in Table A-2.4.

TABLE A-2.4

Acceptable level of interference to radio altimeters

Type of altimeter	A1	A2	A3	A4	A5	A6	D1	D2	D3	D4
Acceptable level of interference, dBW	–137	–151	–142	–131	–133	–128	–148	–139	–140	–126

Calculated values of protection distances for interference from outside WAIC to radio altimeters with account for results provided in Table A-2.4 are presented in Table A-2.5.

TABLE A-2.5

Protection distances for interference from outside wireless avionics intra-communication to radio altimeters

Type of radio altimeter	**Required protection distance, km**			
	Main lobe interference		**Side lobe interference**	
	LR WAIC	**HR WAIC**	**LR WAIC**	**HR WAIC**
A1	5.7	5.1	0.8	0.7
A2	9.9	8.8	1.4	1.2
A3	15.8	14	2.2	1.9
A4	4.3	7.2	0.6	1.0
A5	4.2	5.7	0.6	0.8
A6	2.6	5.7	0.37	0.8
D1	8.4	7.4	1.2	1.0
D2	13.0	11.54	1.8	1.6
D3	13.3	11.8	1.9	1.7
D4	4.8	10.6	0.7	1.5

Analysis of results presented in Table A-2.5 shows that to protect radio altimeters installed onboard one aircraft from interference from outside WAIC system installed on board another aircraft the separation distance of approximately 16 km between the aircraft would be required. This is much more than the separation distance required for protection of outside WAIC systems from interference caused by radio altimeters. Thus, operation of outside WAIC systems having parameters described in Report ITU-R-M.2283 in airport areas would be problematic because of mutual inacceptable interference to and from radio altimeters installed on aircraft that are at initial and terminal stages of flight. For this reason the application of additional mitigation techniques like directional antennas and/or reduction of WAIC transmit power is considered necessary.

A-2.6 Conclusions and proposal

Analysis of the study results for outside WAIC systems using omni-directional antennas as indicated in Table A-2.2 show that additional studies and measures providing compatibility of WAIC systems with radio altimeters are required. Such measures are described and assessed in Annexes 3 and 4.

Annex 3

Study 2

Compatibility analysis between wireless avionics intra-communication systems and radio altimeters in the aeronautical radionavigation service

A-3.1 Technical characteristics and protection criteria of frequency modulated continuous wave and pulsed radio altimeters

The basic function of a radio altimeter is to provide accurate height measurements above the Earth surface with a high degree of accuracy and integrity during the approach, landing, and climb phases of aircraft operation. Such information is used for many purposes. The high degree of accuracy and integrity of those measurements must be achieved regardless of the properties of the Earth surface, representing a wide variety of reflectivity. It is also used to determine the particular altitude in which the aircraft can safely land and as an input to the terrain awareness warning system (TAWS), which gives a “pull up” warning at a predetermined altitude and closure rate; and as an input to the collision avoidance equipment and weather radar (predictive windshear system), auto-throttle (navigation), and flight controls (autopilot).

Radio altimeter systems are designed to operate for the entire life of the aircraft in which they are installed. The installed life can exceed 30 years, resulting in a wide range of equipment age, performance and tolerance. Tables A-3.1 and A-3.2 provide technical characteristics of the radio altimeter systems operating in the 4 200-4 400 MHz frequency band as contained in Recommendation ITU-R M.2059.

The following protection criteria must be considered and need to be met for any new service or application which shall share the frequency band with radio altimeters. These criteria are also contained and described in more detail in §§ 2.3, 2.4 and 2.5 of Recommendation ITU-R M.2059.

Due to the fact that radio altimeters provide a safety-of-life service, harmful interference needs to be avoided when the aircraft is in operation. In order to avoid harmful interference the following protection criteria have to be fulfilled in flight-critical operating scenarios:

Desensitization:

$$I/N = -6 \text{ dB} \tag{A-3.1}$$

Front end overload:

$$I_{RF} \leq I_{T,RF} \tag{A-3.2}$$

where:

$I_{T,RF}$: is as defined in Tables A-3.1 and A-3.2.

False altitudes (for FMCW altimeters only):

$$I_D < I_{T,FA} \quad \text{(A-3.3)}$$

where:

$I_{T,FA}$ = –143 dBm/100 Hz *

*following the instantaneous altimeter local oscillator

Power spectral density:

$$I_{PSD} < P_{1dBSD} \quad \text{(A-3.4)}$$

with:

$$I_{PSD} = P_{RI} - 10\log(B_i)$$

where:

P_{RI} : received interference power at f_{ci} in dBm

f_{ci} : center frequency of the potential interference source, and

B_i : the –40dB bandwidth of the interferer.

with:

$$P_{1dBSD} = P_{T,RF} - 10\log(B_{R,IF})$$

where:

$P_{T,RF}$: input receiver overload threshold (see Tables A-3.1 and A-3.2)

$B_{R,IF}$: IF-bandwidth of the radio altimeter.

The receiver desensitization criterion refers to the interference power level captured by the IF-stage I_{IF} of the radio altimeter (RA). Within Recommendation ITU-R M.2059 this fact is already considered for FMCW type RAs and is extended here for the case of pulsed RAs. The IF-stage of a pulse RA only captures a fraction of the interfering WAIC OPS signal power if the bandwidth occupied by WAIC OPSs is greater than the IF-bandwidth of the RA. This fraction is determined by the ratio between the pulsed RA IF-bandwidth and the bandwidth occupied by the WAIC system.

$$R_{xy,s} = \begin{cases} 10\log\left(\frac{B_{IF,RA}}{N_{xy,OPS}\,B_{x,OPS}}\right) & \text{if } B_{IF,RA} \le N_{xy,OPS}B_{x,OPS} \\ 0 & \text{if } B_{IF,RA} > N_{xy,OPS}B_{x,OPS} \end{cases} \quad \text{(A-3.5)}$$

where $B_{IF,RA}$ is the IF-stage bandwidth of the RA under consideration, $B_{x,OPS}$ is the bandwidth required by a low or high data rate OPS, see Table A-1.6, and $N_{xy,OPS}$ is corresponding number of LI, LO, HI or HO OPSs as derived by equation (A-1.2).

TABLE A-3.1

Analogue radio altimeters

	Radio altimeter A1	Radio altimeter A2	Radio altimeter A3	Radio altimeter A4	Radio altimeter A5	Radio altimeter A6	Units
Transmitter							
Nominal center frequency	4 300	4 300	4 300	4 300	4 300	4 300	MHz
Transmitted power	0.600	1	0.1 to 0.25	100	5	40	W (peak)
Modulation (FMCW or Pulsed)	FMCW	FMCW	FMCW	Pulsed	Pulsed	Pulsed	
Chirp bandwidth excluding temperature drift	104	132.8	133	Not applicable	Not applicable	Not applicable	MHz
Typical number of altimeter systems installed on an aircraft	Up to 3	Up to 3	Up to 3	Up to 3	Up to 3	Up to 3	Per aircraft
3 dB emission bandwidth	110	162.8	171	8	7	15	MHz
Receiver							
Noise Figure	10	6	6	10	10	10	dB
$I_{T,RF}$ Input Threshold Receiver Overload	–30	–53	–56	–40	–40	–40	dBm
–3 dB Intermediate Frequency (IF) bandwidth	2	0.25	0.025 to 2	9.2	6.0	16	MHz
Antenna							
Antenna gain	10	9.5-10	10 typical, but different Antenna could be used	13	11	11	dBi
Cable loss (single path)	6	6	2 to 7	6	6	6	dB
–3 dB beam width	40 to 60	55	45 to 60	35	45	45	degrees

TABLE A-3.2

Digital radio altimeters

	Radio altimeter D1	Radio altimeter D2	Radio altimeter D3	Radio altimeter D4	Units
Transmitter					
Nominal center frequency	4 300	4 300	4 300	4 300	MHz
Transmitted power (peak)	0.400	0.100	0.1 to 1	5	W (peak)
Modulation	FMCW	FMCW	FMCW	Pulsed	
Chirp bandwidth excluding temperature drift	150	176.8	133	Not Applicable	MHz
Typical number of systems fitted	2 or 3	2 or 3	1 or 2	1 or 2	Per aircraft
3 dB emission bandwidth	150	177	175	5 or 31	MHz
Receiver					
Noise figure	8	9	8 to 12	10	dB
$I_{T,RF}$ Input Threshold Receiver Overload	–30	–43	–53	–40	dBm
–3 dB Intermediate Frequency (IF) bandwidth	0.312 MHz (LPF – Single sided)	1.95 MHz	0.1 to 2.0	30	MHz
Antenna					
Antenna gain	11	10	8 to 11	13	dBi
Cable Loss (single path)	6 (10 max)	0	2 to 7	0 to 2	dB
–3 dB beam width	40 to 60	45 to 60	45 to 60	45	degrees

A-3.1.1 Radio altimeter antenna characteristics and installation location

The scope of this section is to describe the model assumptions for the position and the antenna pattern of the radio altimeter on board an aircraft, throughout the following referred to as “RA-aircraft”. The onboard radio altimeter is assumed to be located at the geometrical center of the aircraft, as shown in Fig. A-3.1. The radio altimeter antenna is oriented towards the Earth surface with its mainbeam direction pointing into the direction of the RA-aircraft’s yaw axis.

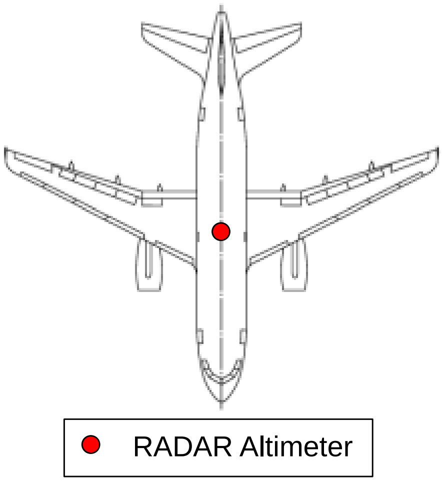
For the radio altimeter antenna pattern a circular-symmetric parabolic shape is assumed. It is parameterized by ϕ_{3dB}, the 3dB-beamwidth and $G_{RA,dBi}$, the isotropic antenna gain as stated in Tables A-3.1 and A-3.2. Because of its symmetry a single incident angle ϕ, which represents the combination of azimuth and elevation, is required in order to specify the antenna gain $G_{RA,dBi}$. Hence the parabolic antenna pattern is described by:

$$G_{\mathrm{RA,dB}}(\phi) = -\frac{12}{{\phi_{3\mathrm{dB}}}^2}\phi^2 + G_{\mathrm{RA,dBi}} \tag{A-3.6}$$

Figure A-3.2 shows the antenna patterns of all FMCW and pulsed type radio altimeters considered in this study. Any signal observed at the radio altimeter frontend input is additionally attenuated by a cable loss C_L after the antenna output, as defined in Tables A-3.1 and A-3.2.

FIGURE A-3.1

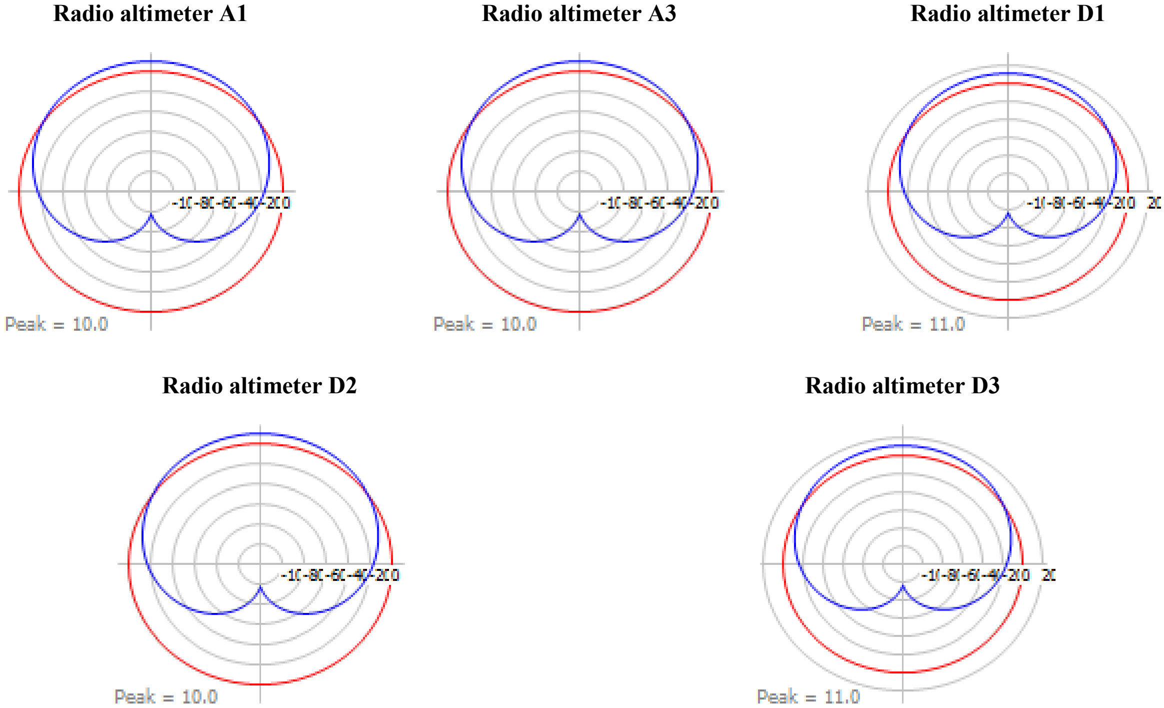
Radio altimeter antenna position onboard the aircraft



While the maximum gain and beamwidth for the various radio altimeter types are provided in Recommendation ITU-R M.2059, the antenna patterns are not. Therefore, antenna patterns using the given information with the parabolic roll-off described by equation (A-3.5) have been assumed. Figure A-3.2 provides a graphical representation of these antenna patters.

FIGURE A-3.2

Antenna patterns of various radio altimeters types



A-3.2 Compatibility analysis

A-3.2.1 Introduction

The study contained in this section analyzes whether and under which conditions FMCW and pulsed type radio altimeters operating in the frequency band of 4 200-4 400 MHz (see § A-3.1 of this Annex) and WAIC systems (described in Annex 1) can share the frequency band. The study analyzes the potential interference impact of WAIC systems onto radio altimeters as well as the potential interference impact of radio altimeters onto WAIC systems. The radio altimeters and WAIC systems are assumed to be installed at different aircraft. The aircraft equipped with a radio altimeter is hereafter referred to as “RA-aircraft”. Aircraft equipped with WAIC systems are hereafter referred to as “WAIC-aircraft”.

The separation distance between WAIC and RA-aircraft has major influence on the mutual interference impact onto both systems. According to Annex 2 to the Convention on International Civil Aviation (10^{th} Edition) the minimal vertical separation distance between adjacent flight levels is 300 m. According to Doc. 4444 “Procedures for Air Navigation Services – Air Traffic Management” of the International Civil Aviation Organization, the minimum horizontal separation distance is much larger than 300 m. Thus the assumed lower bound for the separation distance between two aircraft in flight is 300 m. Separation distances less than 300 m consequentially only occur in the vicinity of airports between a RA-aircraft performing landing or takeoff procedures and WAIC-aircraft on ground. For these cases, however, specific system characteristics such as antenna patterns, aircraft orientation, etc. influencing the interference geometry for these cases have to be taken into account. The mainbeam-to-mainbeam coupling approach taken for the in-flight case does not apply anymore (see § A-3.2.3).

The following study considers both of the scenarios mentioned above. The first part of the study analyzes the mutual interference impact between aircraft in flight. The second part of the study analyzes the interference impact between an RA-aircraft approaching an airport and one or multiple WAIC-aircraft on ground. The results of both scenarios are summarized in § A-3.2.4.

A-3.2.2 In-flight scenario

In flight the onboard radio altimeter may suffer from harmful interference emitted by WAIC applications on board a WAIC-aircraft flying in proximity of the RA-aircraft and vice versa. In this section the minimal separation distance between aircraft in the air, which is required to protect the RA as well as WAIC systems from harmful interference, is derived. For the analysis it is assumed that the RA antenna mainbeam directly points into the direction of the omni-directional WAIC transmit/receive antenna (mainbeam-to-mainbeam coupling). The described worst-case scenario may occur if the RA-aircraft is located above the WAIC-aircraft.

A-3.2.2.1 Analysis of potential impact of wireless avionics intra-communication systems onto frequency modulated continuous wave and pulsed radio altimeters

The minimal separation distance between a WAIC and RA-aircraft is defined as the distance at which all four RA protection criteria, as described in § A-3.1 are met. These protection criteria are related to the interference power I_{RF} induced at the RA frontend. The highest WAIC interference power level at the RA antenna output is observed when the WAIC-aircraft is flying through the RA antenna mainbeam below the RA-aircraft. Consequently the worst-case interference power level $I_{xI,RF}$ observed at the RA antenna output caused by a LI or HI OPS on board the WAIC-aircraft is given by:

$$I_{xy,RF}(d_{RA}) = 10\log(N_{xI,OPS}) + P_{Tx,x} + G_{WAIC} - L_{body} - L(d_{RA}) + G_{RA} - L_C, \qquad \text{(A-3.7)}$$

where $P_{Tx,x}$ is the maximum transmit power of either the WAIC high or low data rate OPS, G_{WAIC} is the maximum gain of the omni-directional WAIC transmit antenna, L_{body} is fuselage attenuation applied for WAIC applications inside the aircraft fuselage, $L(d_{RA})$ is the free-space path loss at a vertical separation distance d_{RA}, G_{RA} is the maximum RA antenna gain, L_C is the RA cable loss and $N_{xI,OPS}$ is the corresponding number of LI or HI OPSs as derived by equation (A-1.2).

The path loss in dB along the slant range d between an OPS and the RA antenna is calculated in accordance with Recommendation ITU-R P.525 by:

$$L(d) = 32.4 + 20\log f + 20\log d, \qquad \text{(A-3.8)}$$

In equation (A-3.7), f is the carrier frequency in MHz (in this case a value for f of 4 300 MHz is chosen which is the center frequency of the frequency band), d. is the distance between transmitting and receiving antenna in km.

The interference power levels caused by LO and HO WAIC applications are derived by utilizing the maximum tolerable e.i.r.p. pattern described in Annex 1 § A-1.4. Because the RA-aircraft is assumed to be located directly above the WAIC-aircraft, the e.i.r.p into the direction of 0° is used to derive $I_{xO,RF}$, the interference power level observed at the RA antenna output caused by WAIC outside applications:

$$I_{xO,RF}(d_{RA}) = \mathrm{EIRP}_{max}(0°) - L(d_{RA}) + G_{RA} - L_C. \qquad \text{(A-3.9)}$$

In the following sections the minimum separation distance required to protect the RA-aircraft from harmful interference is analyzed. For each WAIC application type, the aggregate interference power levels at the RA antenna output induced by the corresponding OPSs are calculated and utilized for comparison against the protection criteria. Table A-3.3 summarizes all WAIC system parameters utilized for the analysis.

TABLE A-3.3

Wireless avionics intra-communication signal propagation parameters

Parameter	Value	Units
Fuselage attenuation L_{body}	35*	dB
OPS transmit power for high data rate systems $P_{Tx,H}$	17	dBm
OPS transmit power for low data rate systems $P_{Tx,L}$	10	dBm
Gain of omni-directional antennas G_{WAIC} utilized for WAIC inside applications	0	dB
Maximum tolerable e.i.r.p. value into the upward direction $EIRP_{max}(0°)$	–20	dBm
WAIC carrier frequency	4 300	MHz

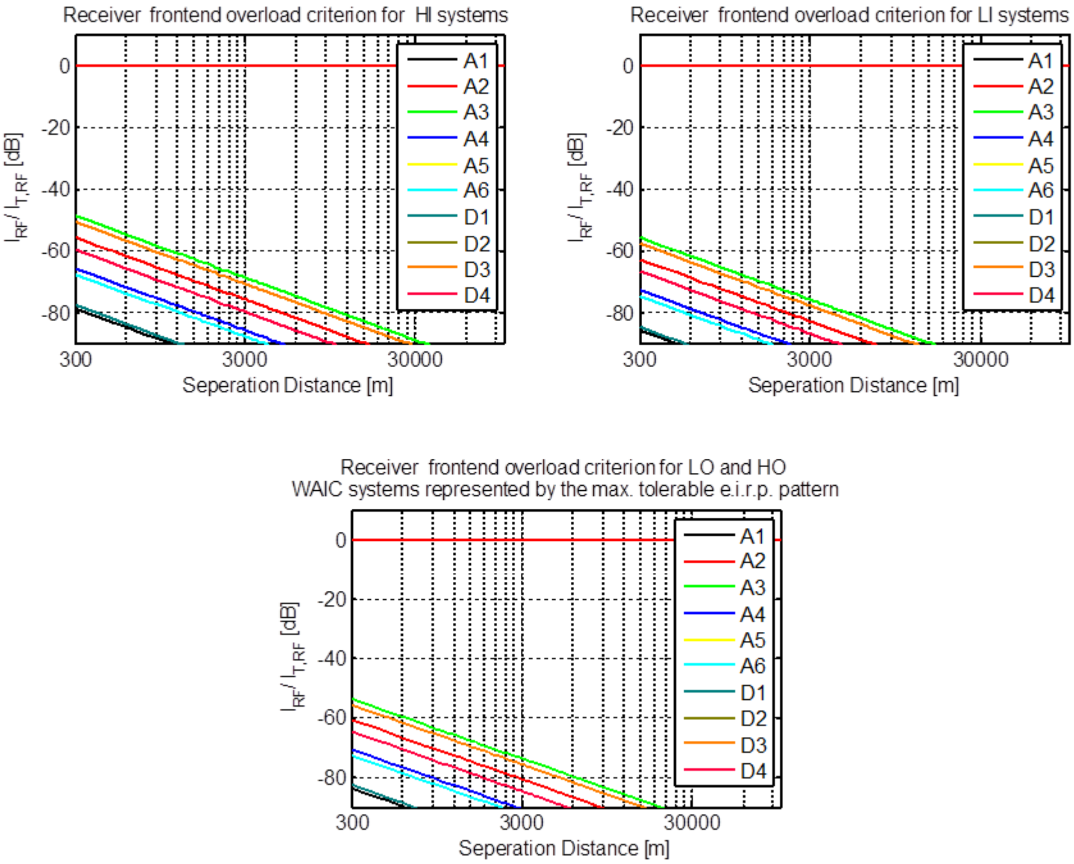
* Shielded attenuation scenario described in Report ITU-R-M.2283.

Radio altimeter frontend overload criterion

In order to avoid overload of the RA receiver frontend, it has to be ensured that the interference power at the frontend input I_{RF} never exceeds the RA-specific overload threshold $I_{T,RF}$ defined in Tables A-3.1 and A-3.2. The results presented in Fig. A-3.3 depict the dependence of I_{RF} on the separation distance between the RA and the WAIC-aircraft. Because the threshold $I_{T,RF}$ is specific to the respective RA type, all plots are normalized to the overload threshold $I_{T,RF}$ for the considered radio altimeter types. A violation of the frontend overload criterion occurs if $I_{RF}/I_{T,RF}$ > 0 dB for any radio altimeter type. The threshold is never exceeded by inside WAIC systems and outside WAIC systems characterized by the maximum tolerable e.i.r.p. pattern described in Annex 1 § A-1.4.

FIGURE A-3.3

Frontend overload protection criterion versus separation distance

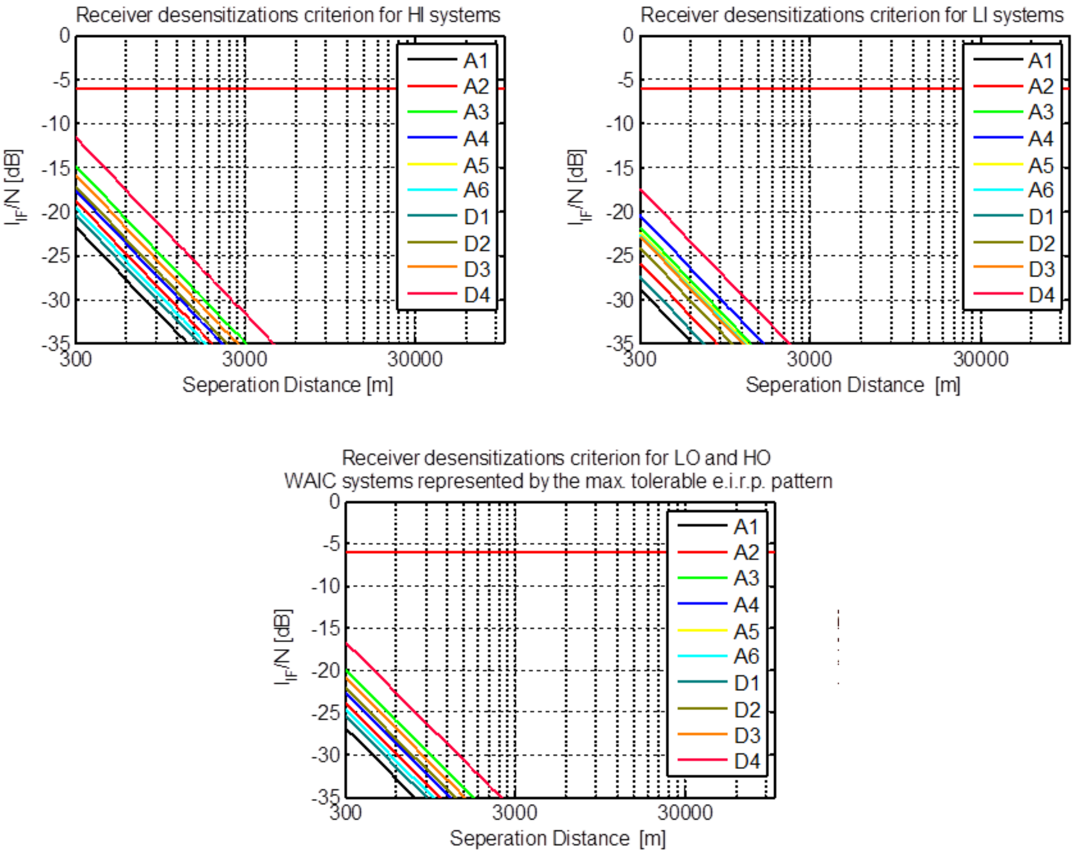


Radio altimeter receiver desensitization criterion

A desensitization of the RA receiver is likely to occur if the ratio of I_{IF} (the interference power in the IF-stage, i.e. the interference power referred to the IF-bandwidth) to N (the noise power referred to the IF bandwidth) exceeds –6 dB. Figure A-3.4 shows the I_{IF}/N ratio versus the separation distance for all RA types and WAIC system categories. In each of the plots shown in Fig. A-3.4 a red line marks the –6 dB I_{IF}/N protection threshold. For inside WAIC systems and outside WAIC systems characterized by the maximum tolerable e.i.r.p. pattern described in Annex 1 § A-1.4 the protection threshold is not exceeded for separation distances larger than 150 m.

FIGURE A-3.4

Receiver desensitization protection criterion versus separation distance

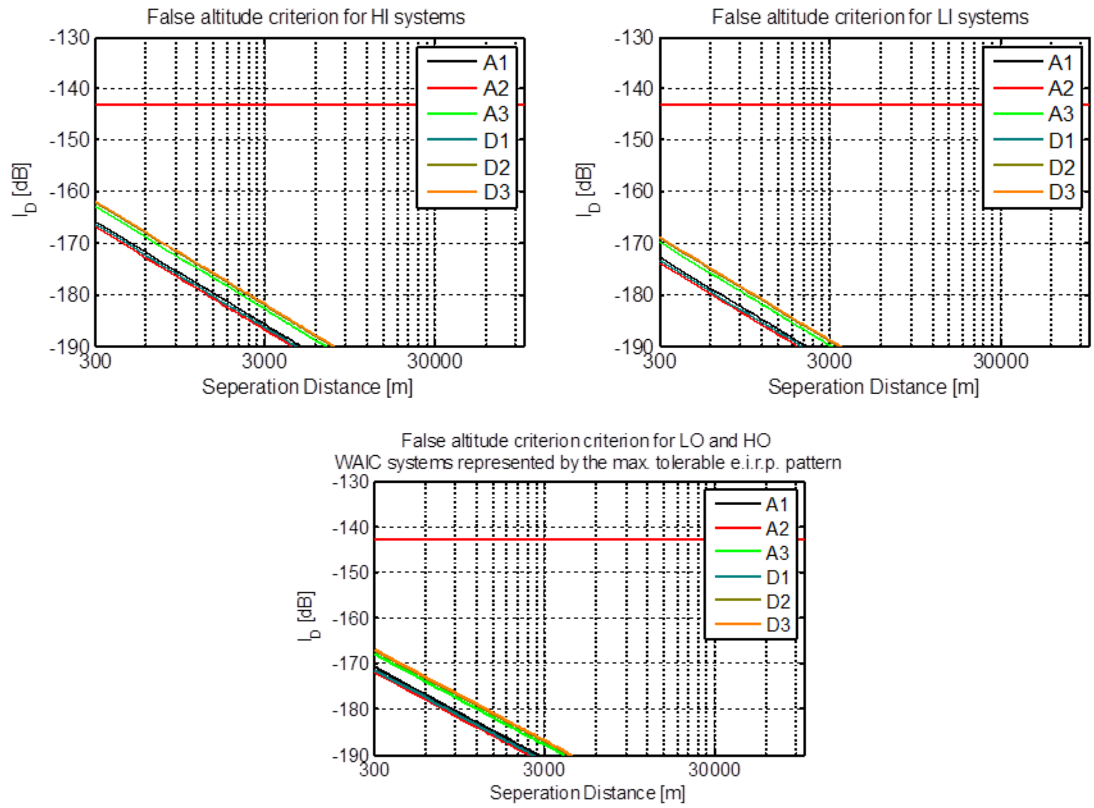


Radio altimeter false altitude report criterion

Interference in the RA detector stage may result in false altitude reports. To prevent false altitude detections caused by interference within the bandwidth of the detector stage the corresponding interference power level I_D is to be considered. In this context a detector bandwidth of 100 Hz is assumed for all FMCW RA types (see Recommendation ITU-R M.2059). For that reason the protection threshold which I_D must not exceeded is defined as $I_{T,FA}$ = –143 dBm/100 Hz. The criterion is not applicable for pulsed type RAs. For that reason Fig. A-3.5 only shows the relation between I_D and the separation distance for FMCW type RA. In each plot of Fig. A-3.5 a horizontal red line marks the absolute –143 dBm/100 Hz protection threshold. For inside WAIC systems and outside WAIC systems characterized by the maximum tolerable e.i.r.p. pattern described in Annex 1 § A-1.4 the protection threshold is not exceed for separation distances larger 100 m.

FIGURE A-3.5

False altitude protection criterion versus separation distance

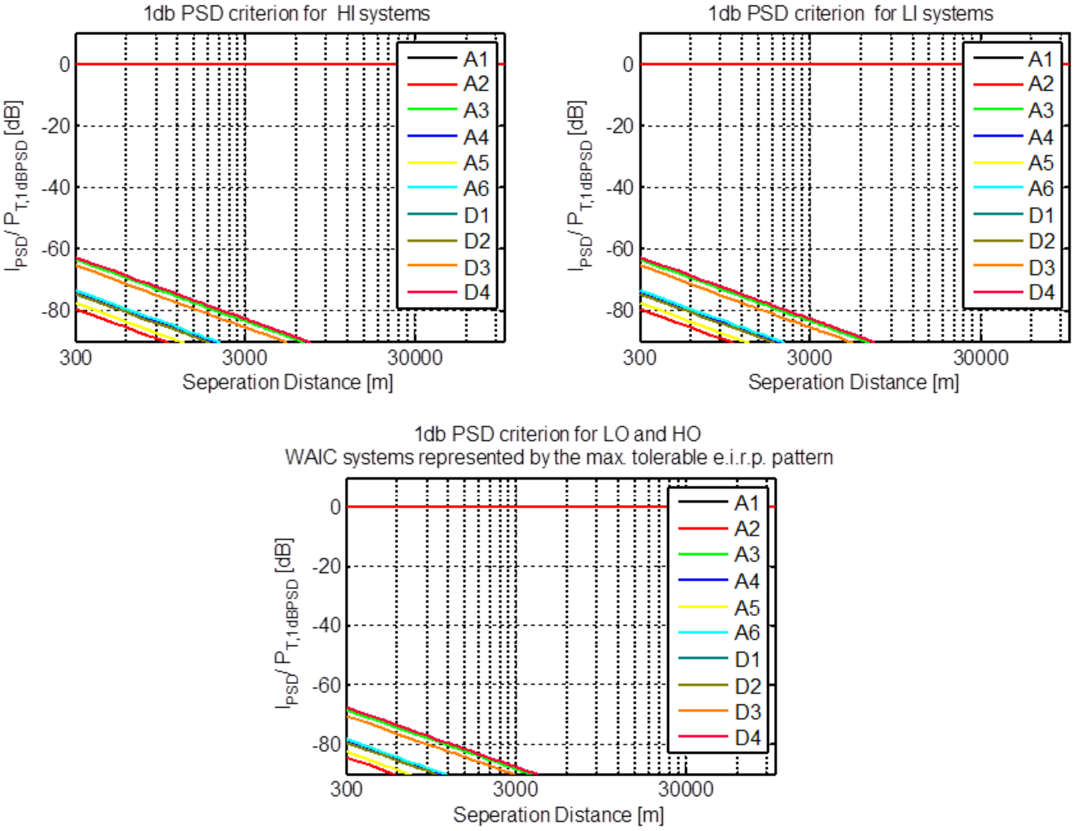


Radio altimeter power spectral density criterion

To ensure that the IF-stage is protected from overload conditions, the average power spectral density of the WAIC interference signal I_{PSD} is not allowed to exceed the protection threshold $I_{T,1dBPSD}$. Figure A-3.6 depicts the dependency of I_{PSD} on the separation distance. Because the protection threshold $I_{T,1dBPSD}$ is specific to the respective RA type, all corresponding plots are normalized to $I_{T,1dBPSD}$. A violation of the power spectral density criterion in this representation occurs if $I_{PSD}/I_{T,1dBPSD} > 0$ dB for any type of RA. For inside WAIC systems and outside WAIC systems characterized by the maximum tolerable e.i.r.p. pattern described in Annex 1 § A-1.4 the protection threshold $I_{T,1dBPSD}$ is never exceeded for separation distances larger than 1 m.

FIGURE A-3.6

1 dB power spectral density criterion versus separation distance



Summary

Analysis of the in-flight scenario shows that a minimal separation distance of 150 m is required to protect the radio altimeter from harmful interference of WAIC outside applications represented by the maximum tolerable e.i.r.p. pattern described in Annex 1 § A-1.4. Consequently no harmful interference is expected to be caused by LI, LO, HI and HO WAIC systems in flight, since the minimal separation distance between two aircraft in flight is 300 m, see § A-3.2.1.

A-3.2.2.2 Analysis of potential impact of frequency modulated carrier wave and pulsed radio altimeters onto wireless avionics intra-communication systems

WAIC systems are designed to provide reliable wireless communication between two stations onboard an aircraft. The reliability of a wireless communication link is primarily defined by four parameters:

– the propagation environment,

– the distance between the transmitting and receiving WAIC station dWAIC,

– the transmit power PTX,x, and

– the coupling gain of the transmitting and receiving node antenna GWAIC,coupling see Fig. A-3.7.

Depending on the propagation environment, d_{WAIC}, $G_{WAIC,coupling}$ and $P_{TX,x}$, WAIC high or low data rate systems are configured such that a sufficiently high signal power level *S*, required for reliable communication at the receiver is always guaranteed.

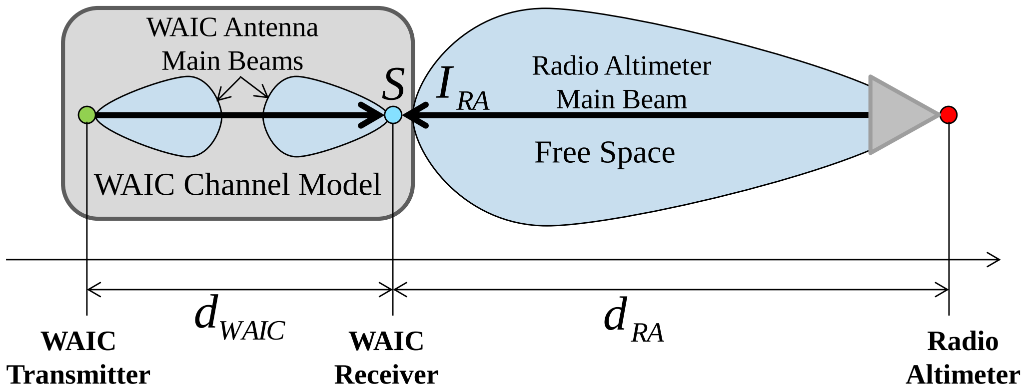
Report ITU-R M.2283 specifies maximum allowable values for d_{WAIC} and $P_{TX,x}$. The Report also provides a set of path loss models for different propagation environments between points inside and outside the aircraft structure. A detailed description of these models can be found in Annex 3 of Report ITU-R M.2283. Consequently S is given by:

$$S(d_{WAIC}) = P_{TX,x} + G_{WAIC,coupling} - L_{WAIC,n}(d_{WAIC}), \tag{A-3.10}$$

where $L_{WAIC,n}(d_{WAIC})$ is the pathloss at distance d_{WAIC} of the nth model listed in Table A-1.3 and G_{WAIC} the transmit and receive antenna gain of the WAIC stations, as depicted in Fig. A-3.7.

FIGURE A-3.7

Graphical representation of the calculation of the Signal-to-Interference power ratio for wireless avionics intra-communication systems



According to Table A-1.1 the maximum distance between two WAIC stations on board an aircraft is 15 m. The minimal signal power level observed at a receiving WAIC station at this distance of d_{WAIC} = 15 m for all propagation environments can be derived.

WAIC systems are organized in cellular sub networks on a compartment basis as specified in Report ITU-R-M.2283. That implies that there is no communication among WAIC stations located in different aircraft compartments, or between a station internal and another station external to the aircraft structure. For that reason, only the radio channel models A, B and F of Table A-1.3 are deemed applicable for determining the minimum WAIC receive signal power level.

The minimal receive signal power levels of inside WAIC systems resulting from the channel models mentioned above are listed in Table A-3.4. The minimal receive signal power levels are derived assuming a HI WAIC system transmit power of $P_{TX,H}$ = 17 dBm, a LI WAIC system transmit power of $P_{TX,L}$ = 10 dBm and omni-directional WAIC transmit/receive antennas with a gain of 0 dBi as stated in Table A-1.1.

For deriving the minimum receive signal power levels for LO and HO applications, the antenna concept described in Annex 1 § A-1.4 is utilized. Thus the receive signal power levels of the WAIC communication links benefit from the mainbeam-to-mainbeam coupling of transmit and receive antennas. For End Nodes and Gateway Nodes antenna gains of 25 dBi and 10 dBi, respectively is assumed. Consequently, the coupling gain sums up to $G_{WAIC,coupling}$ = 35 dBi. Furthermore, the transmit power of both LO and HO WAIC systems is set to –7 dBm in order to comply with the maximum tolerable e.i.r.p. pattern defined in Annex 1 § A-1.4. The resulting minimum receive signal power levels for LO and HO WAIC systems are listed in Table A-3.4.

TABLE A-3.4

Minimal wireless avionics intra-communication receive signal power

Group	Group name	WAIC transmit power	WAIC antenna gain	Min. WAIC high rate receive signal power	Min. WAIC low rate receive signal power
A	Intra-Cabin & Intra-Flight Deck	$\boldsymbol{P_{TX,L}}$ **= 10 dBm** $\boldsymbol{P_{TX,H}}$ **= 17 dBm**	$\boldsymbol{G_{WAIC,coupling}}$ **=0 dBi**	$S_{A,H}$ = –52.7dBm	$S_{A,L}$ = –59.7dBm
B	Inter-Cabin	$\boldsymbol{P_{TX,L}}$ **= 10 dBm** $\boldsymbol{P_{TX,H}}$ **= 17 dBm**	$\boldsymbol{G_{WAIC,coupling}}$ **=0 dBi**	$S_{B,H}$ = –57.5dBm	$S_{B,L}$ = –64.5dBm
F	Inter-Exterior	$\boldsymbol{P_{TX,L}}$ **= –7 dBm** $\boldsymbol{P_{TX,H}}$ **= –7 dBm**	$\boldsymbol{G_{WAIC,coupling}}$ **=35 dBi**	$S_{F,H}$ = –55.5dBm	$S_{F,L}$ = –62.5dBm

The potential impact of an interfering FMCW or pulsed RA-signal onto WAIC systems is only experienced at receiving WAIC stations. In-flight, the worst-case power level of an interfering RA signal received at a WAIC station is given by:

$$I_{RA}(d_{RA}) = P_{TX,RA} + G_{RA,dBi} - C_L - L(d_{RA}) - L_{body} + G_{WAIC} + R_E \qquad \text{(A-3.11)}$$

where $L(d_{RA})$ is the free-space pathloss at the distance between the receiving WAIC station and the RA transmit antenna d_{RA}, $P_{TX,RA}$ is the transmit power of the radar altimeter, L_{body} is attenuation applied for WAIC applications inside the aircraft fuselage, $G_{RA,dBi}$ is the maximum RA antenna gain and C_L is the RA cable loss.

The gain G_{WAIC} of the omni-directional LI and HI WAIC receiving antenna is 0 dBi according to Table A-1.1. The antennas used for LO and HO WAIC systems considered by the directional antenna concept described in Annex 1 § A-1.4 have a negative gain of –25 dBi into the upwards direction. The radar altimeter signal power of a RA-aircraft located above the WAIC aircraft is attenuated accordingly. For this reason the directional antenna gain for LO and HO WAIC systems utilized to determine $I_{RA}(d_{RA})$ is G_{WAIC} = –25 dBi.

The bandwidth ratio R_E is applied to account for the fact that only a fraction of the energy of an interfering RA-signal with a 3 dB emission bandwidth B_{RA} larger than the 3dB IF-bandwidth $B_{IF,WAIC}$ of a WAIC station, is observed as interference at a receiving station.

Considering pulse type RAs the bandwidth ratio R_E is given by:

$$R_E = \begin{cases} 10\log\left(\frac{B_{IF,WAIC}}{B_{RA}}\right) & \text{if } B_{IF,WAIC} \le B_{RA} \\ 0 & \text{if } B_{IF,WAIC} > B_{RA} \end{cases} \qquad \text{(A-3.12)}$$

The instantaneous signal bandwidth of FMCW type RAs is small compared to $B_{IF,WAIC}$. Thus the entire energy of an FMCW signal falls into the IF-stage of a receiving WAIC station. Consequently the bandwidth ratio equals one (R_E = 0 dB) for FMCW type radio altimeters.

Harmful interference from FMCW or pulse type RAs onto WAIC systems does not occur as long as the interference to signal power ratio (I/S) is below the thresholds defined by the WAIC protection criteria described in Report ITU-R-M.2283. For WAIC low data rate systems the I/S threshold is given by:

$$I_{RA}(d_{RA})/S_{x,L} < -9 \text{ dB}, \qquad \text{(A-3.13)}$$

where $S_{x,L}$ is the minimal receive signal power of low data rate systems derived by the use of channel model x (A,B or F).

For WAIC high data rate system the threshold is:

$$I_{RA}(d_{RA})/S_{x,H} < -14 \text{ dB}, \qquad \text{(A-3.14)}$$

where $S_{x,H}$ is the minimal receive signal power of high data rate systems.

Given the dependencies described above, the potential impact of a radio altimeter onto WAIC systems can be analyzed for any given separation distance between a receiving WAIC station and a RA transmit antenna. A list of parameters used for the analysis is given in Table A-3.5.

TABLE A-3.5

Fixed parameters utilized for the analysis of the potential impact of radio altimeters onto wireless avionics intra-communication systems

	LI and HI WAIC systems	**LO and HO WAIC systems**	**Unit**
$P_{TX,L}$	10	–7	dBm
$P_{TX,H}$	17	–7	dBm
L_{body}	35	0	dB
G_{WAIC}	0	–25	dBi

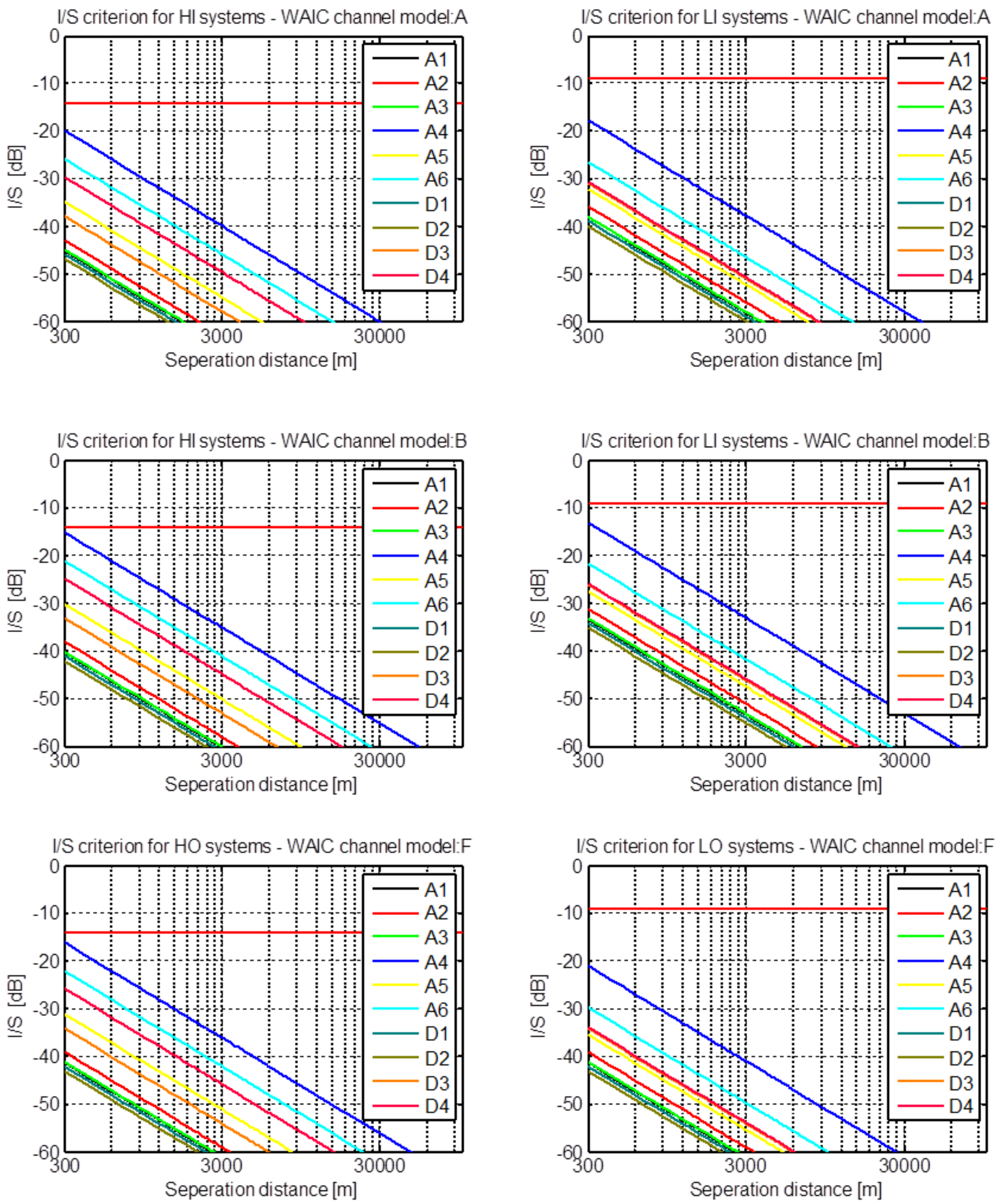
Results

The plots in Fig. A-3.8 show the corresponding I/S ratios of the radio altimeter interference power level I_{RA} and the WAIC receive signal power level S vs. separation distance for all four WAIC system categories and their associated protection thresholds (red lines). In accordance with § A-1.2 channel models A and B are applied for the inside WAIC system categories. For outside WAIC systems, channel model F and the concept of directive antennas described in Annex 1 § A-1.4 is applied.

The analysis shows that the minimum separation distance between two aircraft in flight of 300 m is always sufficient to protect all LI, LO, HI and HO WAIC systems from harmful interference.

FIGURE A-3.8

***I/S* observed at a wireless avionics intra-communication receiving station vs. separation distance**



A-3.2.3 Airport scenarios

The most critical operational phase for the radio altimeter of the RA-aircraft is during final stage of landing. Consequentially, interference from aircraft equipped with WAIC systems occurring during landing is most critical. Because the distances between aircraft lining up in the air for landing are large (~5 km), interference from WAIC systems is only expected from aircraft on ground at the airport premises. In this case the separation distances between the RA- and WAIC-aircraft can be less than 300 m.

In this case potentially harmful interference is only expected if WAIC-aircraft are located in close vicinity to the volume illuminated by the radio altimeter antenna beam beneath the landing

RA-aircraft. Consequentially, situations in which potentially harmful interference may occur are limited to scenarios where WAIC-aircraft are located on taxiways near to the runway approached by the landing RA-aircraft.

For that reason, the following sections analyze two scenarios. The first scenario describes a situation where multiple WAIC-aircraft are taxiing for takeoff next to the runway which the RA-aircraft is approaching for landing. This scenario is hereafter referred to as airport taxiway scenario. The second scenario describes a situation in which a WAIC-aircraft is located on a taxiway holding position next to the touchdown zone of the runway which is approached by a landing RA-aircraft. The described scenario is hereafter referred to as airport holding bay scenario.

A-3.2.3.1 Airport taxiway scenario description

In the scenario described throughout the following, the landing approach of an RA-aircraft is specified by a model with two parameters:

– the RA-aircraft altitude aRA, see Fig. A-3.10;

– the orthogonal projection of the RA-aircraft's position on the centerline of the runway in the y-axis direction yRA, see Fig. A-3.9.

Thus, the center point of the RA-aircraft is always assumed to be located above the centerline of the runway.

The scenario considers a configuration with several WAIC-aircraft queuing on a taxiway parallel to the runway dedicated for landing, as shown in Fig. A-3.9. A separation distance of d_{Taxi} = 80 m for aircraft on the taxiway is assumed.

The LI and HI WAIC systems on board the taxiing WAIC-aircraft are modelled by the OPS concept introduced in § A-1.3. The OPSs representing inside WAIC applications are located in the center of the aircraft cabin, OPSs representing outside WAIC applications are located at the wingtip closest to the RA-aircraft, as shown in Fig. A-3.11. The selected locations lead to minimal slant ranges between the RA antenna and the OPSs representing inside and outside WAIC application categories on board the taxiing WAIC-aircraft. This can be seen as a worst-case scenario regarding the impact of mutual interference. In reality WAIC stations are distributed over the entire aircraft and not concentrated at the locations closest to the RA-aircraft.

In addition the LO and HO WAIC systems on board the WAIC-aircraft are characterized by the maximum tolerable e.i.r.p. pattern, described in Annex 1 § A-1.4. The pattern shown in Fig. A-1.4 is rotationally symmetrical with respect to the aircraft's yaw axis. For that reason, only the angle φ between the line-of-sight vector between the WAIC-aircraft and RA-aircraft and the yaw axis of the WAIC-aircraft can be used to determine the maximum tolerable e.i.r.p. value, see Fig. A-3.10.

FIGURE A-3.9

Airport scenario top view

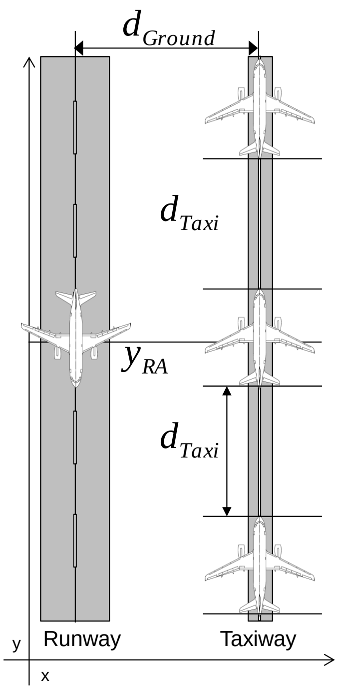


FIGURE A-3.10

Airport scenario frontal view

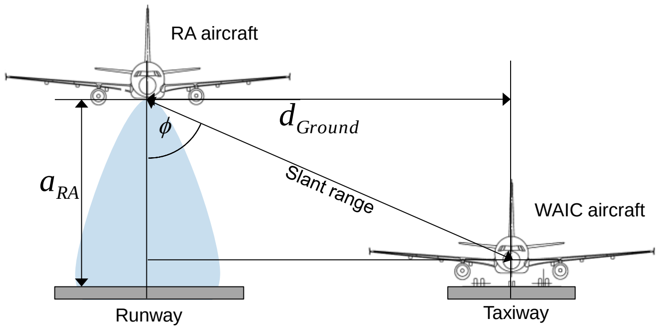
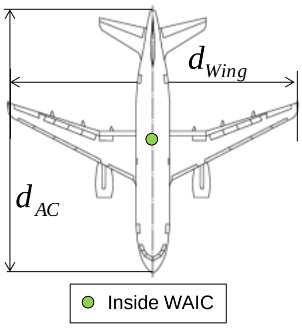


FIGURE A-3.11

Wireless avionics intra-communication -aircraft omni-directional point source distribution



Considering the WAIC-aircraft models described above, the interference impact of the RA-aircraft onto WAIC-aircraft and vice versa is significantly influenced by four parameters:

– the slant range between the RA antenna position and the WAIC OPS;

– the angle-dependent antenna gain GRA,dB(ϕ);

– the angle-dependent maximum tolerable e.i.r.p. EIRPmax(φ), described in Annex 1 § A-1.4, for the analysis of the interference impact of LO and HO WAIC applications onto the RA-aircraft;

– the isolation provided by the directional antenna concept, described in Annex 1 § A-1.4, for the analysis of the interference of the RA onto LO and HO WAIC applications.

All parameters are directly dependent on a_{RA}, y_{RA} and d_{Ground}, the distance between the runway and taxiway centerlines.

Annex 14 to the Convention on International Civil Aviation and the IATA Airport Development Reference Manual provide design rules for the definition of d_{Ground}.

Six reference aerodromes (ICAO code letters A-F) and the associated maximum dimensions for aircraft allowed to land on the corresponding runways are introduced. The determining factor in this context is the aircraft wingspan. The reference aerodromes and the associated reference aircraft types are listed in Table A-3.6.

In the following a scenario where a RA-aircraft on ground (a_{RA} = 0) and a single WAIC-aircraft on the taxiway located abreast the y_{RA} position of the RA-aircraft is considered. Regarding this scenario, the slant ranges between radio altimeter antenna and the inside/outside OPS are minimal and depend linearly on d_{Ground}. Because the slant ranges are proportional to the path loss of the WAIC signal observed at the radio altimeter antenna, lower values of d_{Ground} lead to higher interference power. However, the airport type and the associated WAIC-aircraft size influence the minimum possible slant range, i.e. the maximum possible coupling between WAIC systems and the radio altimeter receive antenna of the RA-aircraft. The corresponding ranges are listed in Table A-3.6.

TABLE A-3.6

Airport classification with associated aircraft types

Reference Aerodrome (ICAO Aerodrome Reference Code)	**WAIC-aircraft**			**Distance between taxiway and runway centerlines d_{Ground} (m)**	**Distance between outside OPS and runway centerline (m)**	**Distance between inside OPS and runway centerline (m)**
	Type	**Length (m)**	**Span (m)**			
B	**CRJ 200**	**26.76**	**21.21**	**87.00**	**65.79**	**87.00**
C	A319	33.84	34.10		133.90	168.00
	A320-200	37.57	34.10	168.00	133.90	168.00
	B737-800	39.50	34.30		133.70	168.00
D	A310-300	46.66	43.90		132.10	176.00
	B757-200	47.33	38.06	176.00	137.94	176.00
	B767-300ER	57.94	47.57		128.43	176.00
E	A340-600	75.30	63.45		119.05	182.50
	B777-200	63.73	60.95	182.50	121.55	182.50
	B747-400	70.67	64.94		117.56	182.50
F	A380	73.00	79.80	190.00	110.20	190.00

Considering an increasing RA-aircraft altitude, the slant ranges remain minimal as long as the RA-aircraft is not moved along the *y*-axis. Consequently the pathloss for any value of a_{RA} also remains minimal. But an increasing value of a_{RA} will lead to a decreasing incident angle ϕ at the RA antenna, see Fig. A-3.10. Therefore, this leads to an increase of antenna gain $G_{RA,dB}$. Again the angle ϕ will remain minimal for any value of a_{RA} as long as the RA-aircraft's y_{RA} position remains unaltered and abreast to the taxiing aircraft. Hence, the described scenario leads to maximum impact of a RA-aircraft onto WAIC-aircraft and vice versa for any value of a_{RA} and any given airport type. In this regard, the highest potential interference impact can be expected for reference aerodrome type B and its associated aircraft type since for this aerodrome type the resulting slant ranges are minimal.

Although the maximum interference scenario described above only takes a single WAIC-aircraft into account, corresponding considerations do also apply for multiple taxiing WAIC-aircraft. For that purpose the geometrical center point on the y-axis of all WAIC-aircraft has to be abreast the RA-aircraft y_{RA} position, as shown in Fig. A-3.9.

Five WAIC aircraft are assumed taxiing in line for calculation of the aggregate interference power in the airport taxiway scenario. This number is deemed to be appropriate since any higher number will only cause a maximum deviation of less than 0.5 dB from the results presented in §§ A-3.2.3.3 and

A-3.2.3.4. The parameters used for the investigation of the airport taxiway scenario are shown in Table A-3.7.

TABLE A-3.7

Airport taxiway scenario parameters

Parameter	Value
d_{Taxi}	80 m
d_{Ground}	87 m
WAIC-aircraft wingspan	21.21 m
WAIC-aircraft length	26.76 m
Number of WAIC-aircraft	5

A-3.2.3.2 Airport holding bay scenario description

In this scenario potential mutual interference between a landing RA-aircraft and a WAIC-aircraft waiting for takeoff at a runway holding bay next to the runway touchdown zone is analyzed. The minimal distance on ground between the RA-aircraft and the WAIC-aircraft is given when the RA-aircraft is located directly above the touchdown zone (see Figs A-3.12 and A-3.13). As a consequence, the mutual interference impact solely depends on the landing RA-aircraft altitude.

The LI and HI WAIC systems on board the WAIC-aircraft waiting at the runway holding bay are modelled using the OPS concept introduced in § A-1.3. The OPSs representing inside WAIC applications are located at the nose tip of the WAIC-aircraft. The selected location leads to minimal slant ranges between the RA antenna and the OPS representing LI and HI WAIC systems on board the WAIC-aircraft. This can be seen as a worst-case scenario regarding the impact of mutual interference. In reality WAIC stations are distributed across the entire aircraft and not concentrated at the locations closest to the RA.

The LO and HO WAIC systems on board the WAIC-aircraft waiting at the runway holding bay are represented by the maximum tolerable e.i.r.p. pattern, described in Annex 1 § A-1.4. The pattern shown in Fig. A-1.4 is rotationally symmetrical with respect to the aircraft's yaw axis. For that reason, only the angle φ between the line-of-sight vector between WAIC-aircraft and RA-aircraft and the yaw axis of the WAIC-aircraft can be used to determine the maximum tolerable e.i.r.p. value, see Fig. A-3.13. In correspondence to the LI and HI WAIC applications, the slant range between the WAIC-aircraft nose tip and the RA antenna is used to determine the pathloss of the WAIC signals. Placing the OPSs at the aircraft's nose tip causes a higher potential interference impact as if assuming a more realistic distribution of WAIC nodes across the entire aircraft. Consequentially, the chosen method will result in a worst-case estimate of the potential interference impact.

FIGURE A-3.12

Airport holding bay scenario top view

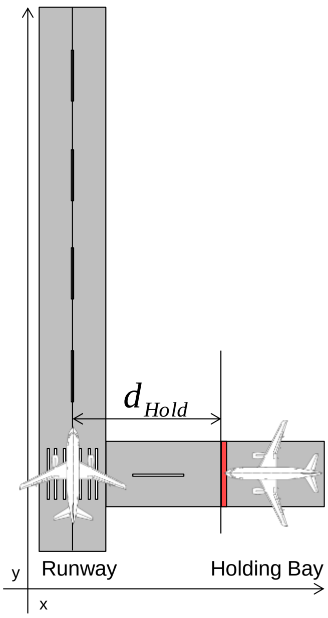


FIGURE A-3.13

Airport holding bay scenario frontal view

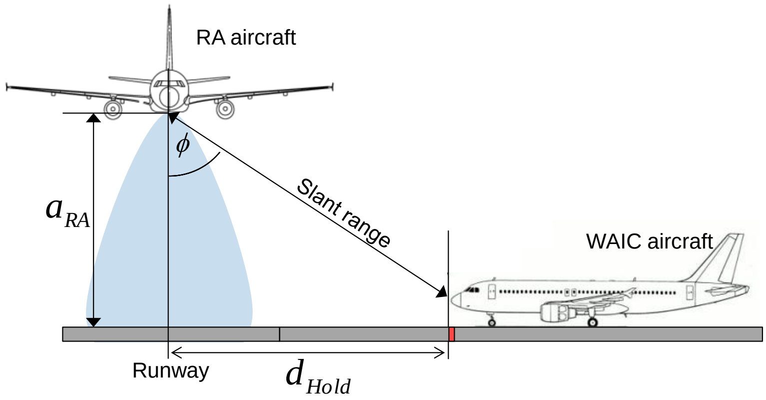
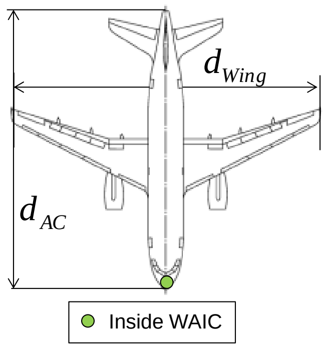


FIGURE A-3.14

Wireless avionics intra-communication-aircraft omni-directional point source distribution



Given the WAIC-aircraft model described above the interference impact of the RA onto WAIC systems and vice versa is influenced by four parameters:

– the slant range between the RA antenna position and the LI and HI WAIC OPSs;

– the angle-dependent antenna gain GRA,dB(ϕ);

– the angle-dependent maximum tolerable e.i.r.p. EIRPmax(φ), described in Annex 1 § A-1.4, for the analysis the interference impact of LO and HO WAIC applications onto the RA-aircraft;

– the isolation provided by the directional antenna concept, described in Annex 1 § A-1.4, for the analysis of the potential interference impact of the RA onto LO and HO WAIC applications.

All parameters directly depend on the RA-aircraft's altitude a_{RA}, the distance between the runway touchdown zone and the runway holding bay position d_{Hold}, the aircraft dimensions and the location of the OPS on board the WAIC-aircraft as shown in Fig. A-3.14.

According to the airport design rules described in Annex 14 to the Convention on International Civil Aviation, the separation distance d_{Hold} depends on the length of the associated runway, as shown in Table A-3.8. The ICAO reference aircraft type which requires the shortest runway length and hence the lowest separation distance is the Bombardier CRJ 200 (see Table A-3.6). Specifications provided by Bombardier state that the minimal runway length required by the CRJ 200 is 1 479 m, which is a code number 3 type runway (see Table A-3.8). Thus the minimal separation distance which maximizes the impact of mutual interference is d_{Hold} = 75 m. All parameters used for the investigation of the airport holding bay scenario are summarized in Table A-3.9.

TABLE A-3.8

Minimum distance (d_{Hold}) between the runway center line and a runway holding position

	Code Number			
Type of runway	**1**	**2**	**3**	**4**
Runway reference length	Less than 800 m	800 m up to but not including 1 200 m	1 200 m up to but not including 1 800 m	1 800 m and more
Non-instrument	30 m	40 m	75 m	75 m
Non precision approach	40 m	40 m	75 m	75 m
Precision approach category I	60 m	60 m	90 m	90 m
Precision approach categories II and III	–	–	90 m	90 m

TABLE A-3.9

Airport holding bay scenario parameters

Parameter	**Value**
d_{Hold}	75 m
WAIC-aircraft wingspan	21.21 m
WAIC-aircraft length	26.76 m
Number of WAIC-aircraft	1

A-3.2.3.3 Analysis of potential impact of Wireless Avionics Intra-Communication systems onto FMCW and pulsed radio altimeters

The OPSs representing the LI and HI WAIC systems introduced in § A-1.3 are assumed to transmit with a power of $P_{Tx,H}$ = 17 dBm and $P_{Tx,L}$ = 10 dBm (see Table A-3.10). The fuselage attenuation applied for LI and HI WAIC applications is assumed to be constantly 35 dB (‘shielded’ case) as specified in Report ITU-R M.2283. This results in an attenuation of the signals emitted by inside OPSs of L_{Body} = 35 dB. The emissions of LO and HO WAIC applications are assumed to comply with the maximum tolerable e.i.r.p. pattern, as described in Annex 1 § A-1.4.

TABLE A-3.10

Wireless avionics intra-communication signal propagation parameters

Parameter	
Aircraft body attenuation L_{Body}	35 dB
High data rate OPS transmit power $P_{Tx,H}$	17 dBm
Low data rate OPS transmit power $P_{Tx,L}$	10 dBm
WAIC carrier frequency	4 300 MHz

All four protection criteria described in § A-3.1 relate to $I_{xy,RF}$, the interference power caused by WAIC systems observed at the RA-frontend input. The interference power $I_{xI,RF}$ resulting from LI and HI WAIC applications is derived by taking the omni-directional WAIC antenna gain G_{WAIC}, the fuselage attenuation L_{Body}, the signal propagation loss $L(d)$, the RA antenna gain $G_{RA,dB}(\phi)$, the RA cable loss C_L, the WAIC transmit signal power P_{TX} and the corresponding number of LI or HI OPSs $N_{xI,OPS}$ as derived by Equation A-1.2 into account. The interference power level observed at the RA-frontend input is described by:

$$I_{xI,RF} = 10\log(N_{xI,OPS}) + P_{TX,x} + G_{WAIC} - L_{Body} - L(d) + G_{RA,dB}(\phi) - C_L. \qquad \text{(A-3.15)}$$

The interference power levels $I_{xO,RF}$ caused by LO and HO WAIC applications observed at the RA antenna output are derived by utilizing the maximum tolerable e.i.r.p. pattern, described in Annex 1 § A-1.4. $I_{xO,RF}$ is given by:

$$I_{xO,RF}(d_{RA}) = \mathrm{EIRP}_{max}(\varphi) - L(d_{RA}) + G_{RA,dB}(\phi) - C_L. \qquad \text{(A-3.16)}$$

The results of the airport taxiway and airport holding bay scenarios presented throughout the following are depicted in a common format. For each protection criterion three plots are presented. Two plots for LI and HI WAIC systems and one plot for the outside WAIC systems characterized by the maximum tolerable e.i.r.p. pattern defined in Annex 1 § A-1.4. Each of these plots shows an evaluation of a parameter specific to the considered protection criterion vs. the RA-aircraft's altitude.

Frontend overload criterion

In order to avoid overload of the RA receiver frontend, it has to be ensured that the interference power at the frontend input I_{RF} never exceeds the RA-specific overload threshold $I_{T,RF}$ defined in Tables A-3.1 and A-3.2. The results presented in Figs A-3.15 and A-3.16 depict the dependence of I_{RF} on the RA-aircraft's altitude in the airport taxiway and airport holding bay scenarios. Because the threshold $I_{T,RF}$ is RA-specific, all plots are normalized to the overload threshold $I_{T,RF}$ for the considered RA types. A violation of the frontend overload criterion occurs if $I_{RF}/I_{T,RF} > 0$ dB for any type of RA. The results show that the frontend overload criterion is not exceeded for any of the analyzed RA types in both scenarios.

FIGURE A-3.15

Airport taxiway scenario: frontend overload protection criterion

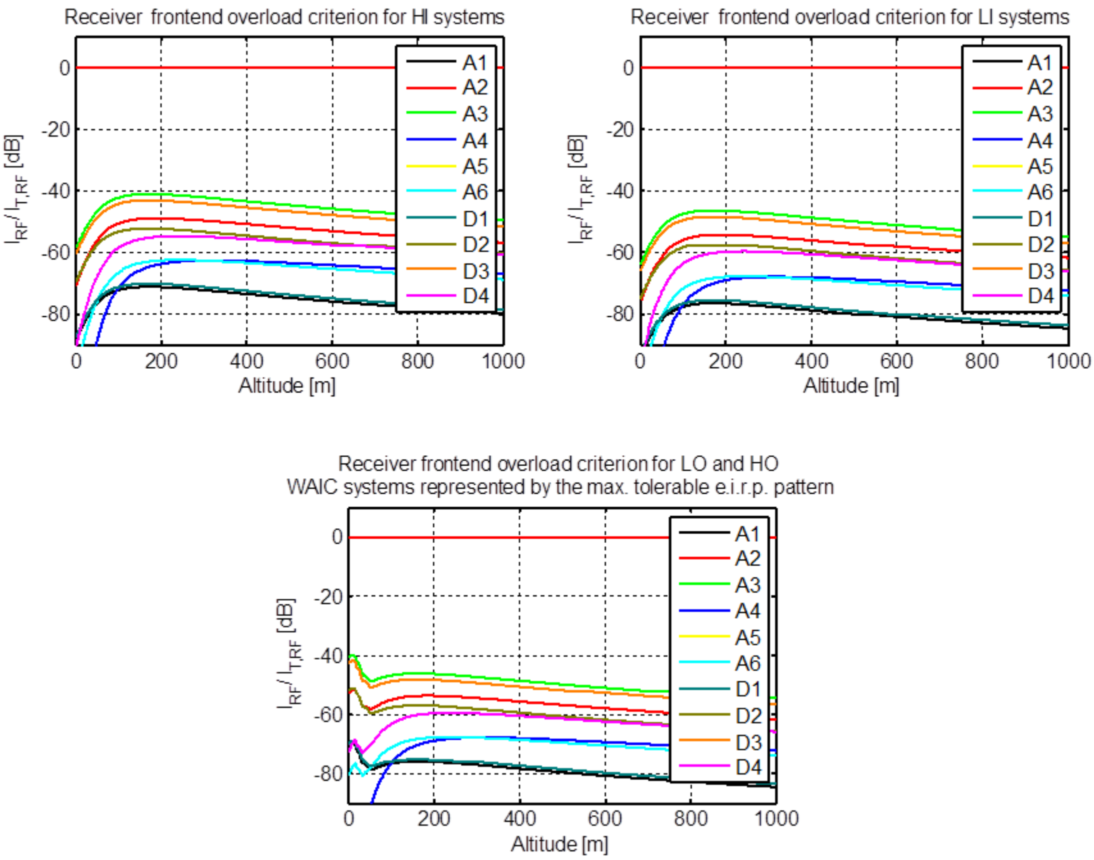
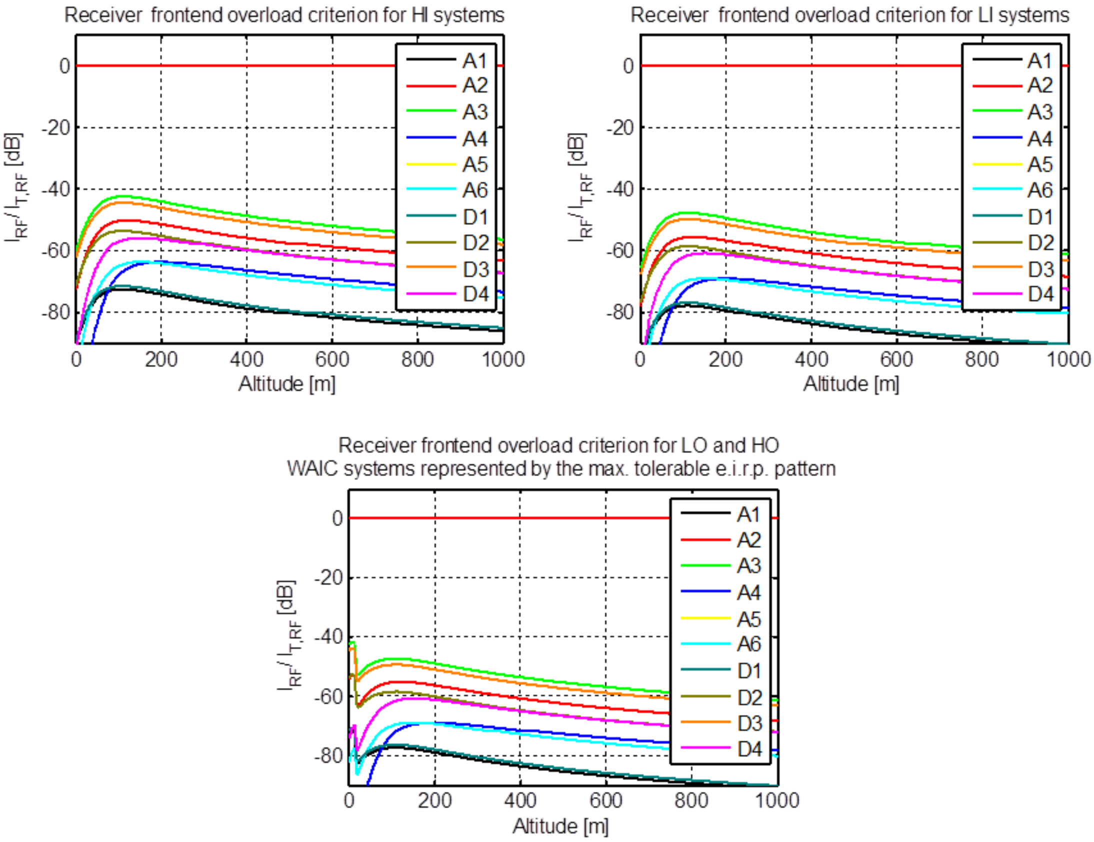


FIGURE A-3.16

Airport holding bay scenario: frontend overload protection criterion



Receiver desensitization

A desensitization of the RA receiver is likely to occur if the ratio of I_{IF} (the interference power in the IF-stage, i.e. the interference power referred to the IF-bandwidth) to N (the noise power referred to the IF-bandwidth) exceeds –6 dB for any of the considered RA types. Figures A-3.17 and A-3.18 show the evaluation of the I_{IF}/N ratio versus the RA-aircraft's altitude for all considerer RA types and WAIC system categories in the airport taxiway and airport holding bay scenarios. In each of the plots shown in Figs A-3.17 and A-3.18 a red line marks the –6 dB I_{IF}/N protection threshold. In both scenarios the receiver desensitization criterion is neither exceeded for inside WAIC systems nor for outside WAIC systems represented by the maximum tolerable e.i.r.p. pattern described in Annex 1 § A-1.4.

FIGURE A-3.17

Airport taxiway scenario: receiver desensitization protection criterion

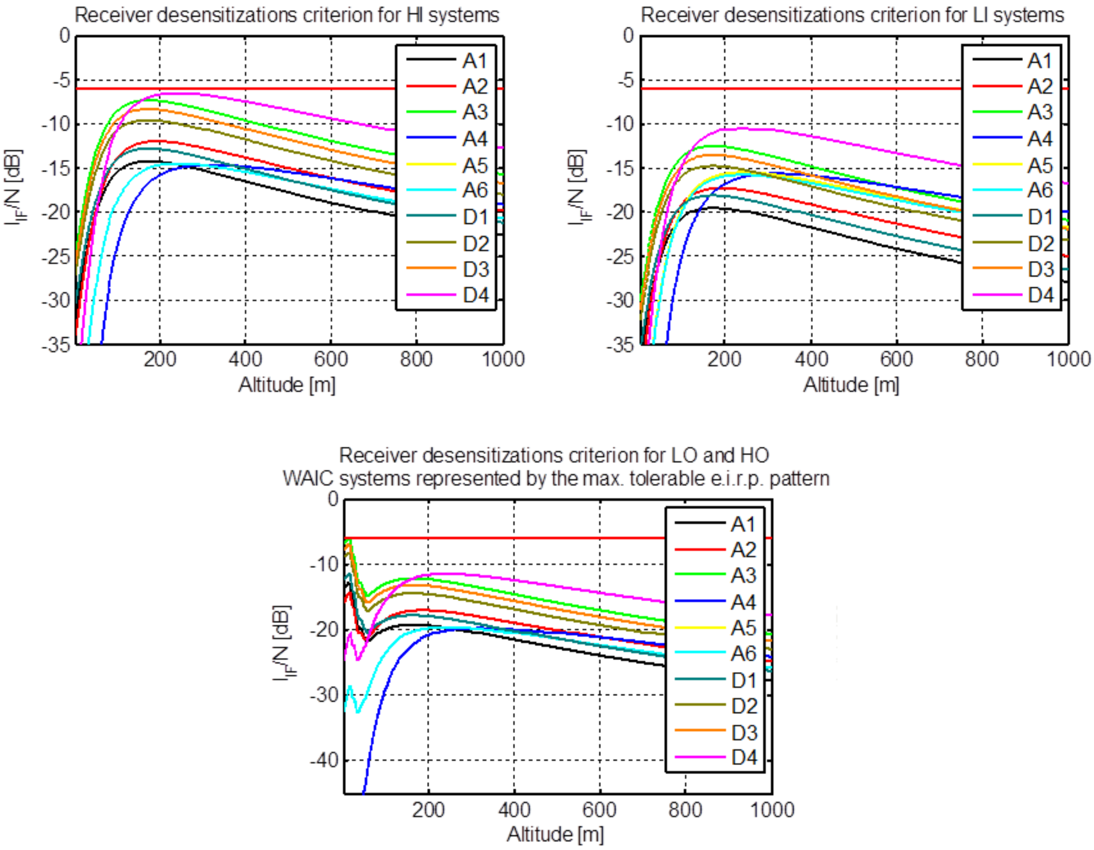
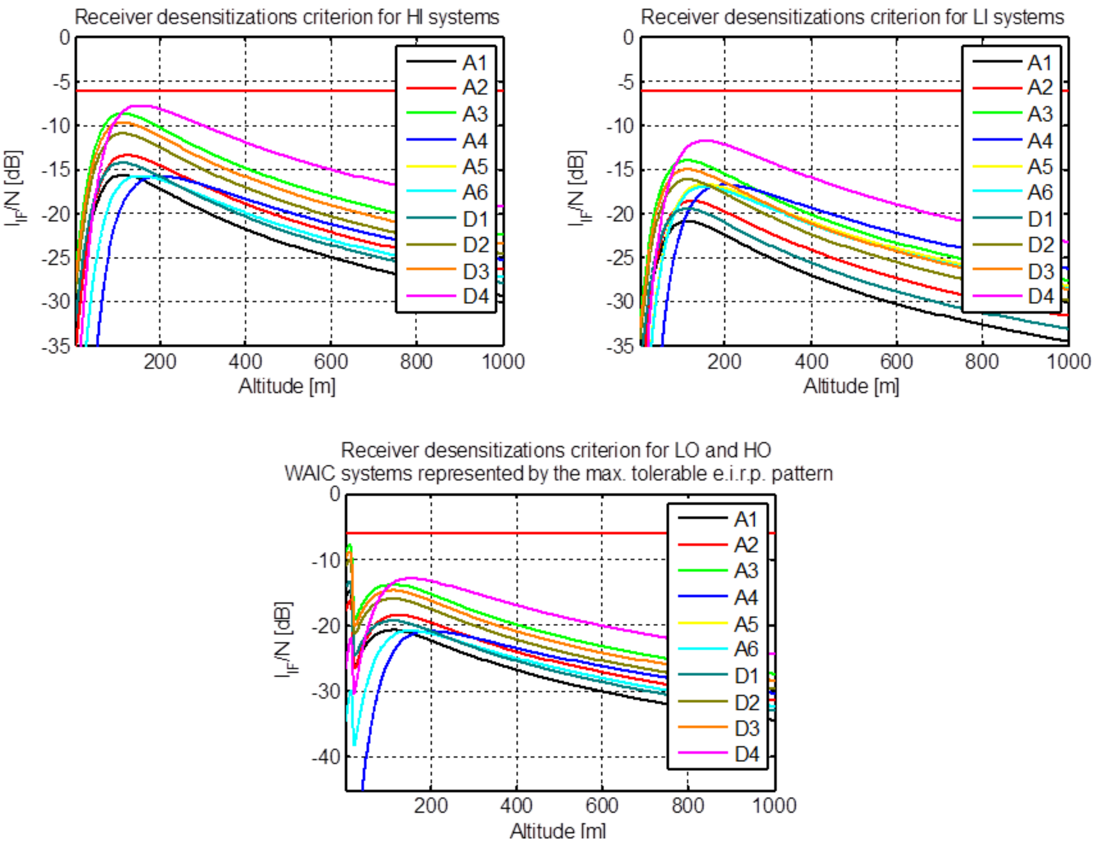


FIGURE A-3.18

Airport holding bay scenario: receiver desensitization protection criterion



False altitude report

Interference in the RA detector stage may result in false altitude reports. To prevent false altitude detections caused by interference within the bandwidth of the detector stage the corresponding interference power I_D is considered. In this context a detector bandwidth of 100 Hz is assumed for all FMCW RA types. For that reason the protection threshold, which should not be exceeded by I_D, is defined to be $I_{T,FA}$ = –143 dBm/100 Hz. Figures A-3.19 and A-3.20 show the relation between I_D and the RA-aircraft's altitude for all considered RA types and WAIC systems in the airport taxiway and airport holding bay scenario. In each plot of Figs A-3.19 and A-3.20 a red line marks the absolute –143 dBm/100 Hz protection threshold. In all cases the threshold is neither exceeded for inside WAIC systems nor for outside WAIC systems characterized by the maximum tolerable e.i.r.p. pattern, described in Annex 1 § A-1.4.

FIGURE A-3.19

Airport taxiway scenario: false altitude report protection criterion

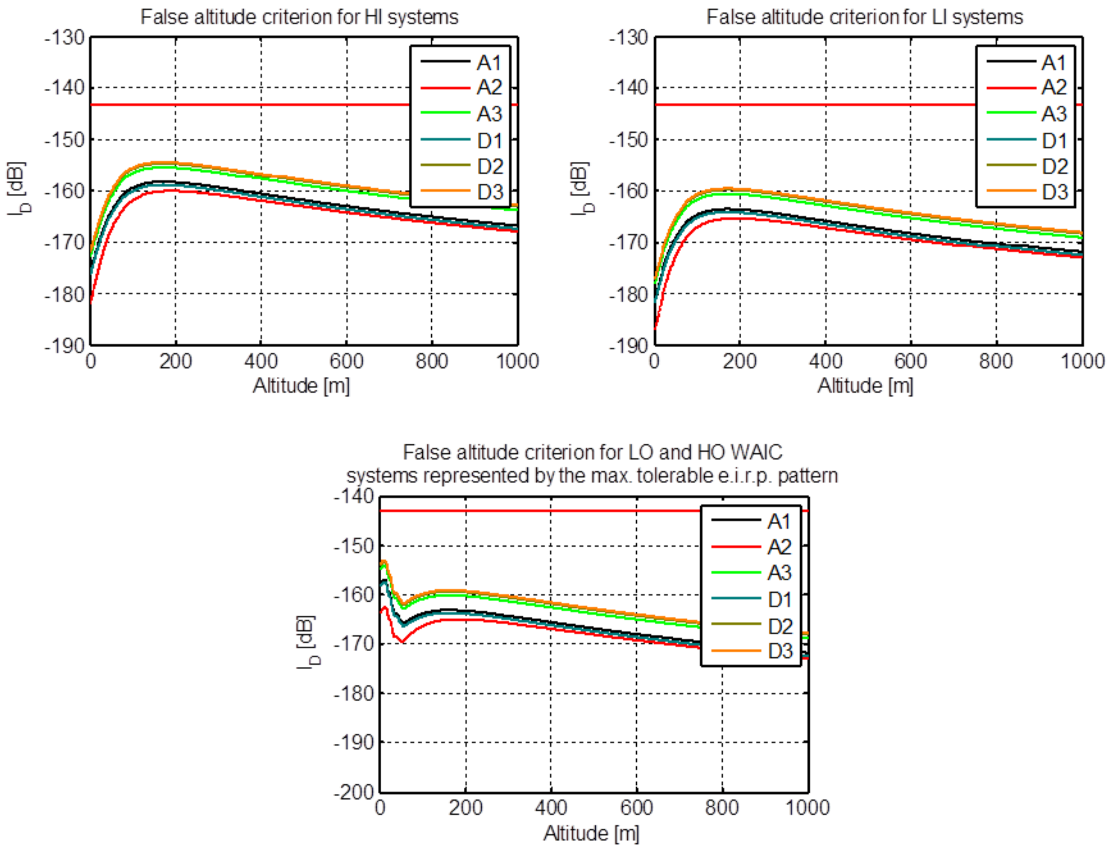
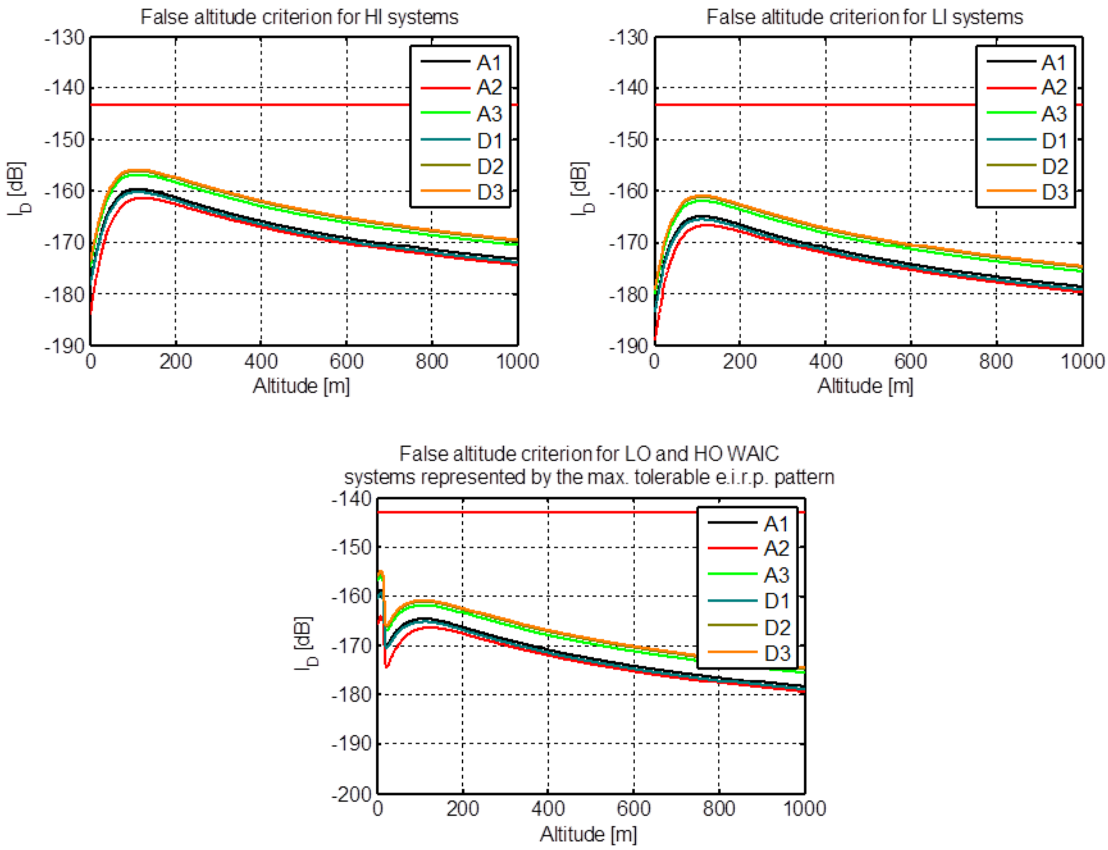


FIGURE A-3.20

Airport holding bay scenario: false altitude report protection criterion



Power spectral density

To ensure that the IF-stage is protected from overload conditions the average power spectral density of the WAIC interference signal I_{PSD} is not allowed to exceed the protection threshold $I_{T,1dBPSD}$. The results presented in Figs A-3.21 and A-3.22 depict I_{PSD} vs. the RA-aircraft's altitude in the airport taxiway and airport holding bay scenarios. Because the threshold $I_{T,1dBPSD}$ is RA-specific, all corresponding plots are normalized to the protection threshold $I_{T,1dBPSD}$ for all considered FMCW RA types. A violation of the power spectral density criterion in this representation occurs if $I_{PSD}/I_{T,1dBPSD} > 0$ dB for any type of RA. In both scenarios the power spectral density criterion is neither exceeded for inside WAIC systems nor for outside WAIC systems represented by the maximum tolerable e.i.r.p. pattern described in Annex 1 § A-1.4.

FIGURE A-3.21

Airport taxiway scenario: power spectral density protection criterion

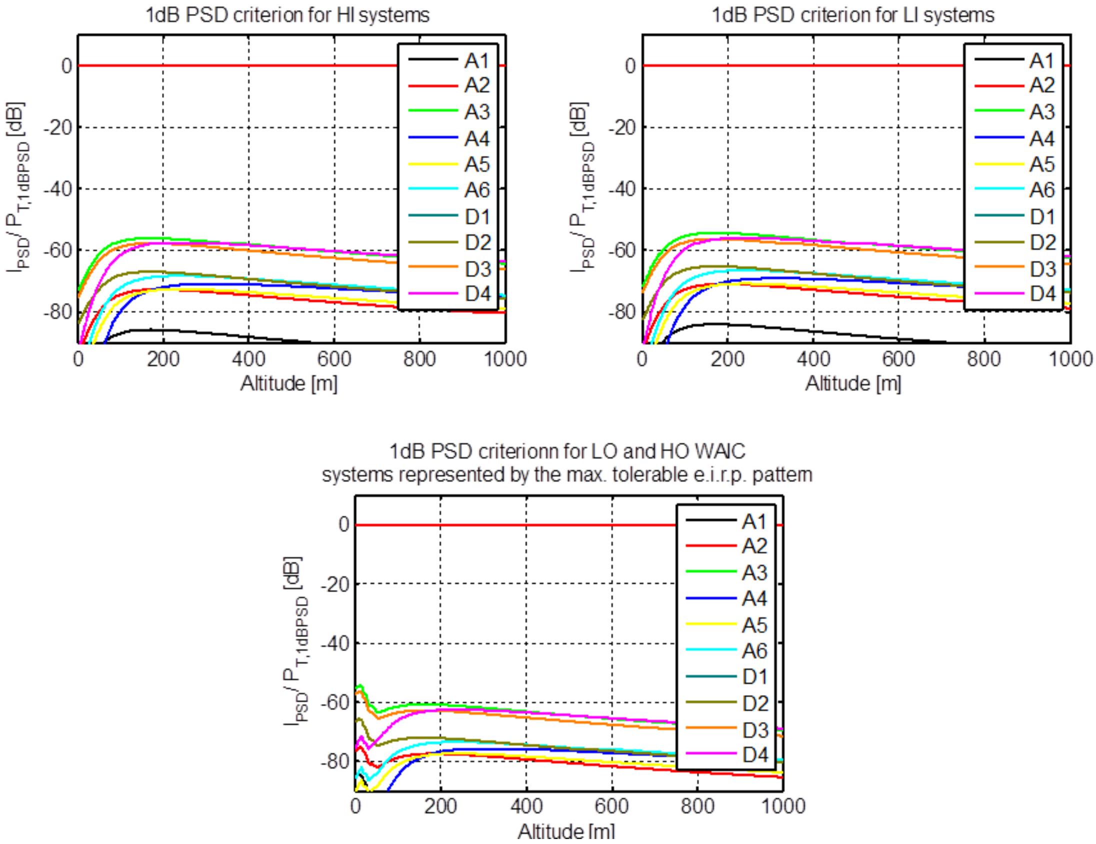
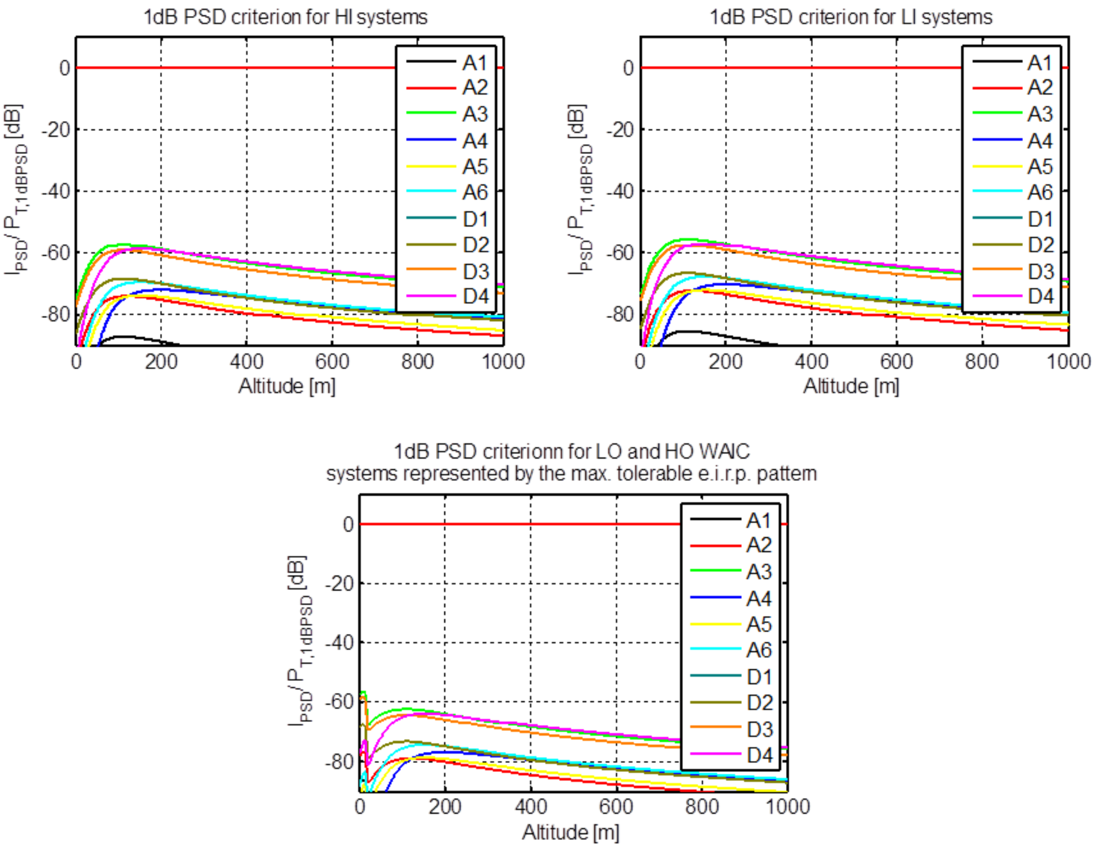


FIGURE A-3.22

Airport holding bay scenario: power spectral density protection criterion



Summary

The analysis of the airport taxiway and holding bay scenarios show that none of the RA protection criteria is violated by WAIC inside applications and WAIC outside applications represented by the maximum tolerable e.i.r.p. pattern, described in Annex 1 § A-1.4. Consequently no harmful interference is expected to be caused by LI, LO, HI and HO WAIC systems.

A-3.2.3.4 Analysis of potential impact of frequency modulated carrier wave and pulsed radio altimeters onto wireless avionics intra-communication systems

The signal propagation model utilized to investigate the *I*/*S* protection criterion of WAIC systems is similar to the model described in § A-3.2.2.2. However, the interference impact of the RA onto WAIC systems may vary at different locations inside the WAIC-aircraft due to the close distance between RA and WAIC-aircraft. For that reason, different positions for receiving WAIC stations representing the WAIC inside and outside system categories as well as the directivities of the involved antennas have to be considered.

For inside WAIC systems the positions at which the WAIC protection criteria are evaluated are the same as the positions of the WAIC OPSs described in §§ A-3.2.3.1 and A-3.2.3.2. Due to the close distance between RA-aircraft and the WAIC-aircraft in the airport scenarios, the pattern of the radio altimeter transmit antenna has to be paid particular attention to for determining $I_{RA}(d_{RA})$, the interference power level of the RA observed at a receiving WAIC station. Therefore, static RA mainbeam equation (A-3.9) is modified in order to reflect the incident angle ϕ between the receiving WAIC station and the RA antenna as described in §§ A-3.2.3.1 and A-3.2.3.2.

Thus the interference power level at the receiving LI and HI WAIC station at a distance d_{RA} to the RA antenna is given by:

$$I_{RA}(d_{RA}) = P_{TX,RA} + G_{RA,dB}(\phi) - C_L - L(d_{RA}) - L_{Body} + G_{WAIC} + R_E \qquad \text{(A-3.17)}$$

The WAIC receive signal power levels S_{xy}, which is required to determine the I/S protection criteria at the receiving WAIC stations described by equations (A-3.11) and (A-3.12) are listed in Table A-3.4.

LO and HO WAIC applications are assumed to utilize the directional antenna concept described in Annex 1 § A-1.4 in order to reduce the interference impact onto the radio altimeter. The aim of the assessment described hereafter is to verify if this concept also ensures that outside WAIC applications can be operated without receiving harmful interference from radio altimeters. For this purpose the interference impact of the RA has to be studied at the WAIC Gateway Node and WAIC End Node which requires a more detailed description of the utilized directional antennas as well as the scenario geometries, as described hereafter.

FIGURE A-3.23

Antenna pattern of a wireless avionics intra-communication end node - vertical and horizontal plane

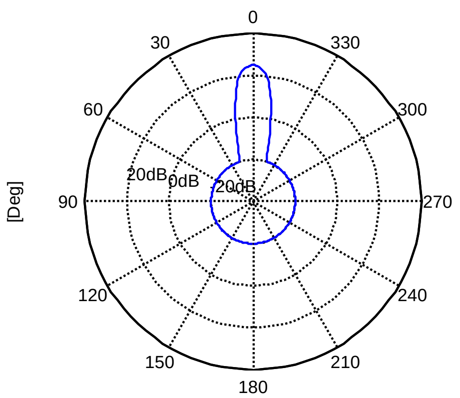


FIGURE A-3.24

Antenna pattern of a wireless avionics intra-communication gateway node - vertical plane

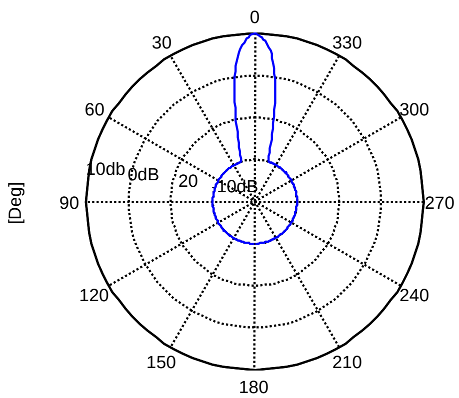


Figure A-3.23 shows the antenna pattern which is utilized to model the antenna beam of the End Nodes. The antenna pattern of the Gateway Nodes is shown in Fig. A-3.24. In both Figures the plots only show the vertical plane of the antenna pattern. The pattern of the horizontal plane has no effect on the calculation of the maximum radar altimeter interference power levels at the End Nodes' and Gateway Nodes' antenna outputs and is therefore not required for the following analysis.

In both, the airport taxiway and the airport holding bay scenario the antenna beams of the End Node and Gateway Node antennas point towards each other as outlined in the description of the directional antenna concept (see Annex 1 § A-1.4). Figures A-3.25 and A-3.26 depict the beam coupling as well as the detailed geometries of the scenarios. The Figures show that the End Node and Gateway Node will be affected differently by the radio altimeter signal. This is because for low altitudes a_{RA} the radio altimeter interference signal will radiate directly into the mainbeam of the Gateway Node antenna. In both scenarios the End Node and Gateway Node are separated by d_{WAIC} = 15 m, the maximum allowed distance between a WAIC transmitter and receiver (see Table A-1.1).

All other parameters correspond to the scenario descriptions contained in §§ A-3.2.3.1 and A-3.2.3.2.

FIGURE A-3.25

Geometries for the airport taxiway scenario taking into account the directional antenna concept

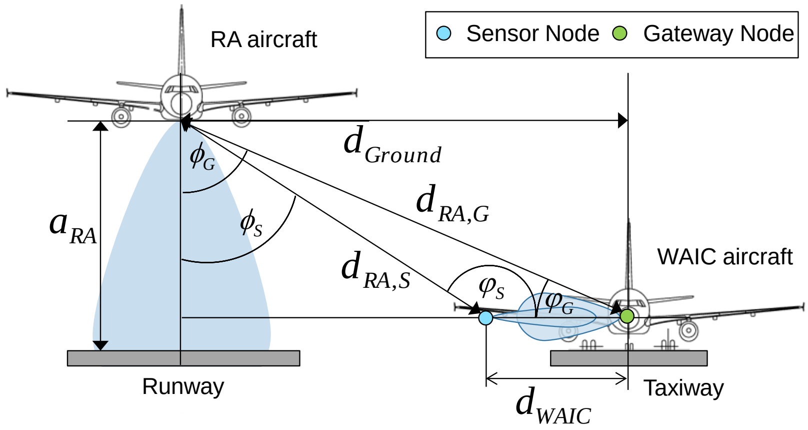
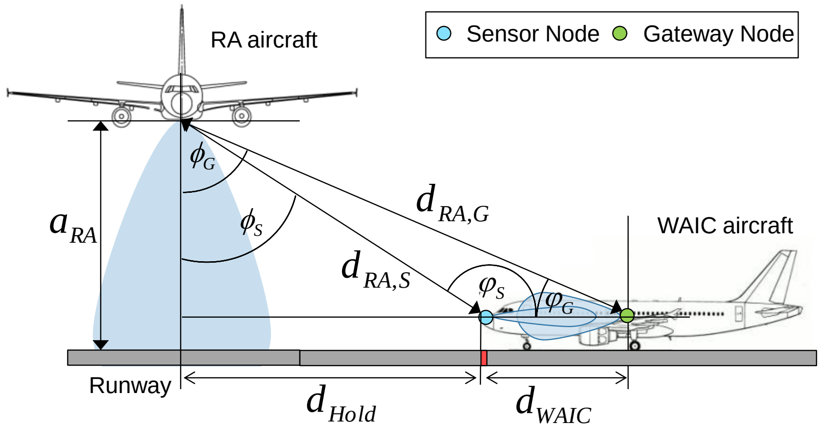


FIGURE A-3.26

Geometries for the airport holding bay scenario taking into account the directional antenna concept



In order to determine the interference power observed by an End or Gateway Node, the antenna pattern shown in Figs A-3.27 and A-3.28 have to be considered. Therefore, equation (A-3.9) is modified to account for the node type-specific directional RA antenna gain and the directional antenna gain of the End Node $G_{WAIC,S}(\varphi_S)$ and Gateway Node $G_{WAIC,G}(\varphi_G)$. Taking into account that the slant range between the RA and the End Node and Gateway Node antennas depends on the RA-aircraft's altitude, the RA interference signal power level at the gateway node is given by:

$$I_{RA,G}(d_{RA,G}) = P_{TX,RA} + G_{RA,dB}(\phi_G) - C_L - L(d_{RA,G}) + G_{WAIC,G}(\varphi_G) + R_E \qquad \text{(A-3.18)}$$

The RA interference signal power level at the sensor node is described by:

$$I_{RA,S}(d_{RA,S}) = P_{TX,RA} + G_{RA,dB}(\phi_S) - C_L - L(d_{RA,S}) + G_{WAIC,S}(\varphi_S) + R_E \qquad \text{(A-3.19)}$$

For the evaluation of the I/S WAIC protection criteria only the worst-case interference impact is of interest. For that reason only the maximum radio altimeter interference power level for any radio altimeter-aircraft altitude is considered.

Thus the radio altimeter interference power level considered for the evaluation of the WAIC protection criteria described by equations (A-3.11) and (A-3.12), is given by:

$$I_{RA}(d_{RA,S}, d_{RA,G}) = \max(I_{RA,S}(d_{RA,S}), I_{RA,G}(d_{RA,G})) \qquad \text{(A-3.20)}$$

In accordance with §§ A-3.2.2.2 and A-1.4 the transmit power of both LO and HO WAIC systems utilizing the directional antenna concept is assumed to be –7 dBm. Given this assumption, the minimum WAIC receive signal power levels $S_{x,y}$ which is required to determine the *I*/*S* protection criteria at the receiving WAIC stations can be obtained from Table A-3.4.

It has to be noted that in the airport taxiway scenario the interference impact of the RA-aircraft onto WAIC is analyzed at the taxiing WAIC-aircraft abreast the RA-aircraft. The interference impact onto the other taxiing WAIC-aircraft is not considered since it will always be lower due to the larger separation distances.

Results

The assessment of the *I*/*S* ratio protection criteria for the airport taxiway and airport holding bay scenarios are presented in a common format. Each of the plots depicted in Figs A-3.27 and A-3.28 shows an evaluation of the *I*/*S* ratio observable at the WAIC receiver input vs. the [radio altimeter]RA-aircraft's altitude. The upper four plots of each figure depict the results for LI and HI WAIC systems for the relevant radio channel models A and B, whereas the bottom two plots show the *I*/*S* ratio vs. the radio altimeter-aircraft's altitude observable at the input of an HO and LO WAIC receiver.

The results show that in both scenarios the *I*/*S* ratio protection criteria for inside and outside WAIC high and low data rate systems is never exceeded.

FIGURE A-3.27

Airport taxiway scenario: scenario: *I/S* protection criterion

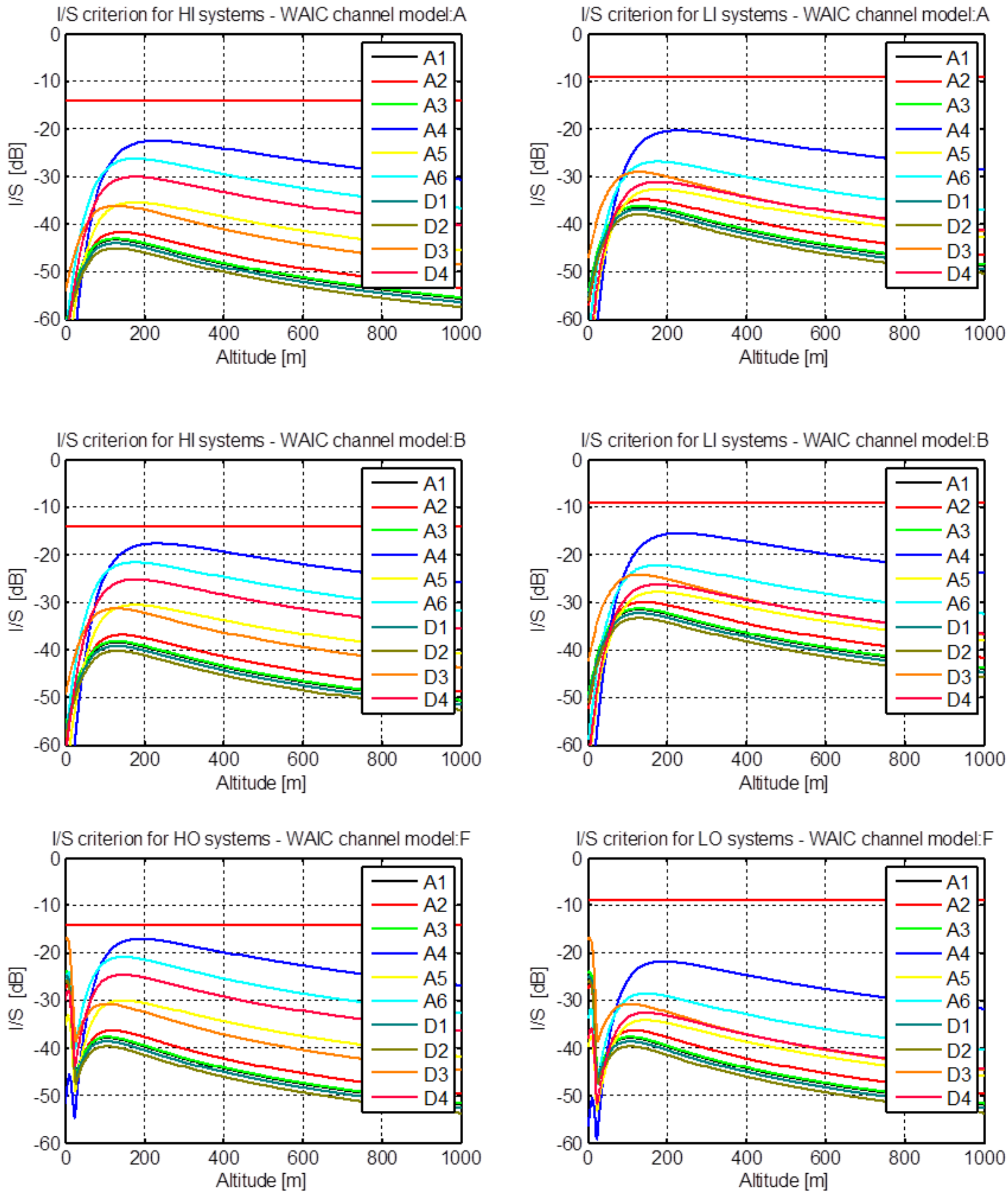
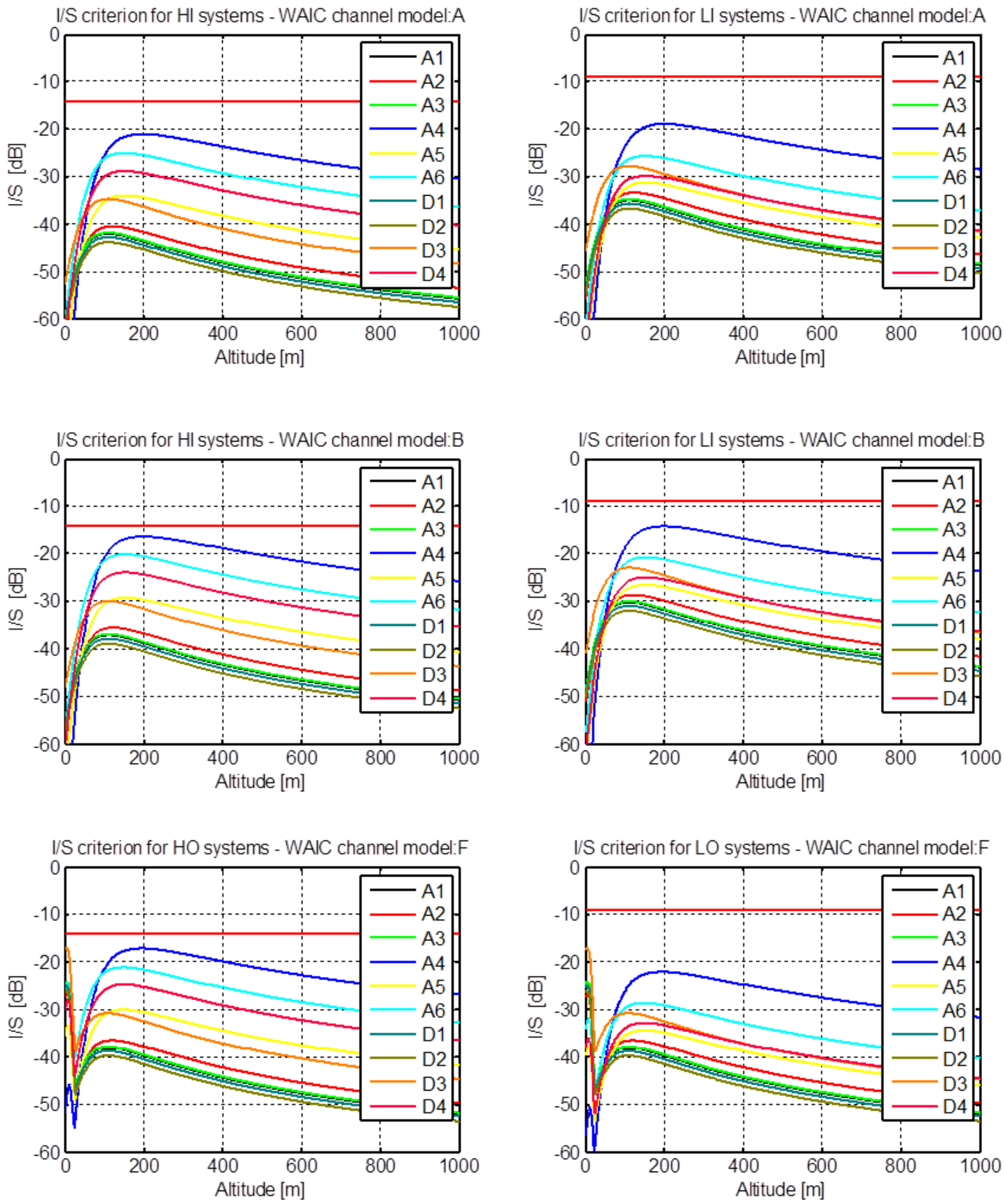


FIGURE A-3.28

Airport holding bay scenario: *I*/*S* protection criterion



A-3.2.4 Conclusions

For assessing the potential mutual impact between radio altimeters and WAIC systems in the frequency band 4 200-4 400 MHz a number of studies were carried out. These studies address two basic scenarios, the in-flight and the airport scenarios.

In the in-flight scenario the situation is analyzed when two flying aircraft are in closest possible proximity on two adjacent flight levels.

In this case it is assumed, that a WAIC equipped aircraft is in the mainbeam of the radio altimeter antenna of another aircraft. Consequently, mainbeam-to-mainbeam coupling was assumed, which represents the worst-case coupling that can occur in practice between both systems.

In the airport scenario the situation when an aircraft approaches the runway for landing while there are WAIC-equipped aircraft taxiing as close as possible to that runway is of concern. The airport scenario was further subdivided into the airport taxiway and the airport holding bay scenarios. Both scenarios differ in the way the taxiing aircraft are mutually oriented and separated from the landing aircraft. To reflect worst-case conditions, minimum possible separation distances between aircraft of concern were taken into account in the assessments. Furthermore, it was assumed, that all WAIC transmitters and receivers are located onboard the aircraft in such a way, that they are concentrated in a single point which is closest to the radio altimeter antenna of the approaching aircraft. Even though such a concentration would not occur in a real WAIC system installation, this approach was taken in order to capture the worst-case coupling.

The assessments of all of the above scenarios consider both, the potential impact of WAIC systems onto radio altimeters as well as the potential impact of radio altimeters onto WAIC systems. The results are presented separately per each combination of WAIC system category (i.e. low data rate inside (LI), high data rate inside (HI), low data rate outside (LO) and high data rate outside (HO)) and radio altimeter type. All radio altimeter types considered in Recommendation ITU-R M.2059 including Frequency Modulated Continuous Wave (FMCW) and pulsed radio altimeter were taken into account.

For all scenarios described above it can be summarized that inside low and high data rate WAIC systems operating in accordance with the characteristics specified in Report ITU-R-M.2283 are compatible with all types of radio altimeters according to Recommendation ITU-R M.2059. This includes both FMCW as well as pulsed radio altimeters.

Furthermore, outside low and high data rate WAIC systems operating in accordance with the characteristics specified in Report ITU-R-M.2283 and in addition using the directive antenna concept introduced in Annex 1 § A-1.4 of this Report are compatible with all types of radio altimeters according to Recommendation ITU-R M.2059.

This includes both FMCW as well as pulsed radio altimeters.

Annex 4

Study 3

Compatibility analysis between wireless avionics intra-communication systems and radio altimeters in the aeronautical radionavigation service

A-4.1 Wireless avionics intra-communication systems on an aircraft

WAIC can be implemented on a wide variety of aircraft, from smaller 50 passenger jet aircraft to larger twin aisle jumbo aircraft that could carry more than 400 passengers. For the studies provided, a single aisle twin-engine passenger aircraft that may carry from 100 to 200 passengers was selected as these types of aircraft are very prevalent around the world and provide a complex platform that may benefit from WAIC.

Within Report ITU-R-M.2283, WAIC systems may be subdivided into two types of nodes within a WAIC network, WAIC Nodes and WAIC Gateway Nodes (GN). WAIC Gateway Nodes are located throughout an aircraft as dictated by the physical sections of an aircraft and by network demand to enable adequate radio coverage. The WAIC Gateway node receives information from the various WAIC Nodes assigned to it and relays the information to the aircraft's overall network. For this study, regions of the aircraft are described by their WAIC Gateway Node, and the WAIC Gateway nodes are continuously transmitting. Additionally, the radio altimeter receive antenna location is located midway along the aircraft near the location of the main landing gear.

FIGURE A-4.1

Side view of example aircraft wireless avionics intra-communication gateway nodes

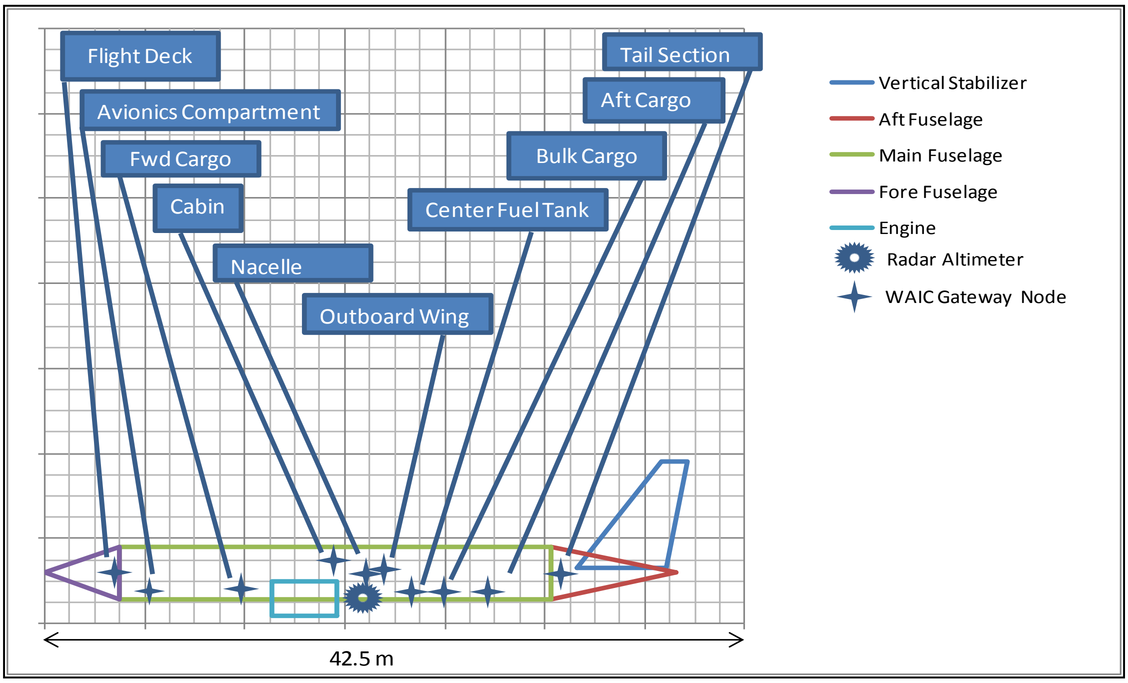
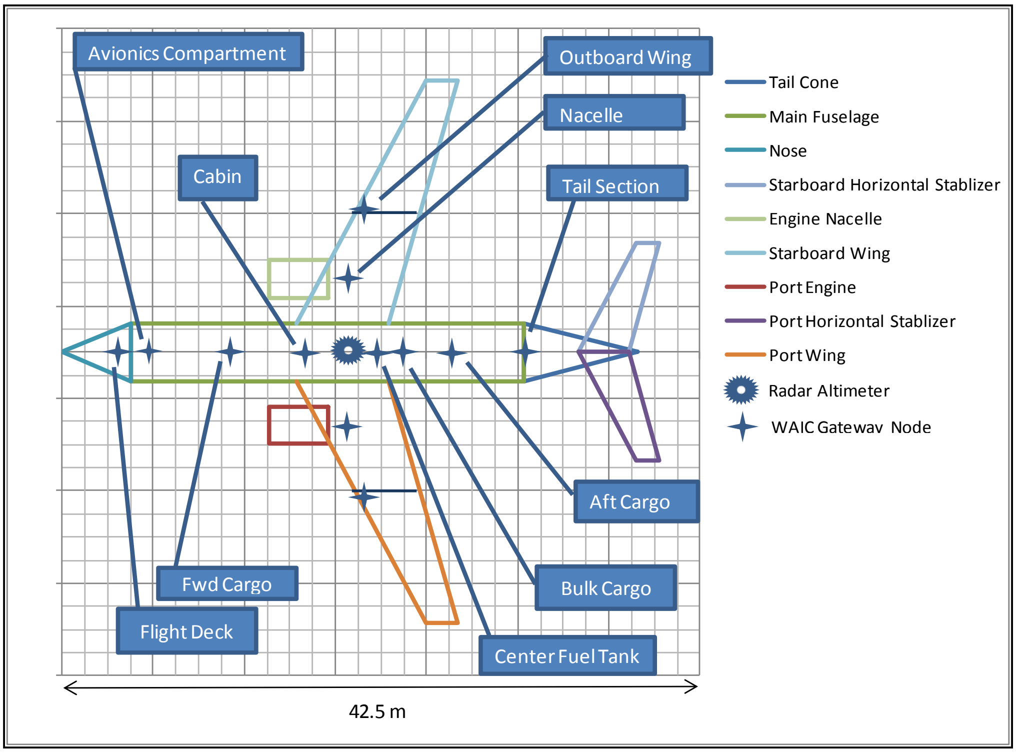


FIGURE A-4.2

Top view of example aircraft wireless avionics intra-communication gateway nodes



While there are many WAIC nodes and WAIC gateway nodes, the duty cycles of these nodes vary greatly depending on the particular usage. The WAIC system may be modelled in terms of effective gateway nodes, since an installed WAIC system will be designed to operate in such a way to take advantage of the various duty cycles of applications in order to effectively use the available spectrum resources, a number of WAIC nodes or gateway nodes can be simplified. This would combine all of the WAIC applications for each type of category: low rate inside (LI), low rate outside (LO), high rate inside (HI), and high rate outside (HO); and creating an appropriate number of effective gateway nodes with a constant duty cycle based upon the spectrum usage. This number corresponds to the number of radio channels derived in § A-1.3.

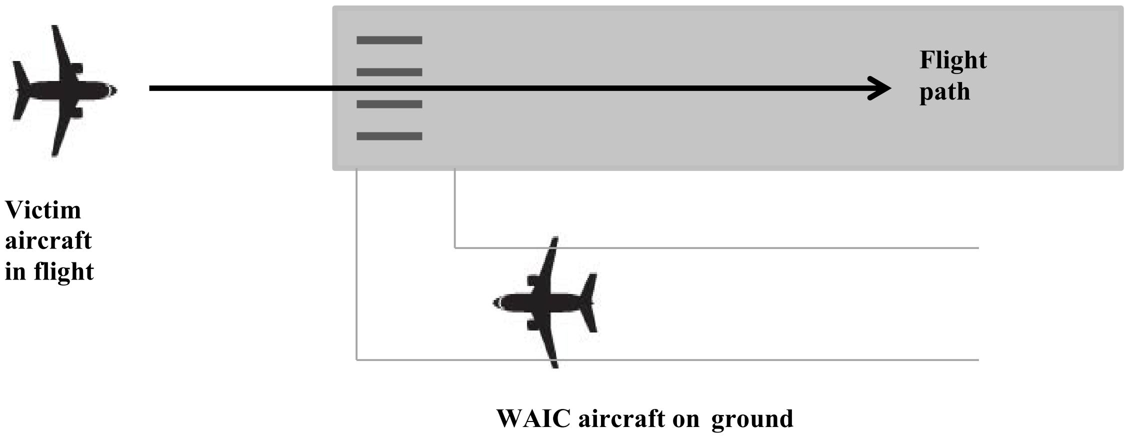
For these studies, it is assumed that the WAIC applications inside the aircraft are within the fuselage region, and WAIC applications outside the aircraft are located in the wing or tail region. Specifically the studies described in § A-4.2, LI uses the cabin, avionics compartment, and bulk cargo nodes, LO uses the starboard (right) wing, starboard nacelle, port (left) wing, port nacelle, and tail section nodes, HO uses the starboard (right) wing and port (left) wing nodes, and HI uses the cabin and bulk cargo nodes as shown in Figs A-4.1 and A-4.2.

A-4.2 Simulation description

An aircraft's radio altimeter is a critical component in an aircraft, particularly during the landing phase of flight. The simulations depict a WAIC equipped aircraft on a taxiway adjacent to a runway where the victim aircraft would be landing. The runway centerline and the taxiway centerline are separated by 80 m, this approximates an airport configuration where the largest aircraft would be a single aisle twin-engine passenger aircraft. Selecting this type of aircraft presents a worst-case scenario as the potential slant range between the aircraft may be quite small. Larger airports would have larger runways and taxiways and larger separation between these elements giving larger potential slant ranges.

FIGURE A-4.3

Simulation scenario with one wireless avionics intra-communication aircraft

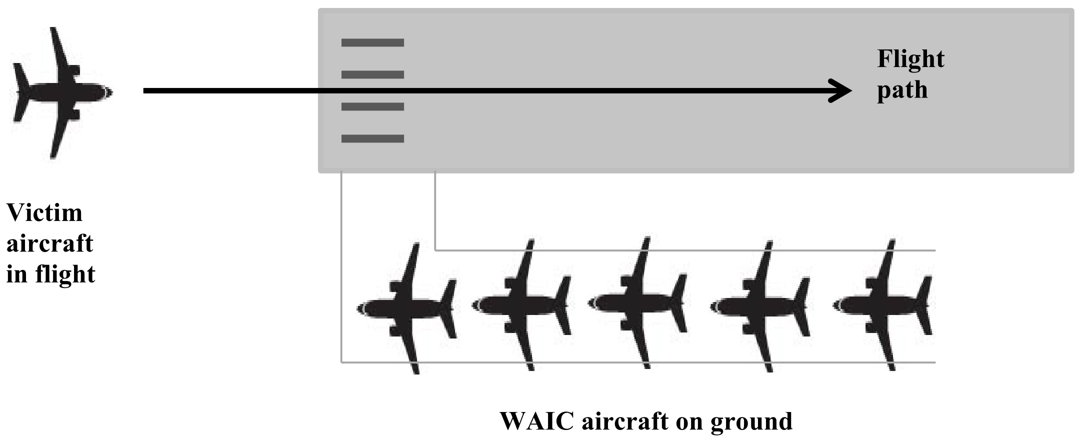


The simulation is run with the victim aircraft flying past the WAIC aircraft at a given altitude. The simulation is then repeated for many different altitudes and the results are compiled, the altitudes used are 10 m, 20 m, 30 m, 40 m, 50 m, 75 m, 100 m, 200 m, 300 m, 400 m, 500 m, 1 000 m, 1 500 m, 2 000 m, 2 500 m, 3 000 m, 3 500 m, 4 000 m, 4 500 m, and 5 000 m. The highest interference value from each of these runs is presented in §§ A-4.3.1, A-4.3.2 and A-4.3.3.

The case for multiple WAIC aircraft is also considered, this is done by increasing the number of WAIC aircraft to 5 waiting to take off to determine the aggregate effect from multiple aircraft to the victim aircraft flying past at the same altitudes as in the single WAIC aircraft case.

FIGURE A-4.4

Simulation scenario with five wireless avionics intra-communication aircraft



In this study, the example WAIC GN locations are used interchangeably for the different WAIC applications: low data rate inside (LI), high data rate inside (HI), low data rate outside (LO), and high data rate outside (HO). For the outside applications the attenuation effects are eliminated. Also, the propagation effects used throughout the studies is assumed to be free-space loss as described by Recommendation ITU-R P.525, and no signal reflection, refraction, or masking is accounted for.

A-4.3 Interference from wireless avionics intra-communication systems into radio altimeters analysis scenarios

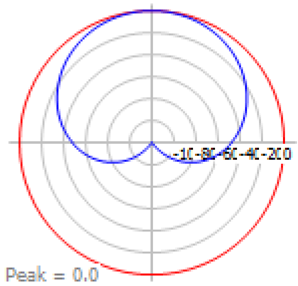
Each of the simulation descriptions described in § A-4.2 are performed aircraft equipped with the different types of WAIC systems as described in § A-4.1 and § 2, as well as an additional analysis with five WAIC equipped aircraft with all four types of WAIC systems.

Simulations with the WAIC systems inside the aircraft, LI, and HI use a fuselage attenuation of 35 dB, and the WAIC transmit antennas are assumed to be omni-directional and LI systems use the maximum power of 10 mW, and HI systems use the maximum power of 50 mW.

Simulations with WAIC systems outside the aircraft, LO, and HO utilize shaped antennas and reduced power levels to reduce the amount of energy directed away from the aircraft. For these studies an antenna pattern with a parabolic rolloff and a beamwidth of 45° and a maximum gain of 0 dB was used. LO systems use a power of 0.5 mW and HO systems use a power of 5 mW.

FIGURE A-2.5

Simulation scenario wireless avionics intra-communication antenna pattern for outside use



The simulations were carried out for the types of radio altimeters detailed in Tables 5 and 6, A1, A3, A4, A5, A6, D1, D2, D3, and D4. Radio Altimeter A2 is not included in the studies since its characteristics are very similar to those of A3. The results of the simulations are presented by interference criteria as described in Recommendation ITU-R M.2059.

A-4.3.1 Receiver desensitization

A desensitization of the radio altimeter receiver is likely to occur if the ratio of I_{IF} (the interference power in the IF-stage, i.e. the interference power referred to the IF bandwidth) to N (the noise power referred to the IF bandwidth) exceeds –6 dB for any of the considered types of radio altimeter. Figures A-4.6 and A-4.7 show the evaluation of the I_{IF}/N ratio versus the radio altimeter aircraft's altitude for all considerer radio altimeter types and WAIC system categories. In each of the plots shown in Figs A-4.6 and A-4.7 a red line marks the –6 dB I_{IF}/N protection threshold.

FIGURE A-4.6

Radio altimeter desensitization (*I*/*N*) from a single wireless avionics intra-communication aircraft

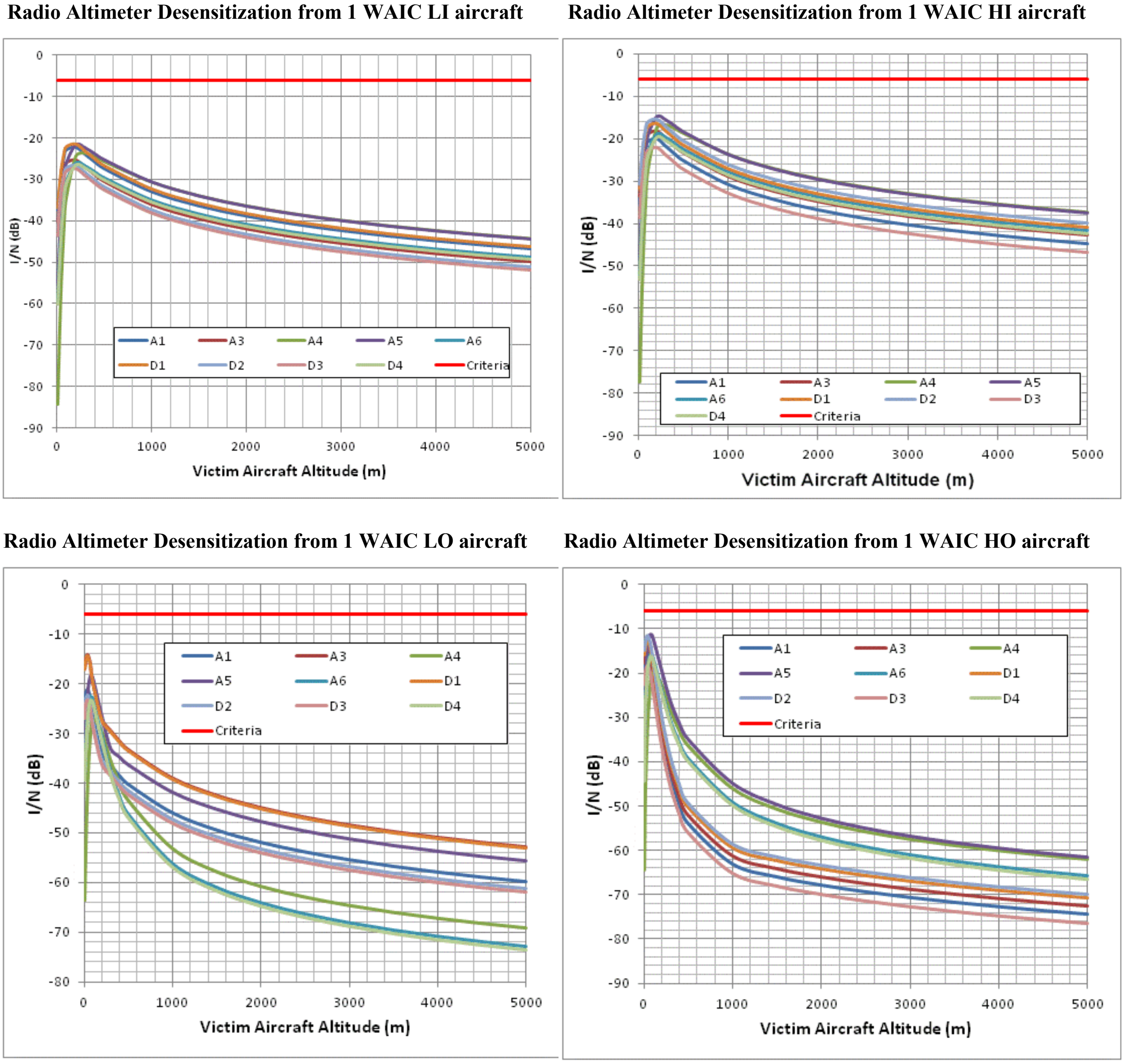
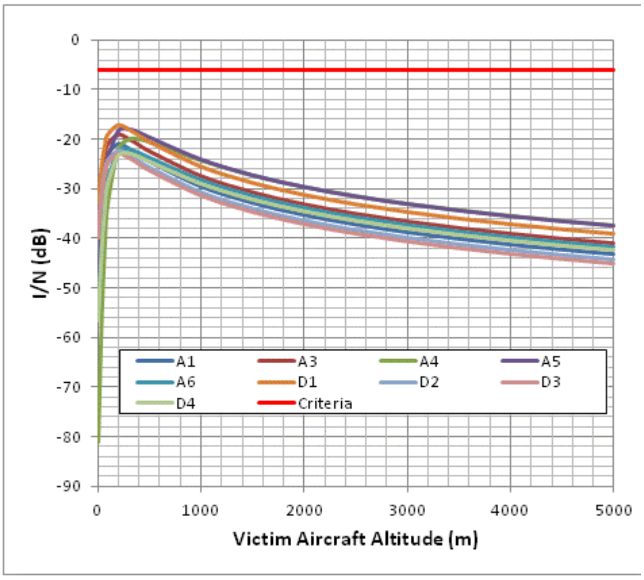


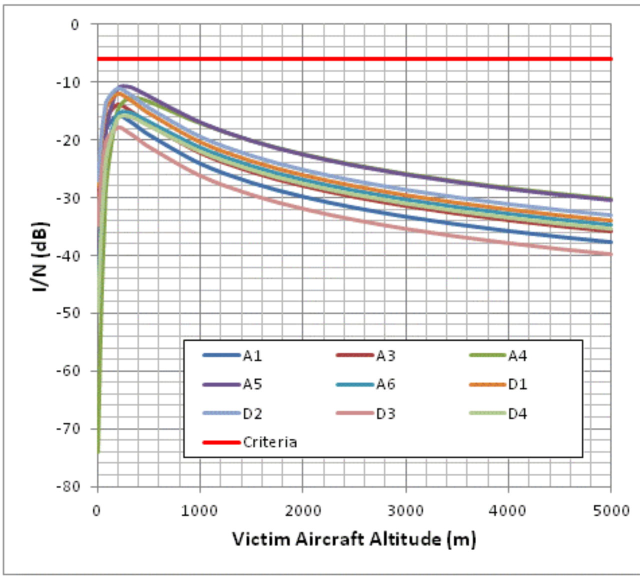
FIGURE A-4.7

Radio altimeter desensitization (*I*/*N*) from five wireless avionics intra-communication aircraft

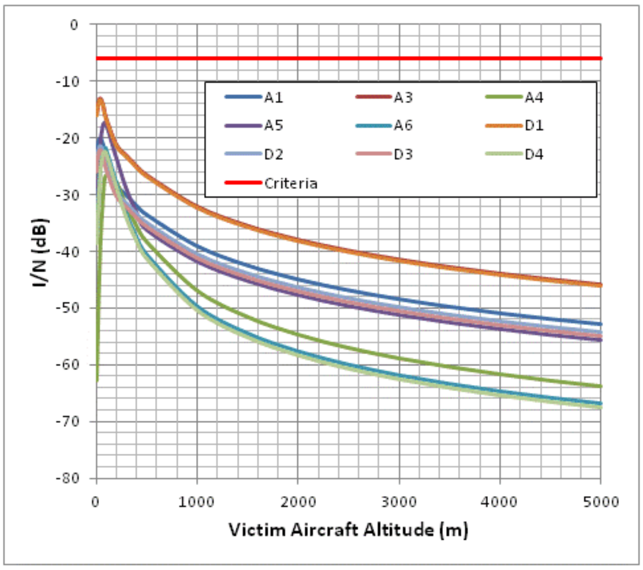
Radio Altimeter Desensitization from 5 WAIC LI aircraft



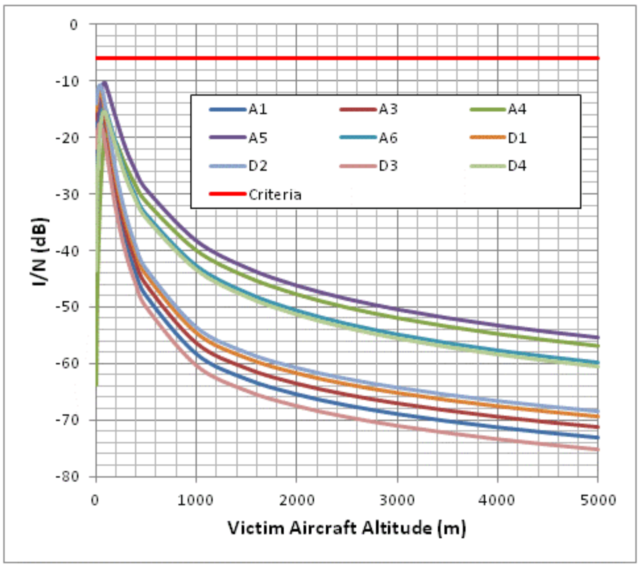
Radio Altimeter Desensitization from 5 WAIC HI aircraft



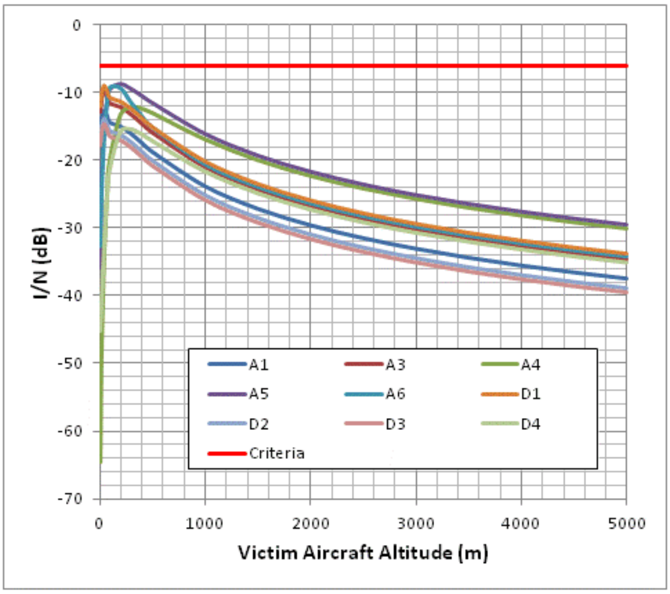
Radio Altimeter Desensitization from 5 WAIC LO aircraft



Radio Altimeter Desensitization from 5 WAIC HO aircraft



Radio Altimeter Desensitization from 5 WAIC LI, HI, LO, HO aircraft



In all the cases presented, the radio altimeter desensitization interference criteria is never exceeded and with some cases there are large amounts of margin.

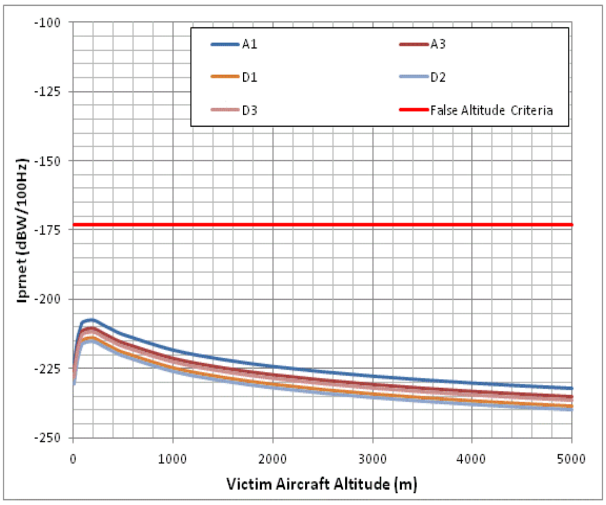
A-4.3.1.1 Radio altimeter false altitude

For FMCW type radio altimeters, interference in the radio altimeter detector stage may result in false altitude reports. To prevent false altitude detections caused by interference within the bandwidth of the detector stage the corresponding interference power I_D is considered. In this context a detector bandwidth of 100 Hz is assumed for these radio altimeter types. For that reason the protection threshold, which should not be exceeded by I_D, is defined to be $I_{T,FA}$=-173 dBW/100 Hz . Figures A-4.8 and A-4.9 show the relation between I_D and the radio altimeter aircraft's altitude for all considered radio altimeter Types and WAIC system categories. In each plot of Figs A-4.8 and A-4.9 a red line marks the absolute –173 dBW/100 Hz protection threshold.

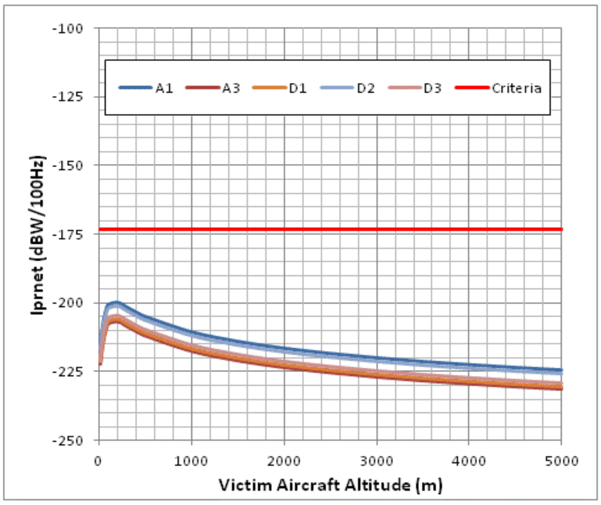
FIGURE A-4.8

Radio altimeter false altitude criterion from a single wireless avionics intra-communication aircraft

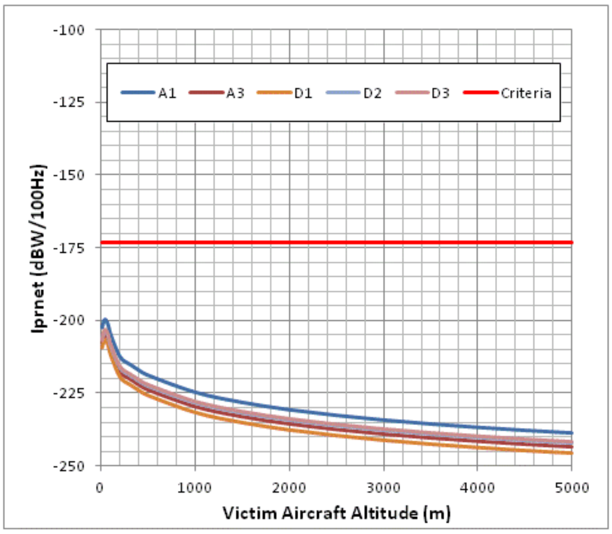
Radio Altimeter False Altitude from 1 WAIC LI aircraft



Radio Altimeter False Altitude from 1 WAIC HI aircraft



Radio Altimeter False Altitude from 1 WAIC LO aircraft



Radio Altimeter False Altitude from 1 WAIC HOaircraft

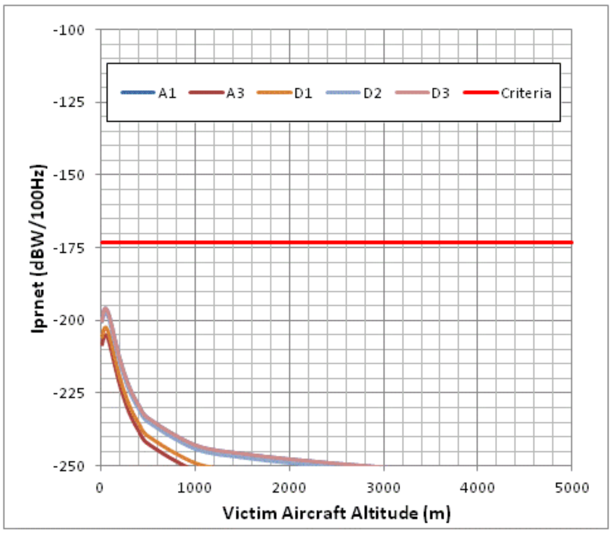
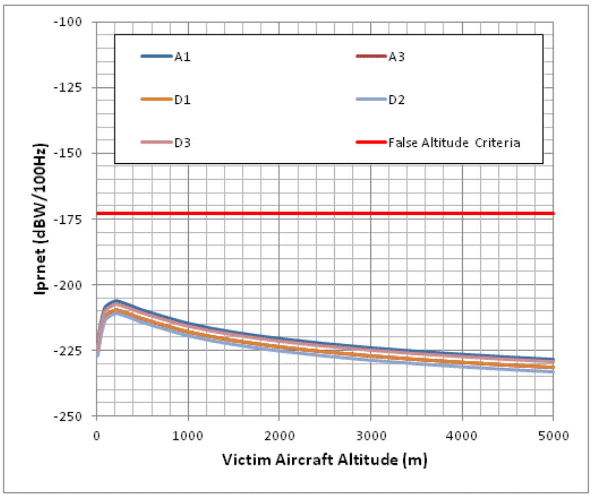


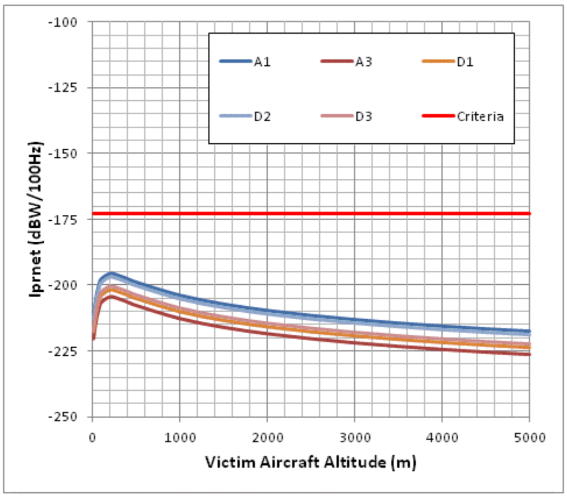
FIGURE A-4.9

Radio altimeter false altitude criterion from five wireless avionics intra-communication aircraft

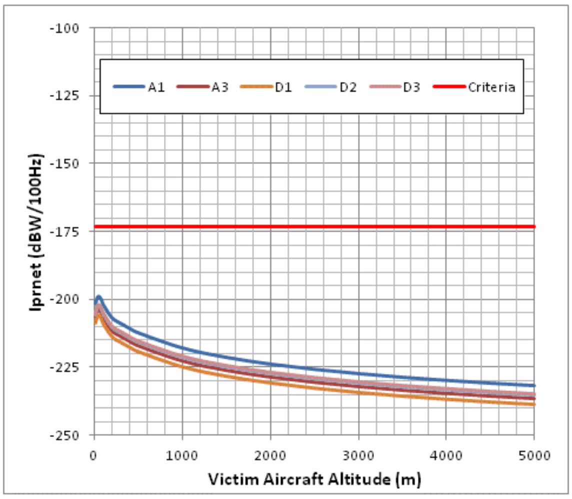
Radio Altimeter False Altitude from 5 WAIC LI aircraft



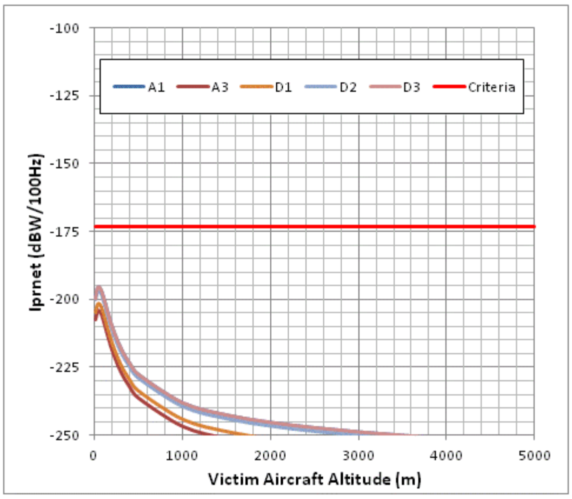
Radio Altimeter False Altitude from 5 WAIC HI aircraft



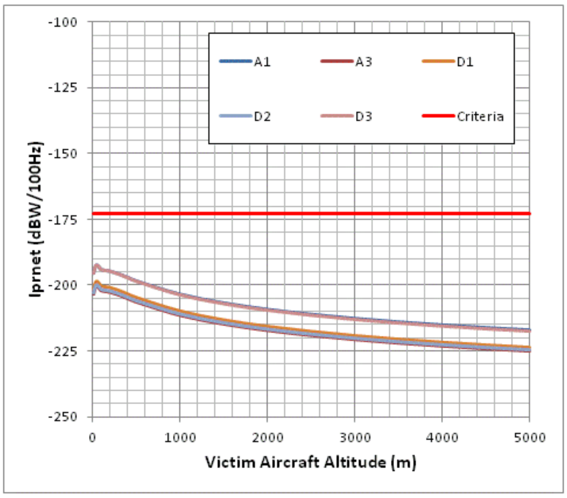
Radio Altimeter False Altitude from 5 WAIC LO aircraft



Radio Altimeter False Altitude from 5 WAIC HO aircraft



Radio altimeter false altitude from 5 WAIC LI, HI, LO, HO aircraft



In all the cases presented, the radio altimeter false altitude interference criteria is never exceeded and with some cases there are large amounts of margin.

A-4.3.1.2 Front end overload criterion

In order to avoid overload of the radio altimeter receiver front end, it has to be ensured that the interference power at the frontend input I_{RF} never exceeds the radio altimeter specific overload threshold $I_{T,RF}$ defined in Tables A-3.1 and A-3.2. The results presented in Figs A-4.10 and A-4.11 depict the dependence of I_{RF} on the radio altimeter aircraft's altitude. Because the threshold $I_{T,RF}$ is radio altimeter specific all plots show the ratio of I_{RF} / $I_{T,RF}$ for the considered FMCW radio altimeter types. A violation of the frontend overload criterion in this representation occurs if $I_{RF}/I_{T,RF}$ > 0 dB for any type of radio altimeter.

FIGURE A-4.10

Radio altimeter front end overload criterion from a single wireless avionics intra-communication aircraft

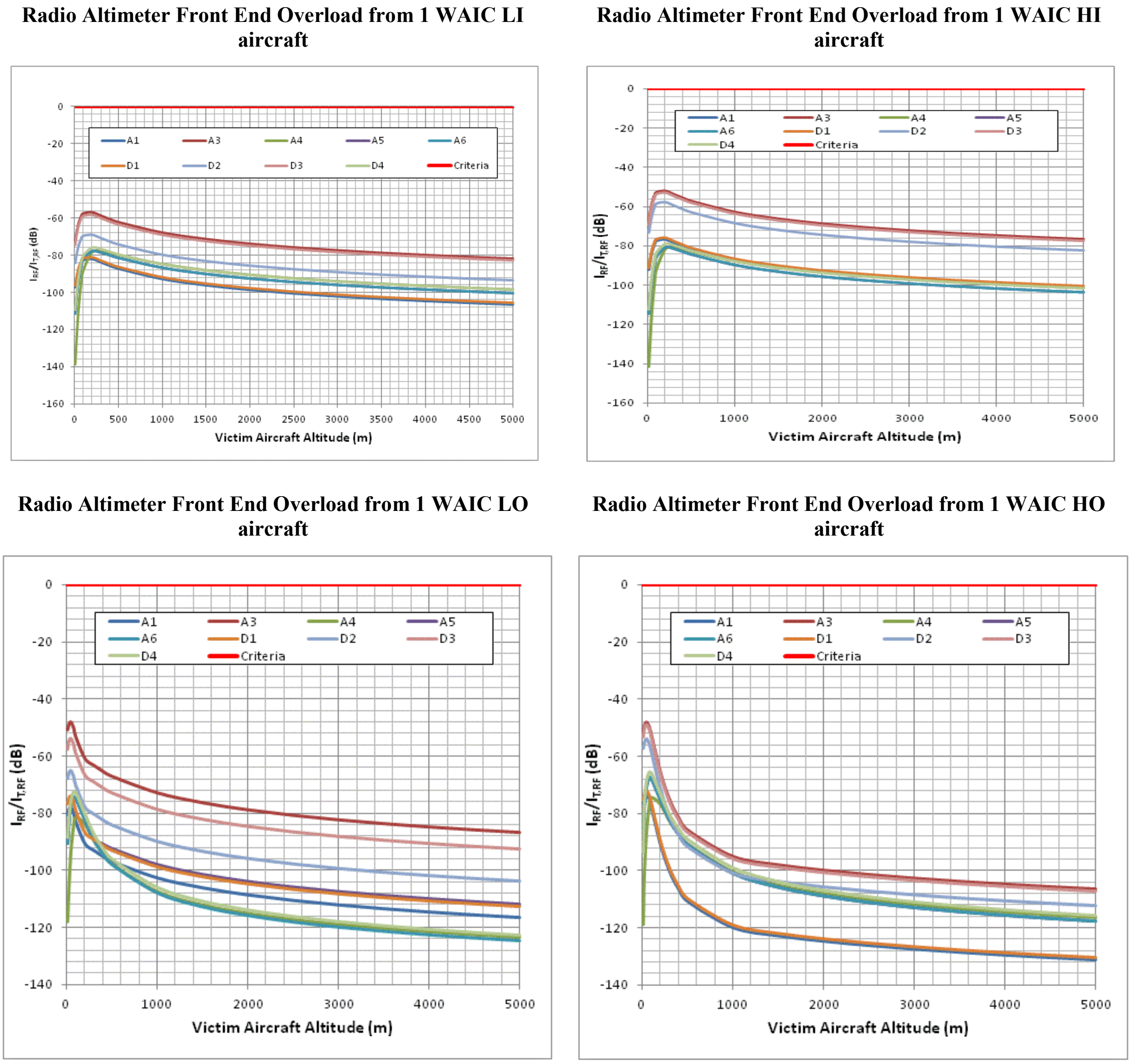
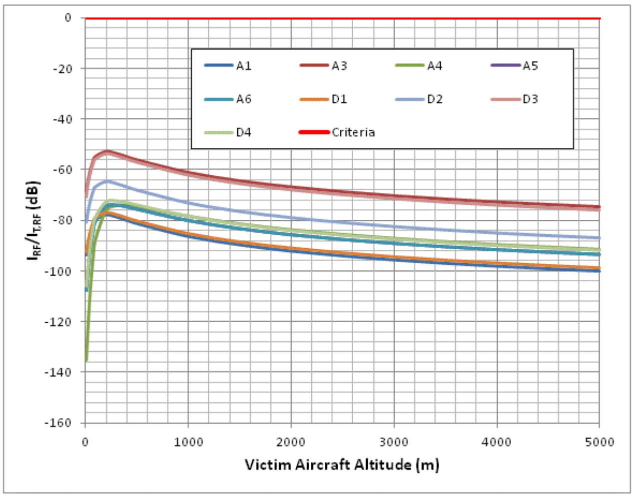


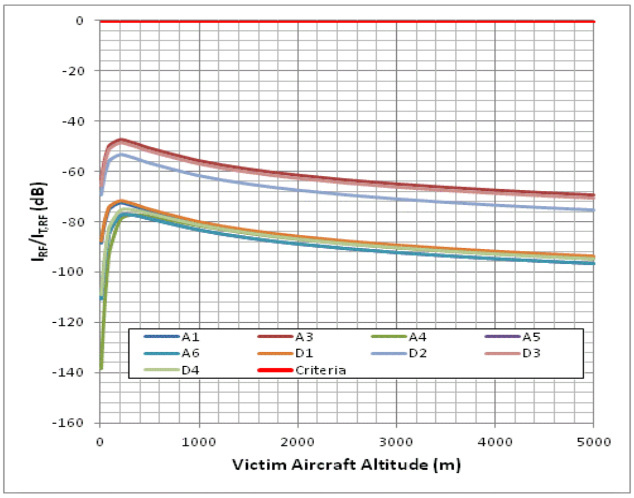
FIGURE A-4.11

Radio altimeter front end overload criterion from five wireless avionics intra-communication aircraft

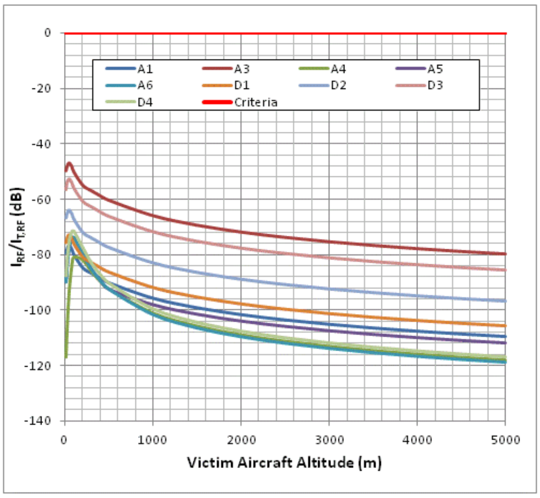
Radio Altimeter Front End Overload from 5 WAIC LI aircraft



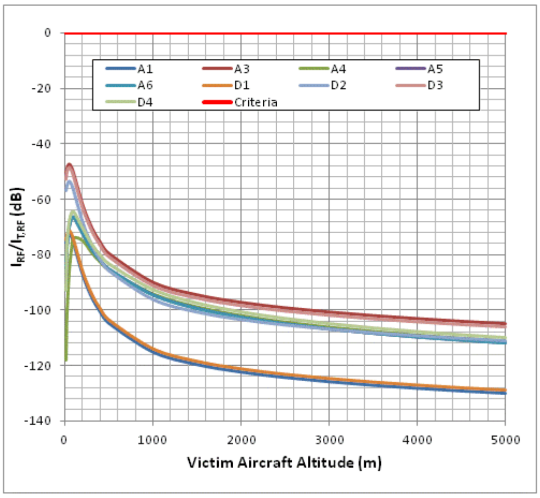
Radio Altimeter Front End Overload from 5 WAIC HI aircraft



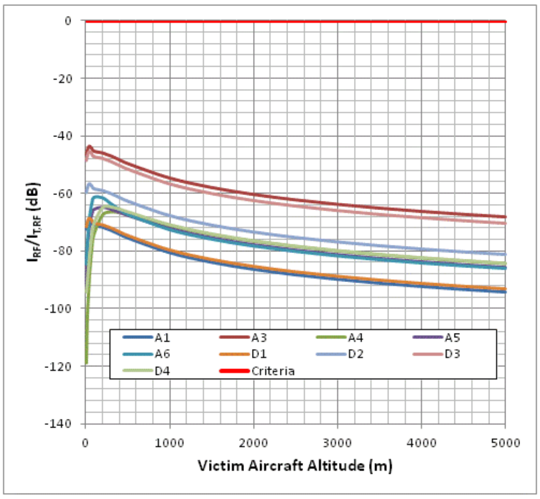
Radio Altimeter Front End Overload from 5 WAIC LO aircraft



Radio Altimeter Front End Overload from 5 WAIC HO aircraft



Radio altimeter front end overload from 5 WAIC LI, HI, LO, HO aircraft



In all the cases presented, the radio altimeter front end overload interference criteria is never exceeded and there are large amounts of margin in each of these cases.

A-4.4 Interference from radio altimeters to wireless avionics intra-communication systems

WAIC systems are designed to provide reliable wireless communication between two stations onboard an aircraft. The reliability of a wireless communication link typically influenced by three parameters: propagation environment, distance between the transmitting and receiving WAIC station $d_{WAIC,}$ and the transmit power $P_{TX,x}$.

Depending on the propagation environment, d_{WAIC} and $P_{TX,x}$ of WAIC high or low data rate systems are configured such that a sufficiently high signal power level S, required for reliable communication at the receiver, is always achieved.

Report ITU-R-M.2283 specifies maximum allowable values for d_{WAIC} and $P_{TX,x}$. The report also provides a set of path loss models for different propagation environments between points inside and outside the aircraft structure. A detailed description of these models can be found in the Report ITU-R-M.2283. Consequently S is given by

$$S(d_{WAIC}) = P_{TX,x} + G_{WAIC} + G_{WAIC} - L_{WAIC,n}(d_{WAIC}), \qquad \text{(A-4.1)}$$

where $L_{WAIC,n}(d_{WAIC})$ is the path loss at distance d_{WAIC} of the nth model listed in Table A-4.1 and G_{WAIC} the transmit and receive antenna gain of the WAIC stations. For the gain/loss prediction a model of the functional form

$$h(f,d) = C_1 d^{-n} f^{-k} \qquad \text{(A-4.2)}$$

is used, where n and k are the distance and frequency exponents and C_1 is a constant offset. Values for the parameters k, n and C_1 are summarized in Table A-2.1 below.

TABLE A-4.1

Channel gain model parameters for each group of test points

Group	Group name	***k*** ***(freq exp)***	***n*** ***(dist exp)***	$C_{1,dB}$
A	Intra-Cabin & Intra-Flight Deck	2.45	2.00	189.8
B	Inter-Cabin	2.09	3.46	167.5
C	Inter-Cabin-to-Lower Lobe & Inter-Cabin-to-Flight Deck	1.86	2.49	124.5
D	Inter-Cabin-to-Exterior (points on wing)	1.86	2.12	118.2
E	Inter-Cabin-to-Landing Gear & Inter-Lower-Lobe to Exterior	1.59	1.51	77.9
F	Inter-Exterior	1.95	2.31	142.5

The maximum distance between two WAIC stations on board an aircraft is 15 m (Table A-1.1). Given this value, the minimal signal power level observed at a receiving WAIC station for all propagation environments can be derived.

WAIC systems are organized in cellular sub networks on a compartment basis as specified in Report ITU-R M.2283. There is no communication among WAIC stations located in different aircraft compartments, or between a station internal and another station external to the aircraft structure. For that reason, only the radio channel models A, B and F of Table A-4.1 are deemed applicable for determining the minimum WAIC receive signal power level.

The minimal receive signal power levels resulting from these channel models are listed in Table A-4.2, assuming a WAIC high data rate system transmit power of $P_{TX,H}$ = –13 dBW, a WAIC low data rate system transmit power of $P_{TX,L}$ = –20 dBW and a WAIC transmit/receive antenna gain of G_{WAIC} = 0 dBi as stated in Table A-1.1.

TABLE A-4.2

Minimal wireless avionics intra-communication receive signal power

Group	Group name	Min. WAIC high data rate receive signal power	Min. WAIC low data rate receive signal power
A	Intra-Cabin & Intra-Flight Deck	$S_{A,H}$ = –82.7dBW	$S_{A,L}$ = –89.7dBW
B	Inter-Cabin	$S_{B,H}$ = –87.5dBW	$S_{B,L}$ = –94.5dBW
F	Inter-Exterior	$S_{F,H}$ = –85.5dBW	$S_{F,L}$ = –92.5dBW

The potential impact of an interfering FMCW or pulsed radio altimeter signal onto WAIC systems is only experienced at receiving WAIC stations. The worst-case power level of an interfering RA signal received at a WAIC station is given by

$$I_{RA}(d_{RA}) = P_{TX,RA} - L(d_{RA}) - L_{body} + G_{RA,dBi} - C_L + R_E. \tag{A-4.3}$$

where L(d_{RA}) is the free-space path loss at the distance between the receiving WAIC station and the RA transmit antenna d_{RA}, $P_{TX,RA}$ is the transmit power of the radar altimeter, L_{body} is attenuation applied for WAIC applications inside the aircraft fuselage, $G_{RA,dBi}$ is the maximum radio altimeter antenna gain and C_L is the radio altimeter cable loss.

The duty cycle factor R_E is applied to account for the fact that only a fraction of the energy of an interfering radio altimeter signal with a 3 dB emission bandwidth B_{RA} larger than the 3 dB IF-bandwidth $B_{IF,WAIC}$ of a WAIC station, is observed as interference at a receiving station.

Considering pulse type radio altimeters the duty cycle is given by:

$$R_E = \begin{cases} 10\log\left(\frac{B_{IF,WAIC}}{B_{RA}}\right) & \text{if } B_{IF,WAIC} \leq B_{RA} \\ 0 & \text{if } B_{IF,WAIC} > B_{RA} \end{cases}. \tag{A-4.4}$$

The instantaneous signal bandwidth of FMCW type radio altimeters is small compared to $B_{IF,WAIC}$. Thus the entire energy of an FMCW signal falls into the IF-stage of a receiving WAIC station. Consequently the duty cycle factor equals one (R_E = 0dB) for FMCW type radio altimeters.

Harmful interference from FMCW or pulse type radio altimeters onto WAIC systems does not occur as long as the interference to signal power ratio (I/S) is below the thresholds defined by the WAIC protection criteria described in Report ITU-R M.2283. For WAIC low data rate systems the I/S threshold is given by:

$$I_{RA}(d_{RA})/S_{x,L} < -9 \text{ dB}, \tag{A-4.5}$$

where $S_{x,L}$ is the minimal receive signal power of low data rate systems derived by the use of channel model x (A,B or F).

For WAIC high data rate system the threshold is

$$I_{RA}(d_{RA})/S_{x,H} < -14 \text{ dB}, \tag{A-4.6}$$

where $S_{x,H}$ is the minimal receive signal power of high data rate systems.

Given the dependencies described above, the potential impact of a radio altimeter onto a WAIC system can be investigated for any given separation distance between a receiving WAIC station and a radio altimeter transmit antenna.

A-4.4.1 Minimum in-flight vertical separation

One mode of interference from radio altimeters into WAIC systems would be the radio altimeter's main beam from directly above the WAIC equipped aircraft. For inside systems, the WAIC system is modeled with omni-directional antennas, so this presents a worst-case main-lobe to main-lobe scenario, while for outside systems, the WAIC system is modeled with antennas as described in § A-4.3 and a radio altimeter main-lobe to WAIC side-lobe scenario is analyzed. This mode may occur during flight, where according to Annex 2 to the Convention of International Civil Aviation (10^{th} Edition), the minimum vertical separation distance between adjacent flight levels in 300 m. Whereas according to ICAO Doc. 4444 "Procedures for Air Navigation Services – Air Traffic Management", the minimum horizontal separation distance is much larger than 300 m. Thus the lower bound for the separation distance for two aircraft in flight is 300 m.

FIGURE A-4.12

Wireless avionics intra-communication *I*/*S* vs vertical separation distance channel model A

Channel Model A LI **Channel Model A HI**

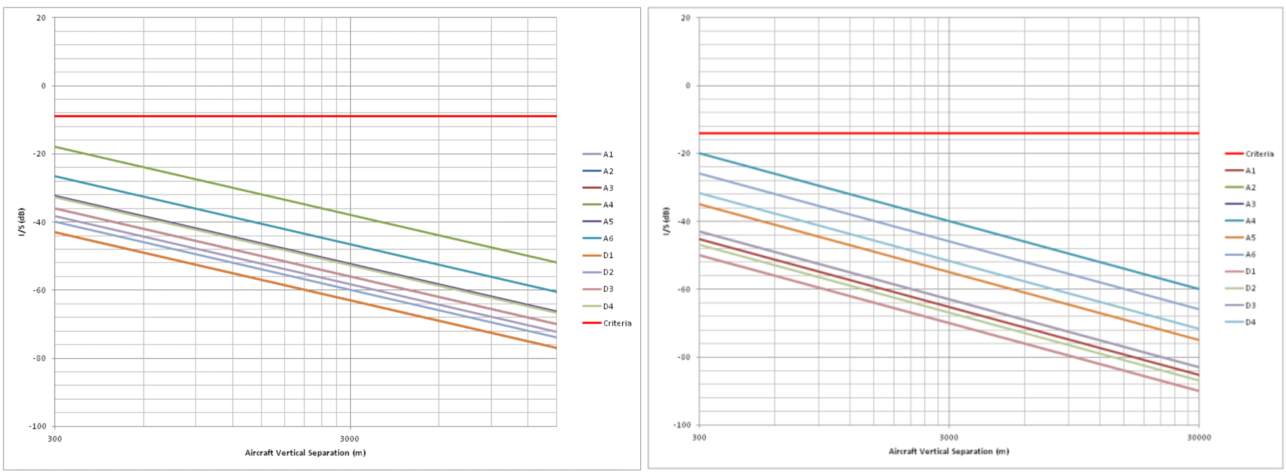


FIGURE A-4.13

Wireless avionics intra-communication *I*/*S* vs vertical separation distance channel model B

Channel Model B LI **Channel Model B HI**

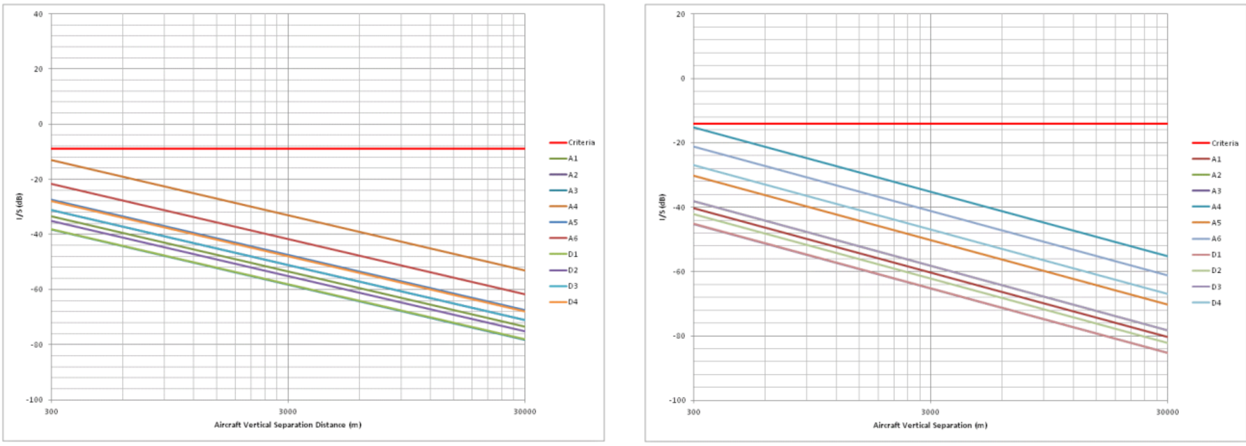
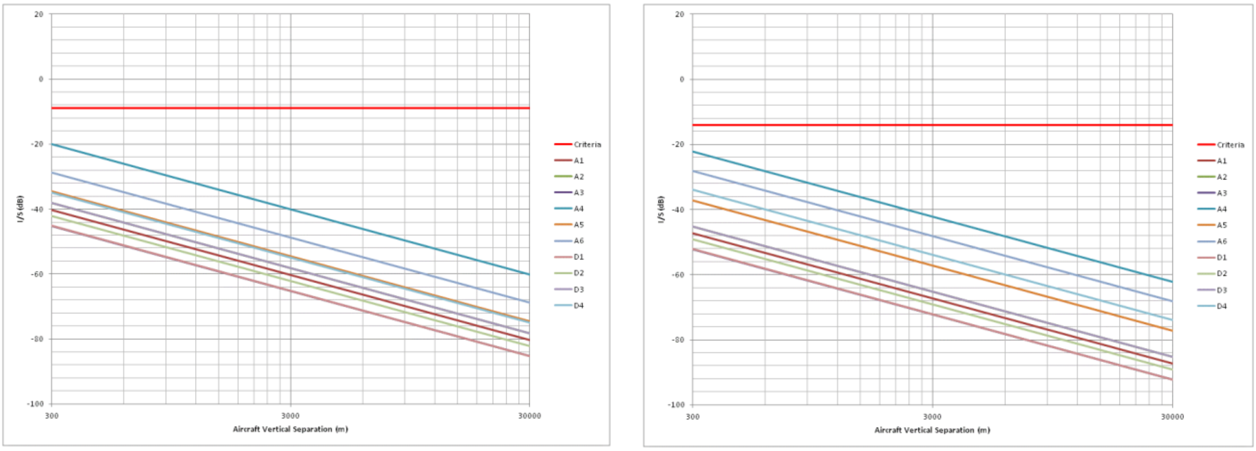


FIGURE A-4.14

Wireless avionics intra-communication *I*/*S* vs vertical separation distance channel model F

Channel Model F LO **Channel Model F HO**



From this analysis, and the corresponding assumptions, a minimum separation distance of at least 270 m would be needed to ensure that WAIC systems could safely operate with radio altimeters which would be adequate to protect an aircraft using the ICAO separation rules.

A-4.4.2 Vertical separation from an aircraft on an adjacent taxiway

At airports where helicopters and airplanes operate it is important to consider that some helicopters perform an operation known as ‘air taxi’ that is that a helicopter follows a taxiway but does so while flying at generally low altitudes (30 m to 40 m). Taxiways offer a horizontal separation of 40 m. This study places a WAIC aircraft on the ground and a single aircraft with a radio altimeter at various altitudes. The *I*/*S* for inside and outside low and high data rate systems is calculated for various radio altimeter altitudes from 10 m to 30 000 m. As in § A-4.4.1, for inside systems, the WAIC system is modelled with omni-directional antennas, so this presents a worst-case main-lobe to main-lobe scenario, while for outside systems, the WAIC system is modelled with antennas as described in § A-4.3 is analyzed, where the worst-cases are when the radio altimeter is within the main-lobe of the WAIC antenna at very low altitudes, or when the altitude of the radio altimeter creates a main-lobe to WAIC side-lobe scenario.

FIGURE A-4.15

Wireless avionics intra-communication *I*/*S* vs vertical separation distance 40 m offset channel model A

Channel Model A LI **Channel Model A HI**

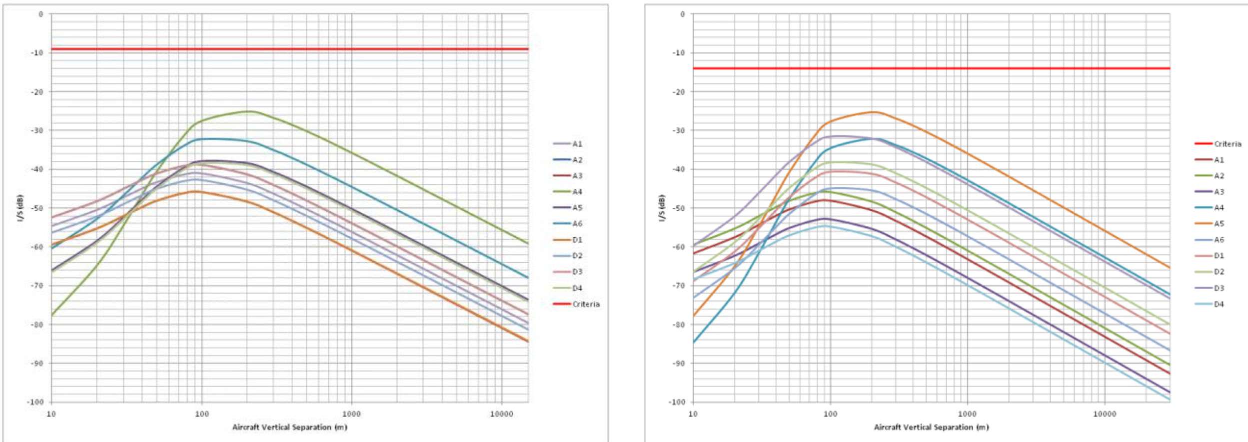


FIGURE A-4.16

Wireless avionics intra-communication *I*/*S* vs vertical separation distance 40 m offset channel model B

Channel Model B LI **Channel Model B HI**

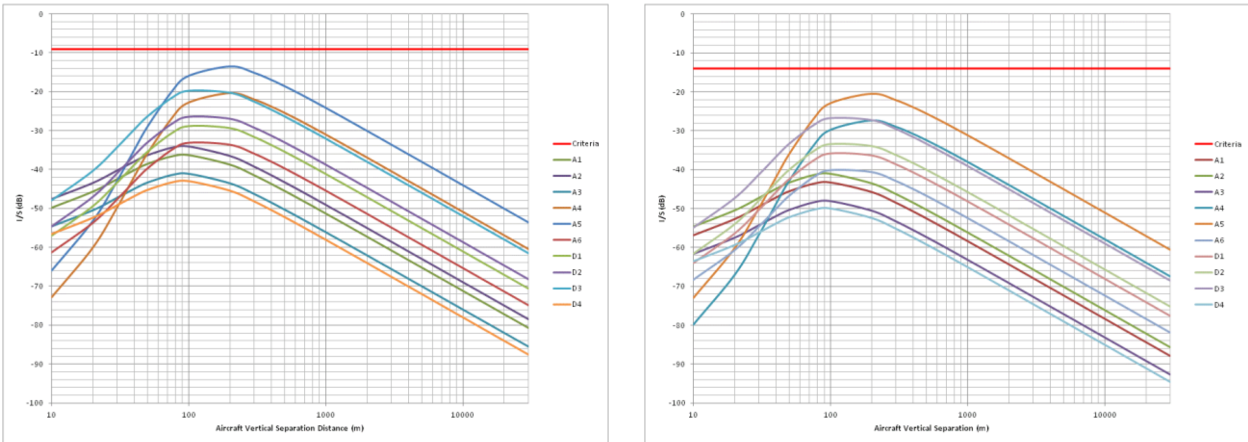
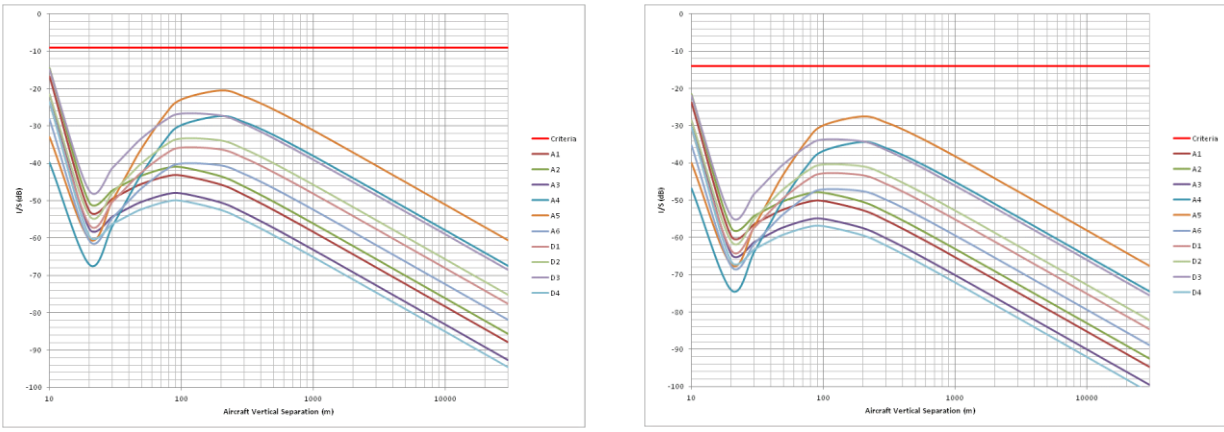


FIGURE A-4.17

Wireless avionics intra-communication *I/S* vs vertical separation distance 40 m offset channel model F

Channel Model F LO **Channel Model F HO**



From this analysis, and the corresponding assumptions, a single radio altimeter would not exceed the interference criteria for WAIC operation.

A-4.4.3 Vertical separation from 3 aircraft on an adjacent taxiway

As mentioned in § A-4.4.2, helicopters may air taxi at an airport. Sometimes multiple helicopters may be performing this action at the same time, so the aggregate interference from multiple aircraft should be considered. In this scenario, as in § A-4.4.2, a WAIC aircraft is on the ground, while three aircraft with radio altimeters are positioned on an adjacent taxiway. The three aircraft radio altimeters are separated by 60 m. The *I*/*S* for inside and outside low and high data rate systems is calculated for various radio altimeter altitudes from 10 m to 30 000 m. As in § A-4.4.1, for inside systems, the WAIC system is modeled with omni-directional antennas, so this presents a worst-case main-lobe to main-lobe scenario, while for outside systems, the WAIC system is modeled with antennas as described in § A-4.3 is analyzed, where the worst-cases are when the radio altimeter is within the main-lobe of the WAIC antenna at very low altitudes, or when the altitude of the radio altimeter creates a main-lobe to WAIC side-lobe scenario.

FIGURE A-4.18

Wireless avionics intra-communication *I/S* vs vertical separation distance three radio altimeters 40m offset channel model A

Channel Model A LI **Channel Model A HI**

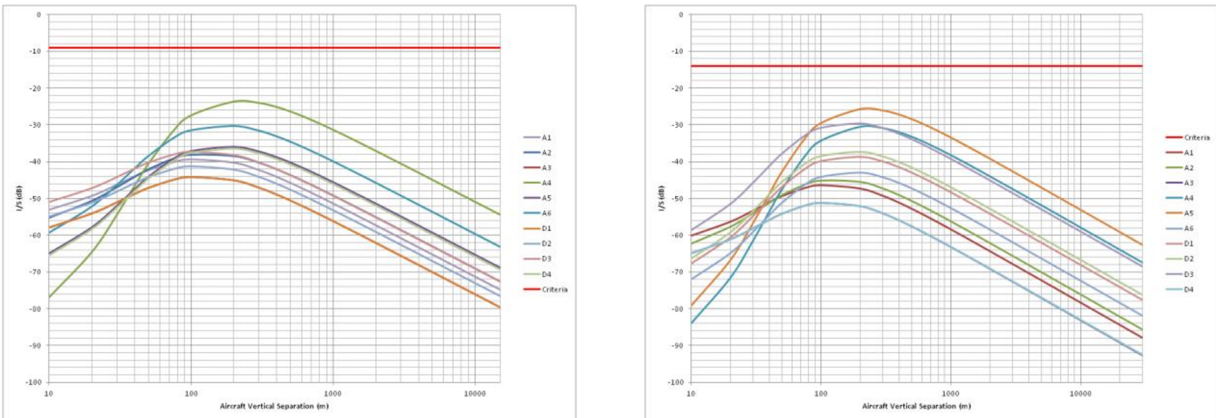


FIGURE A-4.19

Wireless avionics intra-communication *I*/*S* vs vertical separation distance three radio altimeters 40m offset channel model B

Channel Model B LI **Channel Model B HI**

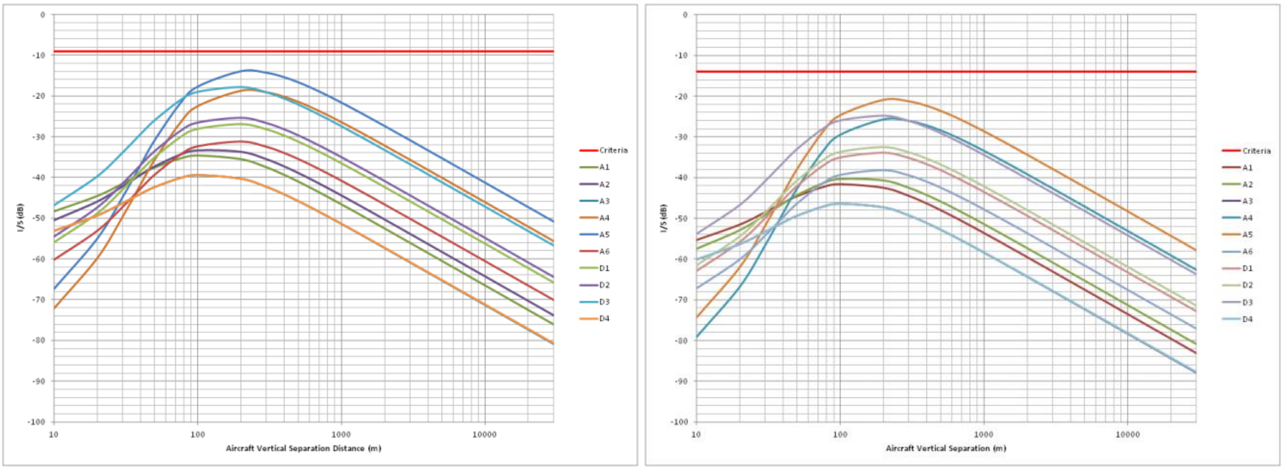
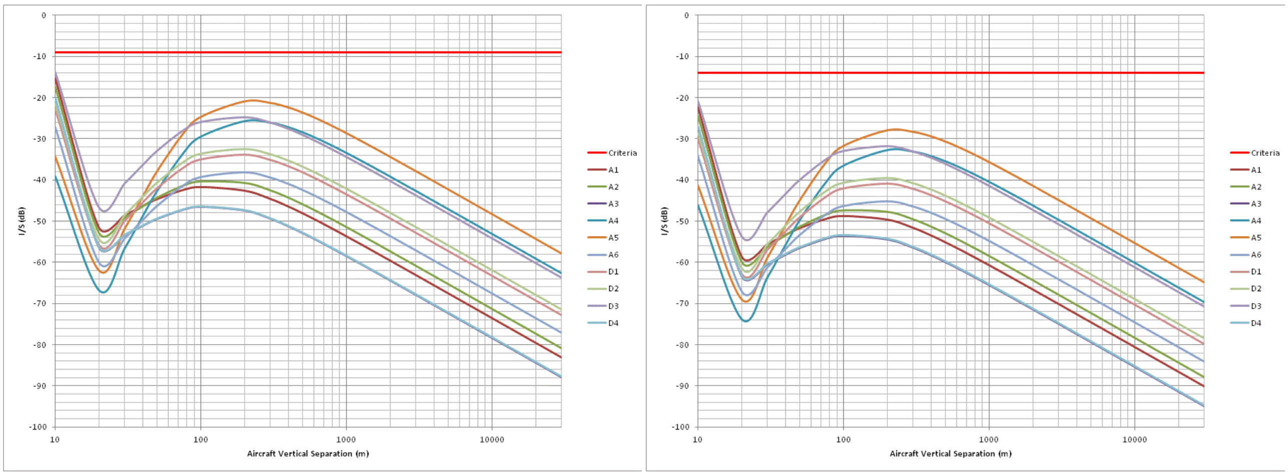


FIGURE A-4.20

Wireless avionics intra-communication *I*/*S* vs vertical separation distance three radio altimeters 40 m offset channel model F

Channel Model F LO **Channel Model F HO**



From this analysis, and the corresponding assumptions, the aggregate interference from three radio altimeter would not exceed the interference criteria for WAIC operation.

A-4.5 Conclusions

The situations in the simulations in §§ A-4.3.1 and A-4.3.2 depict aircraft in a critical stage of flight and introduces many sources of interference to radio altimeters from WAIC systems. These simulation studies, using maximum values and several worst-case assumptions, demonstrate that high data rate and low data rate WAIC systems located within the aircraft structure do not exceed the interference criteria for radio altimeters. High data rate and low data rate WAIC systems located outside the aircraft structure may not exceed the radio altimeter interference criteria if sufficient mitigation methods such as transmit power and antenna design and operation are used. Also, simulations show that aircraft using all four types of WAIC systems used in conjunction also do not exceed radio altimeter interference criteria, provided that the mitigation methods such as transmit power and antenna design are also applied to any systems outside the aircraft to prevent stray emissions.

Analysis in §§ A-4.4.1, A-4.4.2, and A-4.4.3 also demonstrate that WAIC systems can operate in the presence of radio altimeters, as radio altimeter emissions do not exceed the WAIC interference criteria.

Annex 5

Study 4

Compatibility analysis between wireless avionics intra-communication systems and systems in the fixed service

A-5.1 Fixed service characteristics

Recommendation ITU-R F.758-5 provides characteristics for fixed service stations. However, this recommendation does not provide any characteristics for the frequency band 4 200-4 400 MHz. It is therefore proposed to use the characteristics available for the adjacent frequency bands which are summarized in Table A-5.1. The nominal long-term interference power density should be therefore based on an *I*/*N* ratio of –10 dB which shall not be exceeded for more than 20% of the time. An additional short-term protection criterion based on an *I*/*N* ratio of +25 dB which shall not be exceeded for more than 0.005% of the time has also been assumed. The channel spacing in bold is the most commonly used.

TABLE A-5.1

System parameters for PP fixed service systems in allocated frequency bands between 3.6 and 5 GHz

Frequency range (GHz)	**3.600-4.200**		**3.700-4.200**	**4.400-5.000**	
Reference	FS1	FS2	FS3	FS4	FS5
Modulation	64-QAM	512-QAM	QPSK	16-QAM	256-QAM
Channel spacing and receiver noise bandwidth (MHz)	**10**, **30**, 40, 60, 80, 90	10, 30, **40**, 60, 80, 90	28, **29**	8, 9, 10, 13, 16.6, 20, **28**, 33.2, 40, 60, 80	9, 10, 13, 20, **28**, 40, 60, 80
Tx output power range (dBW)	−1	7	0	−5…−10	−5
Tx output power density range (dBW/MHz)	−16…−11	−9.0	−15	−25,2…−1 4.5	−19.5…, −14.5
Feeder/multiplexer loss range (dB)	0	3	3	0	3
Antenna gain range (dBi)	42	40	37	21.5…22.5	22.5
e.i.r.p. range (dBW)	41	44	38	11.5…14.5	14.5
e.i.r.p. density range (dBW/MHz)	26…31	28	23	−3.7…5.0	0.0…5.0

TABLE A-5.1 (*end*)

Frequency range (GHz)	**3.600-4.200**		**3.700-4.200**	**4.400-5.000**	
Receiver noise figure typical (dB)	3	2	4	6.5…7	6.5
Receiver noise power density typical (=N_{RX}) (dBW/MHz)	−141	−142	−140	−137.5… −137	−137.5
Normalized Rx input level for 1×10^{-6} BER (dBW/MHz)	−114.5	−106.5	−126.5	−117.0… −116.5	−104.9
Nominal long-term interference power density (dBW/MHz)	−141 + I/N	−142 + I/N	−140 + I/N	−137.5… −137 + I/N	−137.5 + I/N

Recommendation ITU-R F.1245 was used to model the FS station antenna pattern.

A-5.2 Interference impact of wireless avionics intra-communication systems on systems operating in the fixed service

A-5.2.1 Scenario

The FS station at which the interference impact of WAIC is analyzed is deployed close to Teheran and is assumed pointing in one direction (e.g. 270° azimuth and 10° elevation).

The analysis is normalized to a 1 MHz reference bandwidth in order to take into account all possible FS bandwidths. The received aggregate interference power of all aircraft in visibility of the FS station is computed for each time step (1 second) and compared to the FS protection criteria. Figure A-5.1 gives the air routes on which an aircraft will be in visibility to the FS station. For each aircraft located on these air routes the interference power level observed at the FS station is computed, taking into account the FS antenna gain, using the equation given below.

$$\frac{I}{N} = EIRP(\varphi) + G_{\mathrm{FS}}(\theta) - LP - 10\,log(kT) - F - 90 \qquad \text{(A-5.1)}$$

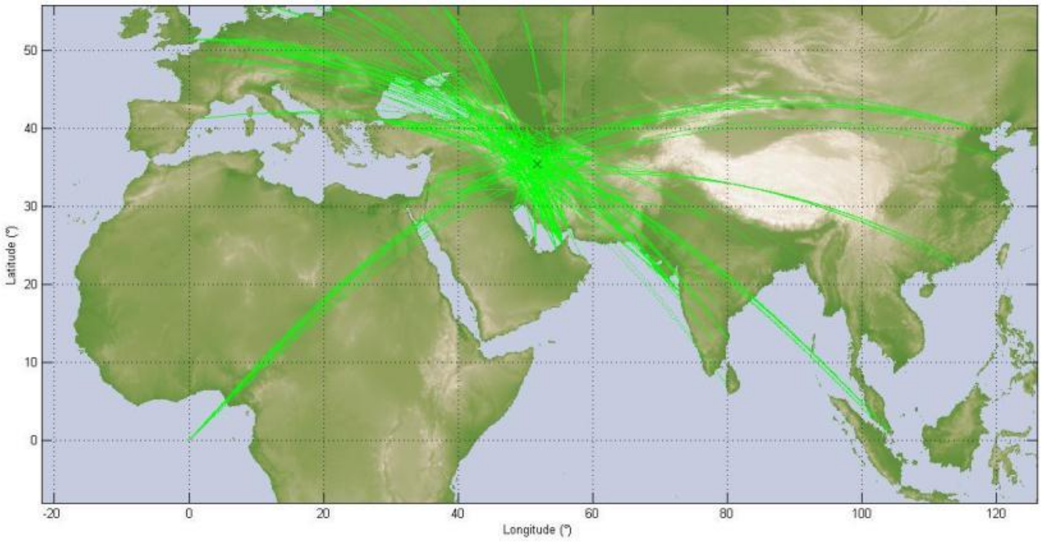
where:

- I/N: Interference to noise level generated by one aircraft in the FS receiver (dB)
- $EIRP$: WAIC e.i.r.p. density (5.6 dBm/MHz)
- G_{FS}: FS station antenna gain in the direction of the aircraft (dBi)
- LP: Propagation loss (free-space loss) (dB)
- θ: Offset angle between the pointing direction of the FS station and the direction of the aircraft (°)
- φ: Offset angle between the aircraft yaw axis and the point direction of the slant range between aircraft and FS station
- k: Boltzman constant
- T: Noise temperature (290K)
- F: Noise figure (dB).

The contributions from each aircraft are then linearly summed up for each time step in order to obtain the aggregate interference to noise level at the FS receiver.

FIGURE A-5.1

Air routes in visibility of the fixed service station



A-5.2.2 Results for low and high data rate inside wireless avionics intra-communication systems

For the evaluation of the interference impact of LI and HI WAIC systems the power spectral density is derived from the OPS model introduced in § A-1.3. The maximum power spectral density of inside WAIC system is –24.3 dBm/MHz, as given by Table A-1.6. The value is derived under the assumption that inside WAIC applications are shielded by the aircraft fuselage as specified in the Report ITU-R-M.2283.

Figure A-5.2 depicts the aggregate interference-to-noise level observed at the antenna port of fixed service station FS1 with parameters described in Table A-5.1 during the simulation duration. The plot shows that neither the long-term nor the short-term protection criteria are exceeded. Figure A-5.3 provides the associated Complementary Cumulative Distribution Function (CCDF) P (I/N > x) of the interference for all FS stations types described in Table A-5.1. The CCDF shows that both the short-term and long-term criteria would be met for all FS types.

FIGURE A-5.2

Calculation results for fixed service system 1

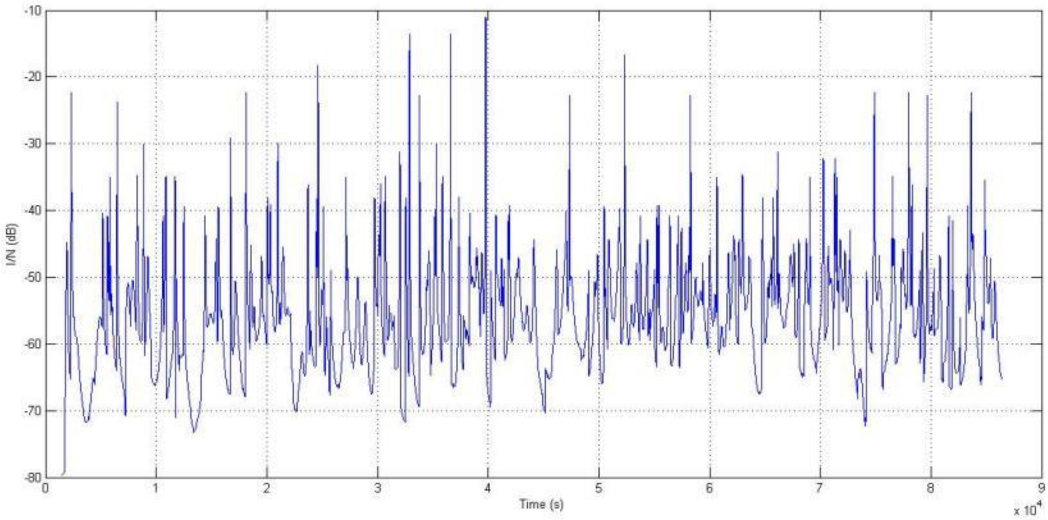
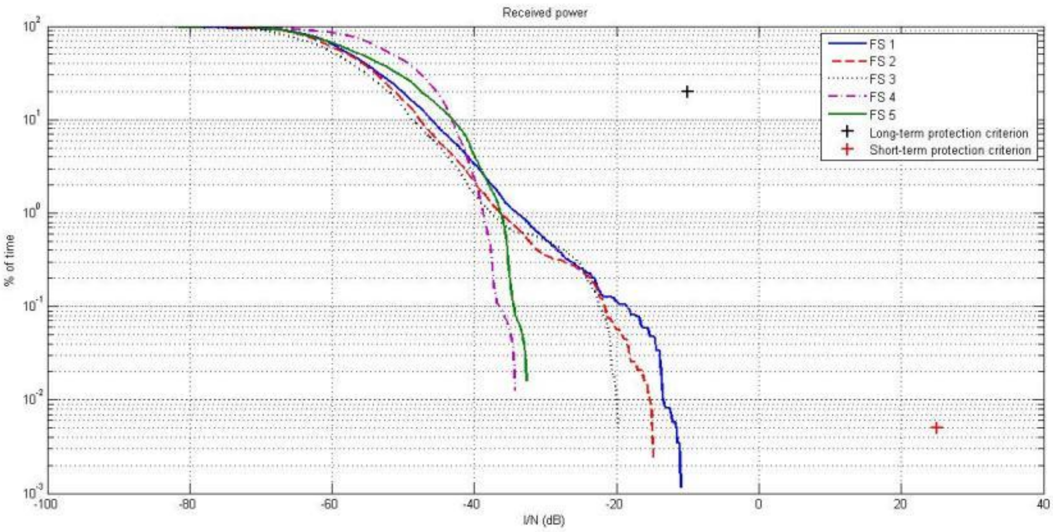


FIGURE A-5.3

Complementary cumulative distribution function

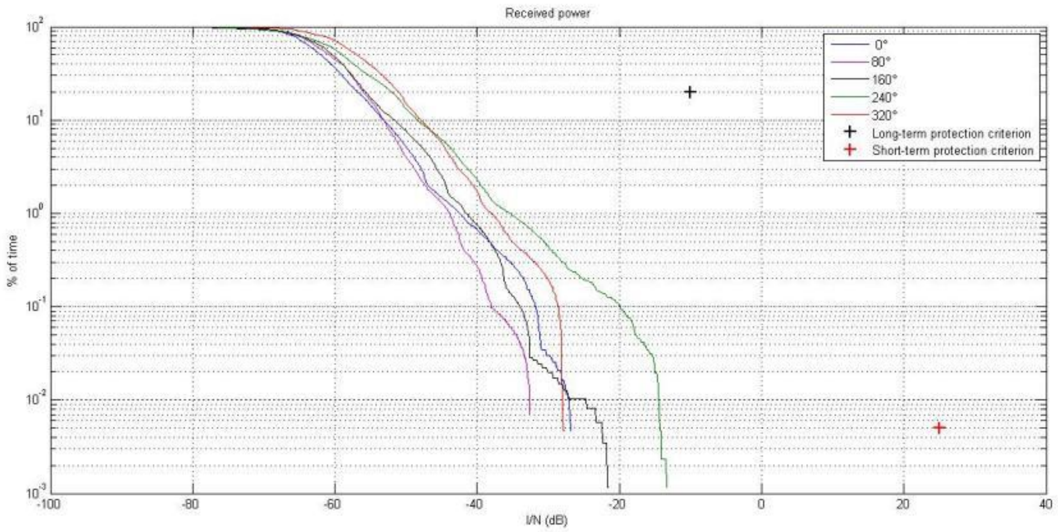


A-5.2.3 Influence of the fixed service station pointing angle

The worst-case WAIC interference impact is observed at fixed service station FS1. Figure A-5.4 shows the influence of the azimuth pointing angle on the observed interference impact at this station. The angle dependent CCDF shows that in all cases the protection criteria are met.

FIGURE A-5.4

Complementary cumulative distribution function for fixed service system 1



A-5.2.4 Results for low and high date rate outside wireless avionics intra-communications systems

Analysis of the interference impact of outside WAIC applications onto the considered FS stations is performed under the assumption that the RF emission of all LO and HO WAIC applications comply with the maximum tolerable e.i.r.p. pattern introduced in Annex 1 § A-1.4. The pattern is described by Fig. A-1.2 and Table A-1.7. Figures A-5.5 and A-5.6 show the CCDF plots describing the interference impact of LO and HO WAIC applications to all FS types listed in Table A-5.1. The obtained results clearly show that all FS protection criteria are met for LO as well as HO WAIC applications complying with maximum tolerable e.i.r.p. pattern introduced in Annex 1 § A-1.4.

FIGURE A-5.5

Complementary cumulative distribution function assuming LO wireless avionics intra-communications radiating with the e.i.r.p. mask

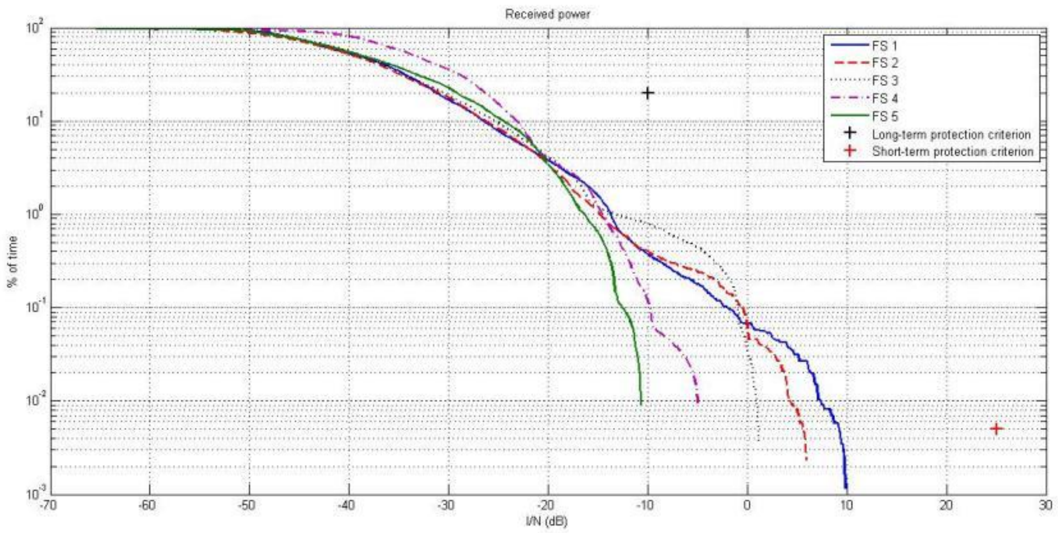
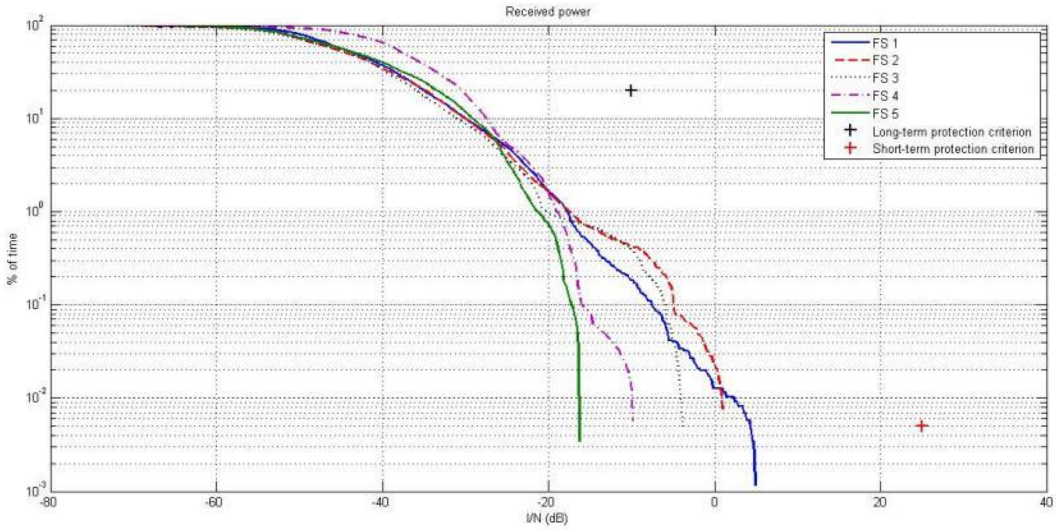


FIGURE A-5.6

Complementary cumulative distribution function assuming HO wireless avionics intra-communications radiating with the e.i.r.p. mask



A-5.3 Interference impact of fixed service stations onto wireless avionics intra-communications

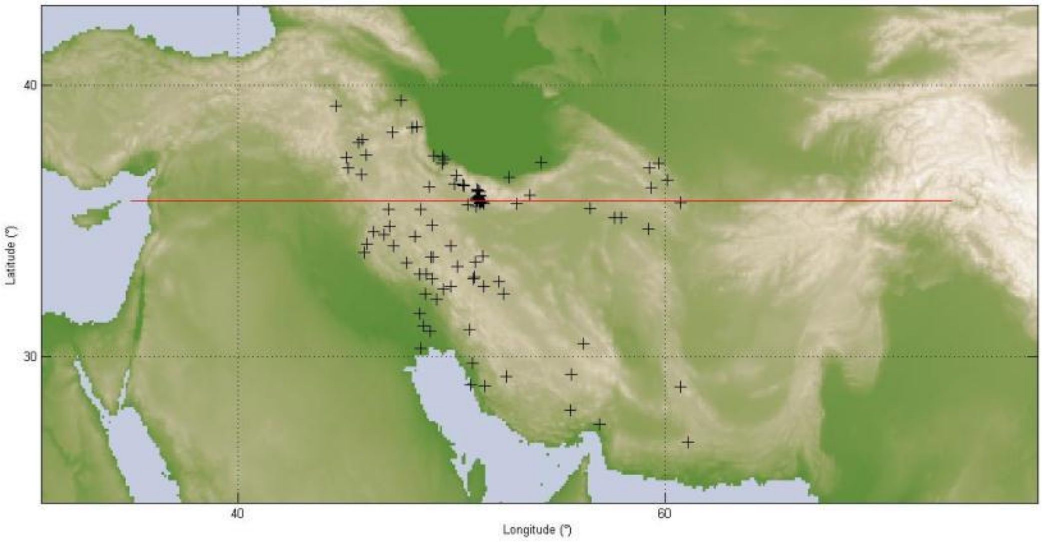
A-5.3.1 Scenario

A dynamic simulation was developed to assess the aggregate interference impact of FS stations onto WAIC receiving stations on board single aircraft flying over an administration.

The calculation is performed using a reference bandwidth of 1 MHz. This implies using the power spectral density of the FS signals for the evaluation of the interference-to-signal power ration (*I*/*S*) WAIC protection criteria within the 1 MHz reference bandwidth. 100 FS stations have been deployed over the geography of the administration, according to the density of population (see http://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-density/data-download) shown in Fig. A-5.7. This corresponds to a total number of 200 FS stations, assuming a bandwidth of 90 MHz, and up to 2 000 FS stations, assuming a bandwidth of 10 MHz, in the entire frequency band 4 200-4 400 MHz. Noting that the allocation is secondary, it is not expected that a higher number of stations use the frequency band.

FIGURE A-5.7

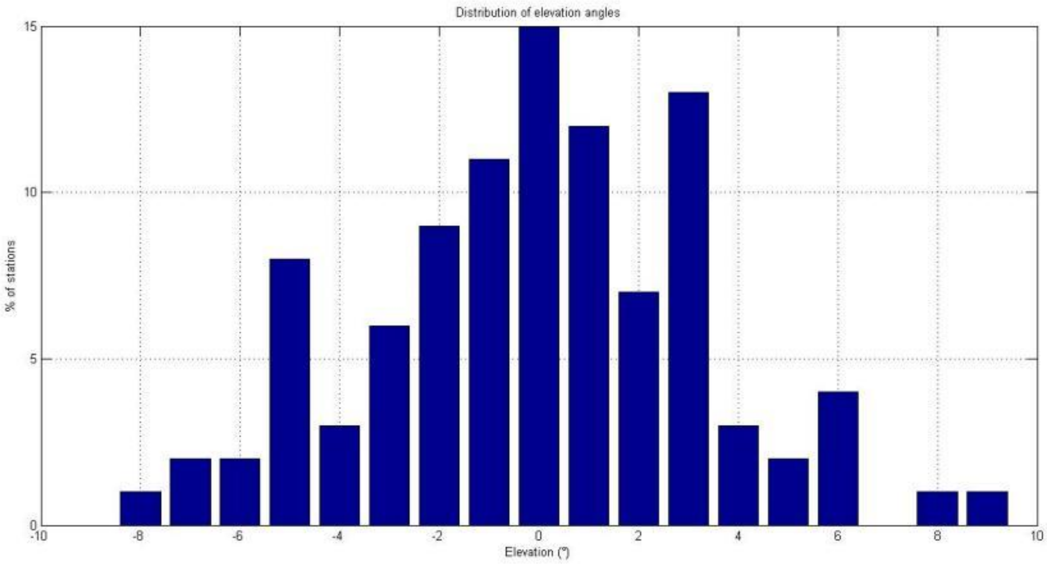
Deployment of fixed service stations



The azimuth pointing angle of each FS station is randomly chosen following a uniform distribution between 0 and 360°. The elevation angle is randomly chosen following a normal distribution between –10 and +10° as shown in Fig. A-5.8.

FIGURE A-5.8

Distribution of elevation angles



The power spectral density is randomly chosen assuming a flat distribution between the two extreme values given in Table A-5.1.

The analysis is performed considering an aircraft flying over Teheran at different altitudes with speed of 700 km/h. The influence of the speed will only affects the duration of interference but not its power. The aggregate interference from all FS stations in visibility is derived using the following equation.

$$I/_S = P_{FS} + G_{FS}(\theta) - LP - LF - S - 30 + G_S(\varphi) \qquad \text{(A-5.2)}$$

where:

I/S: I over S ratio (dB)

P_{FS}: FS power density (dBW/MHz)

G_{FS}: FS station antenna gain in the direction of the aircraft (dBi)

θ: Offset angle between the pointing direction of the FS station and the direction of the aircraft (°)

LP: Propagation loss (free-space loss) (dB)

LF: Fuselage attenuation (dB)

S: WAIC minimum received signal (dBm/MHz)

G_S: Directional antenna gain of a receiving WAIC station only applied for LO and HO WAIC systems (dBi)

φ: Offset angle between the aircraft yaw axis and the line-of-sight vector between aircraft and FS station.

LI and HI WAIC systems are assumed to use omni-directional antennas with a gain of 0 dBi as described in Table A-1.1. Furthermore, WAIC applications inside the aircraft body are assumed to be shielded from the outside as described in Report ITU-R-M.2283. For that reason a fuselage attenuation of LF = 35 dB is applied for LI and HI WAIC systems.

LO and HO WAIC systems are assumed to utilize directive antennas in order to comply with the maximum tolerable e.i.r.p. pattern, as described in Annex 1 § A-1.4. A detailed description of the configuration of the directional WAIC antennas is also given in Annex 1 § A-1.4. The application of directional antennas provides coupling of 35 dBi gain between the transmitting and receiving station, which allows to reduce the transmit power of LO and HO WAIC applications to –7 dBm without a violation of the maximum tolerable e.i.r.p. pattern.

According to Fig. A-1.3 the most severe interference impact of FS stations will be observed at the gateway nodes, because their antenna beams may in some rare cases directly point into the direction of a FS station transmit antenna. The peak gain of the Gateway Node antenna is assumed to be 10 dBi, see Annex 1 § A-1.4. For that reason, it is assumed that in the worst-case the FS interference signal is going to be amplified by 10 dBi at a receiving WAIC station.

The WAIC minimal receive signal power spectral density S required to evaluate the WAIC I/S protection criteria defined in Table A-1.1 are provided in Table A-5.2. The power spectral densities are calculated for a reference bandwidth of 1 MHz using the propagation models in § A1-2.

WAIC systems are organized in cellular sub-networks on a compartment basis as specified in Report ITU-R M.2283. That implies that there is no communication among WAIC stations located in different aircraft compartments, or between a station internal and another station external to the aircraft structure. For that reason, only the radio channel models A, B and F of Table A-1.2 in Report ITU-R M.2283 are deemed applicable for determining the minimum WAIC receive signal power level.

TABLE A-5.2

Minimal wireless avionics intra-communications receive signal power spectral density

Group	Group name	Min. WAIC high data rate receive signal power spectral density	Min. WAIC low data rate receive signal power spectral density
A	Intra-Cabin & Intra-Flight Deck	$S_{A,H}$ = –72.7 dBm/MHz	$S_{A,L}$ = –56.8 dBm/MHz
B	Inter-Cabin	$S_{B,H}$ = –77.5 dBm/MHz	$S_{B,L}$ = –61.6 dBm/MHz
F	Inter-Exterior	$S_{F,H}$ = –58.5 dBm/MHz	$S_{F,L}$ = –49.6 dBm/MHz

From these levels, a minimum signal level has been determined for each installation regime given in Table 5, as shown in Table A-5.3.

TABLE A-5.3

Minimum wireless avionics intra-communications signal S considered in the study

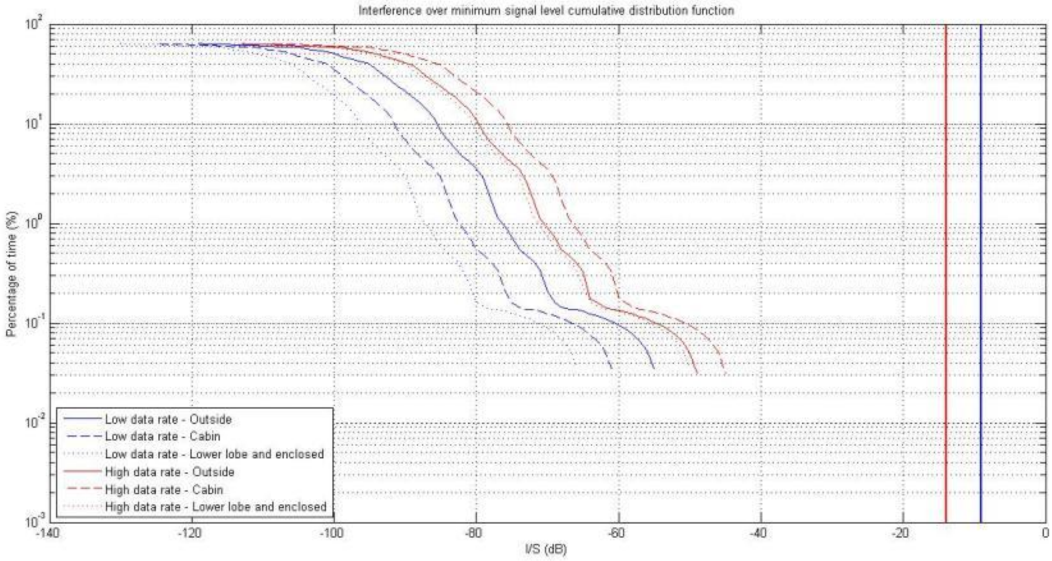
Installation Regime	Equation Applied	High data rate value	Low data rate value
Installed outside	$\mathbf{S_F}$	**–58.5 dBm/MHz**	**–49.6 dBm/MHz**
installed within cabin	min (S_A, S_B)	–77.5 dBm/MHz	–61.6 dBm/MHz
installed in lower lobe of aircraft fuselage	S_A	–72.7 dBm/MHz	–56.8 dBm/MHz
installed in enclosed compartments	Assumed S_A	–72.7 dBm/MHz	–56.8 dBm/MHz

A-5.3.2 Results

The results in Figs A-5.9 to A-5.13 show that the WAIC *I*/*S* protection criteria for LI and HI WAIC systems are met for any altitude and type of FS. Given that LO and HO WAIC utilize directional antennas as described in Annex 1 §§ A-1.4 and A-5.3.1, the WAIC I over S protection criteria for LO and HO WAIC systems are also met for any altitude and type of FS.

FIGURE A-5.9

Complementary cumulative distribution function for fixed service system 1 and an aircraft at 7 000 and 500 m altitudes (directive antenna)



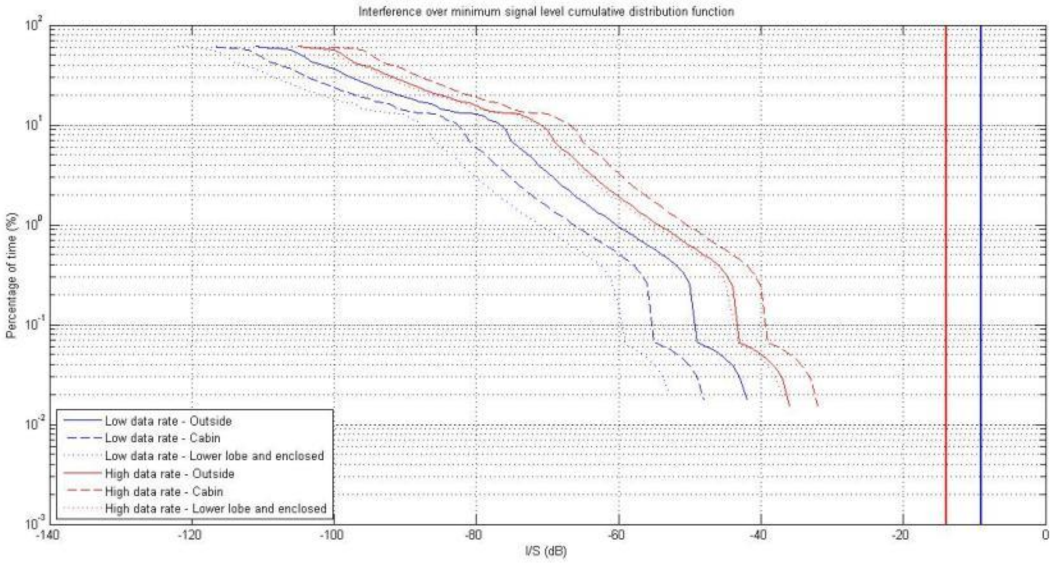
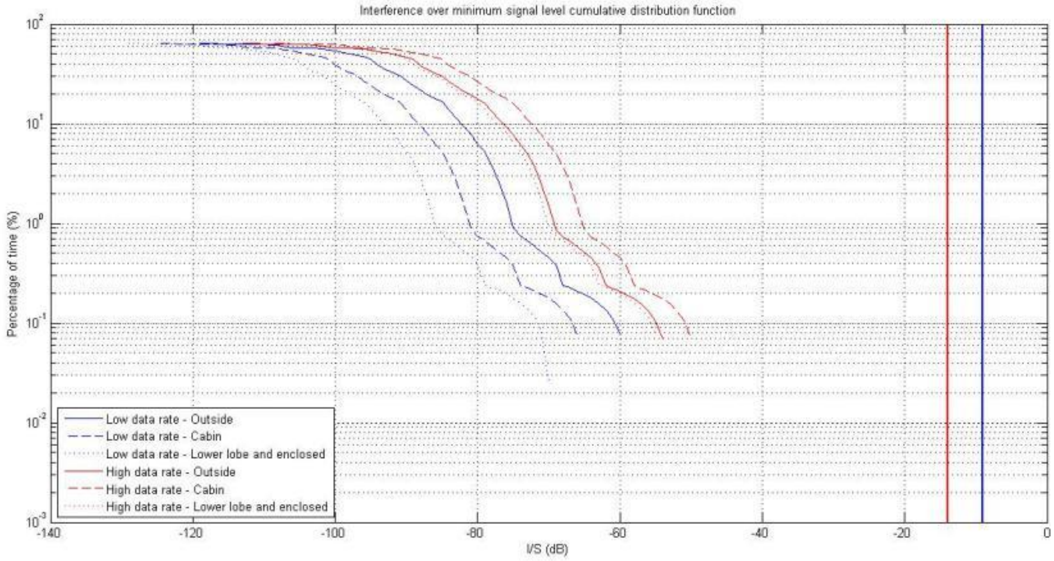


FIGURE A-5.10

Complementary cumulative distribution function for fixed service system 2 and an aircraft at 7 000 and 500 m altitudes (directive antenna)



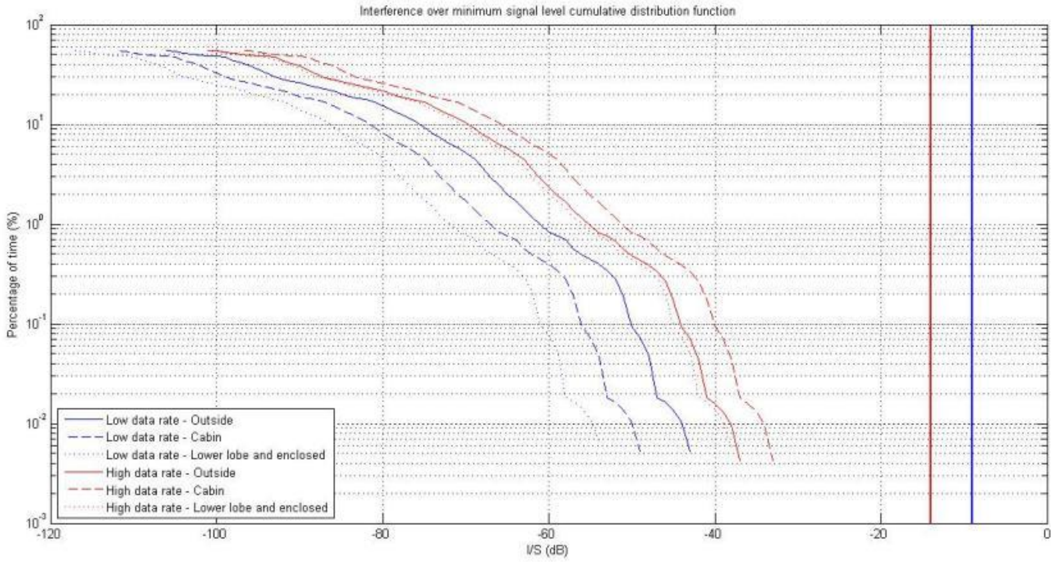
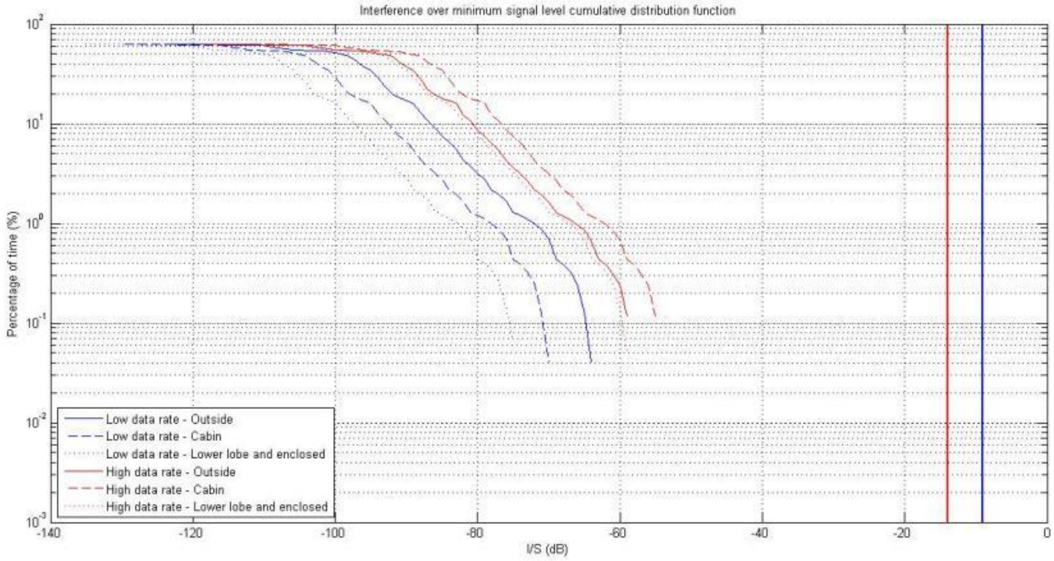


FIGURE A-5.11

Complementary cumulative distribution function for fixed service system 3 and an aircraft at 7 000 and 500 m altitudes (directive antenna)



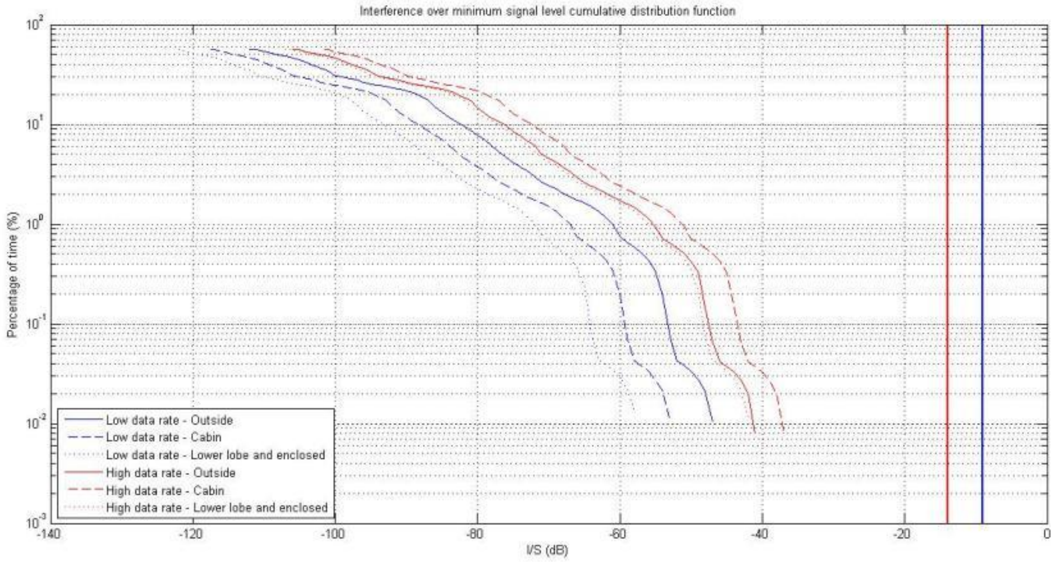


FIGURE A-5.12

Complementary cumulative distribution function for fixed service system 4 and an aircraft at 7 000 and 500 m altitudes (directive antenna)

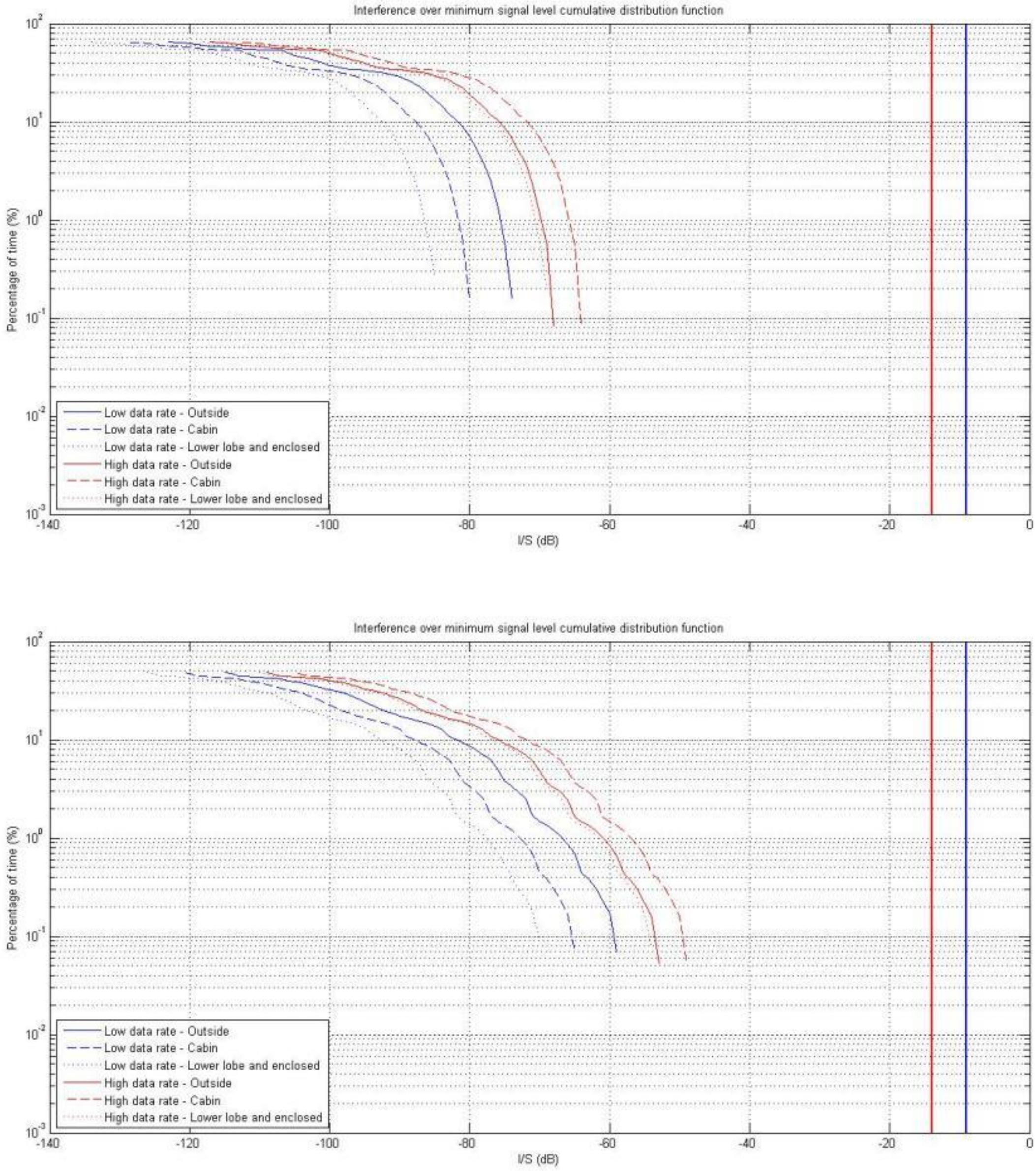
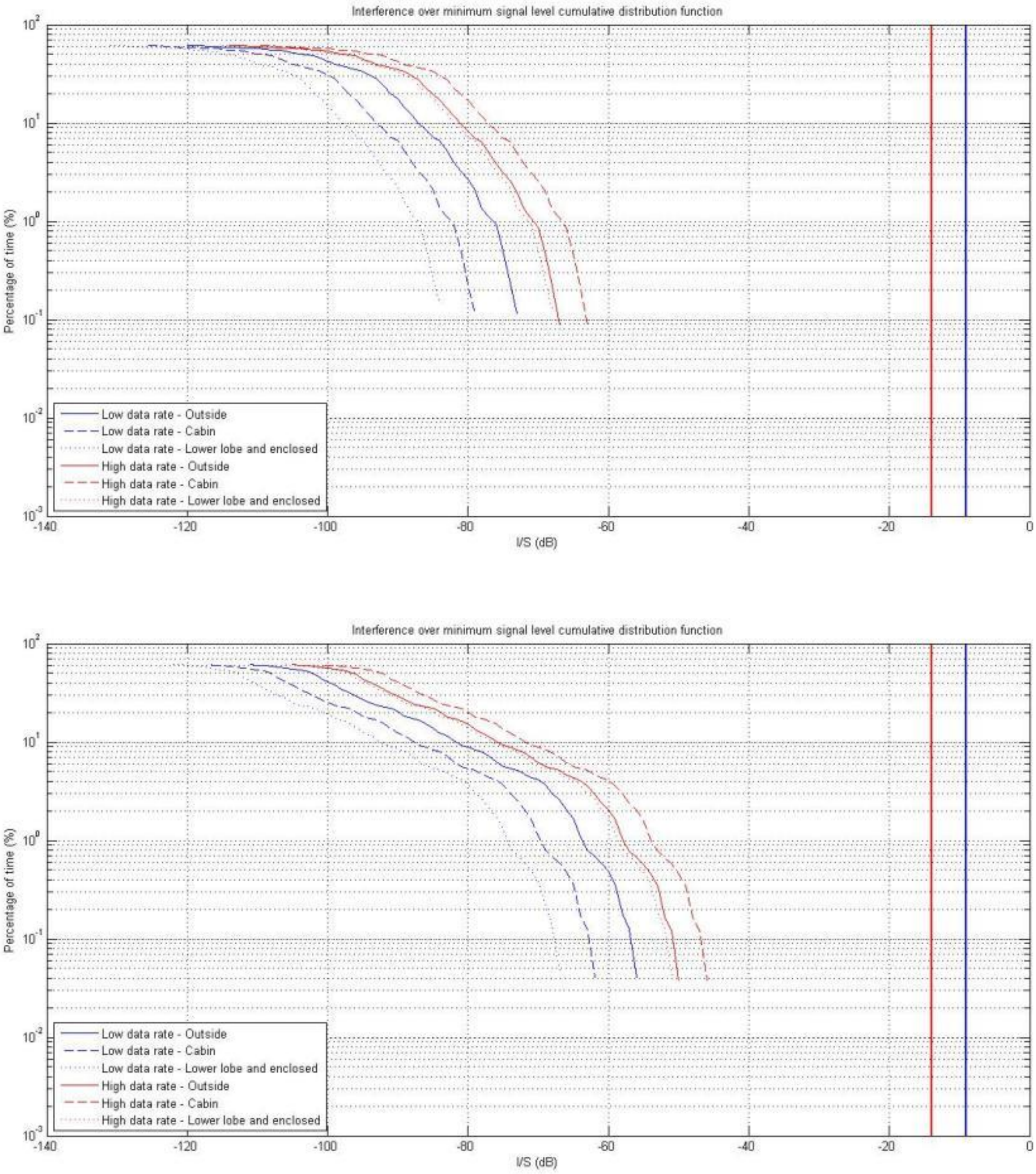


FIGURE A-5.13

Complementary cumulative distribution function for fixed satellite service 5 and an aircraft at 7 000 and 500 m altitudes (directive antenna)



A-5.4 Conclusions for fixed service

The study results presented above show that both the short-term and long-term FS protection criteria are met for LI and HI WAIC systems as well as for LO and HO WAIC systems. The analysis assumes that directional antennas, as described in Annex 1 § A-1.4 are utilized for WAIC systems outside the aircraft structure.

The study results also show that given these assumption, no harmful interference of inside or outside WAIC systems caused by the FS will occur.

Annex 6

Study 5

Compatibility analysis between wireless avionics intra-communication systems and systems in the Earth exploration-satellite service (passive)

A-6.1 Passive sensor characteristics

Recommendation ITU-R RS.1861 does not provide any characteristics for passive sensors using the frequency band 4 200-4 400 MHz since this frequency band is currently not used for passive sensing in the Earth exploration satellite service. However, Recommendation ITU-R RS.1624 provides a compatibility analysis between passive sensors and radio altimeters. In this Recommendation assumptions were taken for a potential passive sensor. These assumed passive sensor characteristics are reused here. The protection criterion has however been revised in order to be consistent with Recommendation ITU-R RS.2017. The assumptions for the study described hereafter are summarized in Table A-6.1.

TABLE A-6.1

Characteristics of a microwave radiometer

Parameter	Value	Units
Frequency band	4 200-4 400	MHz
Sensor bandwidth	200	MHz
Orbit	Circular polar orbit. altitude of 800 km	–
Antenna type	Conical scanning. nadir pointing	–
Incident angle	55 with respect to nadir	degree
Scan angle	± 60	degree
Antenna size	1.6	m
Antenna beamwidth	2.9	degree
Main beam gain	35	dBi
Side-lobe gain	–15	dBi
Permissible interference	–166 (Recommendation ITU-R RS.2017)	dB(W/200 MHz)

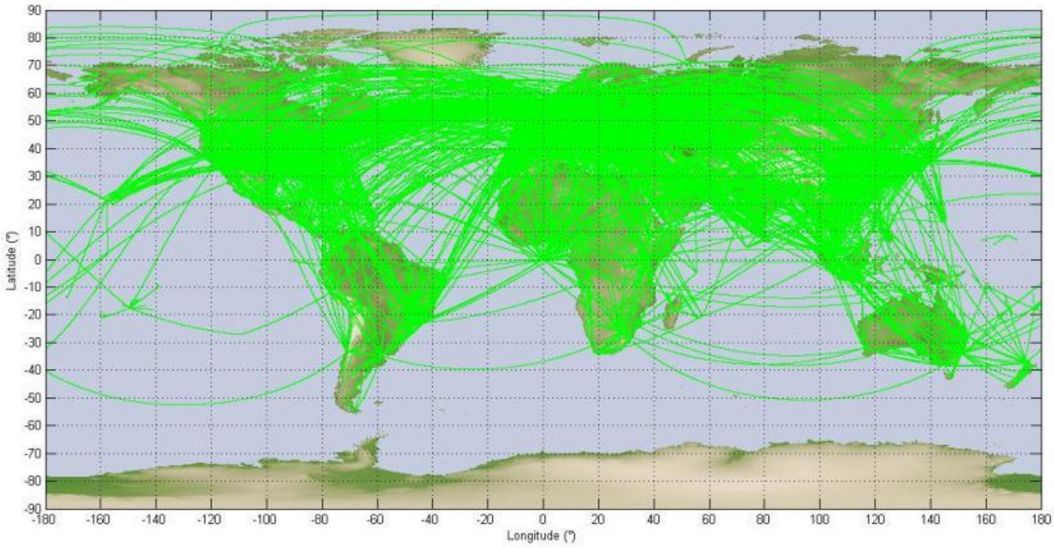
A-6.2 Air traffic

For the studies related to EESS, which operates globally, there is a need for modelling the air traffic worldwide. It is difficult to assess the number of aircraft flying worldwide daily, but also to assess the number of such aircraft that would be equipped with WAIC systems in the future. Information available on the Internet indicates a number of about 30 000 commercial flights daily over the USA only. Based on this, a number of 50 000 commercial flights daily and worldwide was assumed for the study described hereafter.

About 7 000 airports and 59 000 air routes (the departure and arrival airports) were utilized. The air routes were then calculated using the great circle path between airports. They are shown in Fig. A-6.1.

FIGURE A-6.1

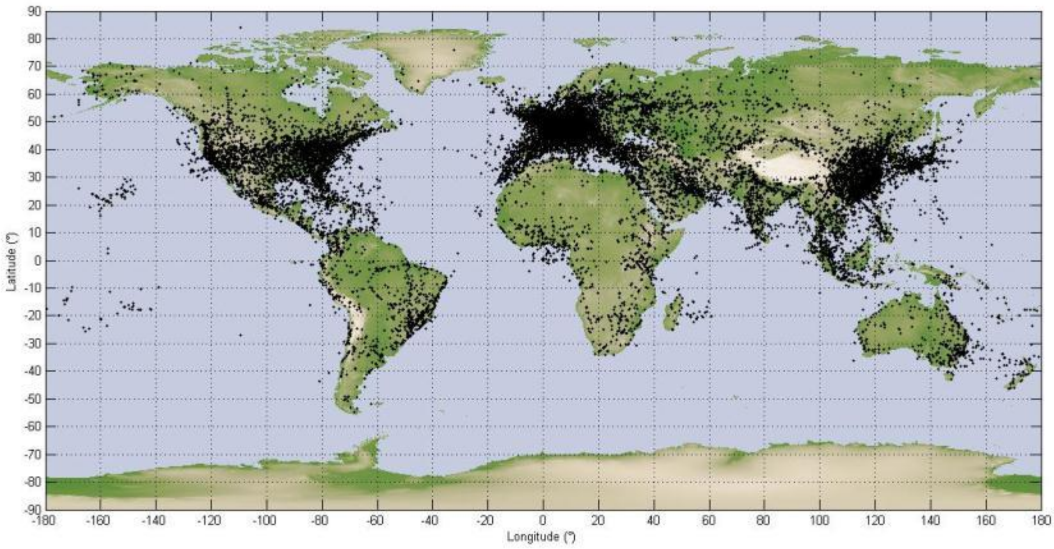
Air routes



In order to consider different altitudes and aircraft speeds, the 50 000 planes are distributed randomly worldwide on the air routes, with altitudes of 7 000 m (for distances lower than 800 km), 9 000 m (for distances lower than 2 000 km) or 11 000 m (for distances greater than 2 000 km). The speed of the aircraft is set to 700, 850 and 1 000 km/h, respectively. Time of departure is also random. The aircraft is set active 15 minutes prior to departure at the airport and stays active 15 minutes after landing. However, the take-off and landing phases are not simulated (i.e. each aircraft passes from 0 to its cruise altitude instantaneously). Figure A-6.2 gives the result of the model for one given time step.

FIGURE A-6.2

Example of aircraft positions worldwide for one particular simulation time step



A-6.2.1 Static analysis

The interference generated by one single aircraft into the EESS (passive) receiver may be calculated using the following equation.

$$I = \mathrm{EIRP} + G_{\mathrm{EESS}} - LP - 30 \qquad \text{(A-6.1)}$$

where:

- I: Interference level generated by one aircraft in the EESS receiver (dBW/200 MHz)
- EIRP: WAIC e.i.r.p. density (dBm) from Table A-1.4
- G_{EESS}: EESS sensor main beam antenna gain (dBi)
- LP: Propagation loss (free-space loss) (dB).

The propagation loss is calculated using the slant range between the satellite and the aircraft.

$$d = (R_t + h_S)\cos\alpha - \sqrt{(R_t + \mathrm{h_A})^2 - (R_t + h_S)^2 \sin\alpha^2} \qquad \text{(A-6.2)}$$

where:

- R_t: Earth radius (6 378 km)
- h_S: Satellite altitude (800 km)
- h_A: Aircraft altitude (10 km)
- α: Offset angle between nadir and sensor pointing direction (55°).

Table A-6.2 gives the results of a static worst-case (mainbeam-to-mainbeam coupling) evaluation of the interference power level observed at a passive sensor that would be created by LI, LO, HI or HO WAIC systems, represented by the OPS model described in § A-1.3, on board a single aircraft. The results show that inside WAIC systems are able to meet the passive sensor protection criteria.

TABLE A-6.2

Interference level from a single wireless avionics intra-communications system in the main lobe of the earth exploration satellite service (passive) sensor

		LO	HO	LI	HI
e.i.r.p.	dBm	17	20	–20.2	–15
d	km	1 620	1 620	1 620	1 620
GEESS	dBi	35	35	35	35
LP	dB	169	169	169	169
I	dBW	–147	–144	–185	–179
Criterion	dB(W/200 MHz)	–166	–166	–166	–166
Exceedance	dB	19	22	–19	–13

The static analysis assumes a mainbeam-to-mainbeam coupling between the outside WAIC systems and an EESS passive sensor. This situation is very unlikely to occur in a reality, particularly if outside WAIC systems use directive antennas to limit their RF emissions into the direction of the EESS passive sensor as described in Annex 1 § A-1.4. For this reason a dynamic analysis is carried out in § A-6.3 in order to assess the utilization of directional WAIC antennas to reduce the interference impact of outside WAIC systems onto the EESS passive sensor.

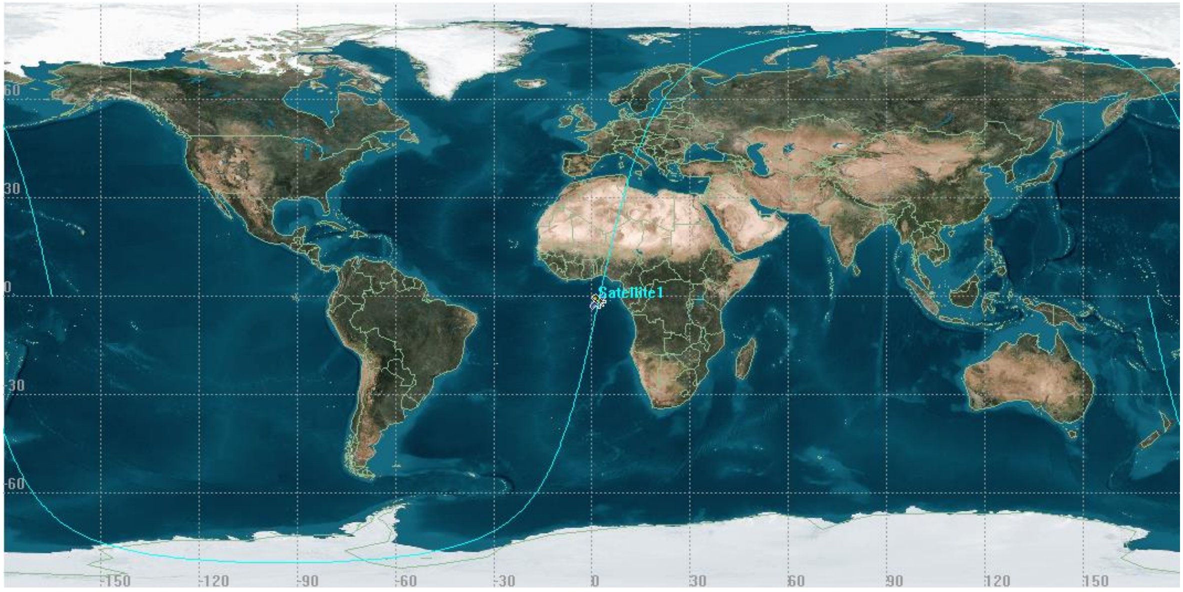
The analysis considers the air traffic model described in § A-6.2 as well as realistic assumptions on the EESS satellite trajectories as described in the following section.

A-6.3 Dynamic analysis

The orbital position of the satellite is simulated during one day, as shown in Fig. A-6.3.

FIGURE A-6.3

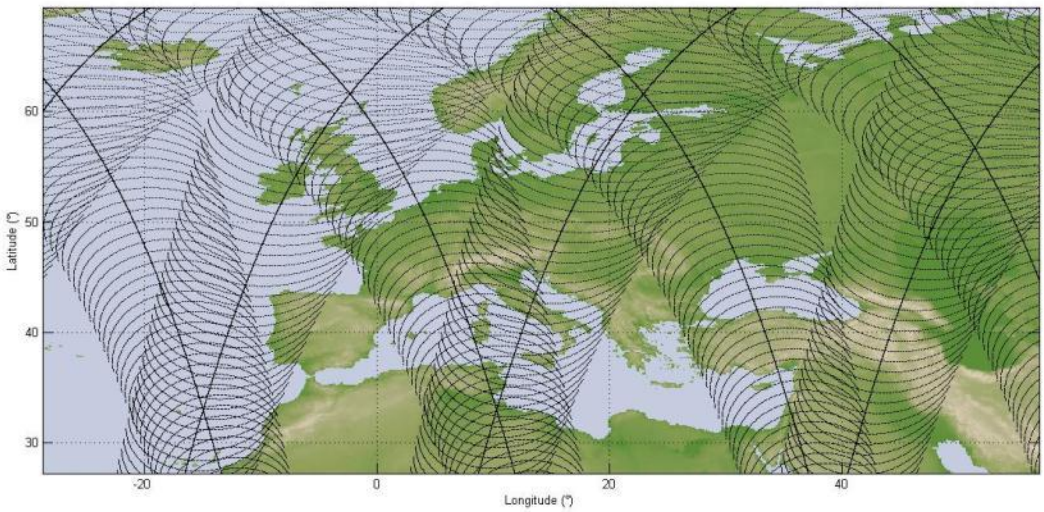
Earth exploration satellite service satellite orbit



The sensor on board the satellite is in rotation, with an angle of 55° from nadir (sub-satellite point) from –60 to +60° in azimuth / satellite path, thus leading to an antenna footprint with a conical scan as shown in Fig. A-6.4.

FIGURE A-6.4

Earth exploration satellite service passive sensor conical scan



The EESS protection criterion is defined with regard to a given measurement area which is 10 000 000 km² wide for a percentage of time of 0.1%. For the calculation of the distribution of interference levels, only the portions of orbits for which the EESS antenna footprint is within the measurement area are retained. For this simulation, the area is chosen as a rectangle centered over Europe.

On actual air routes, 50 000 planes are distributed randomly worldwide following the model described in § A-6.2. They are equipped with WAIC systems which transmit with the e.i.r.p. levels defined in Fig. A-1.2 and Table A-1.6.

The aggregate interference received by the sensor from all aircraft in visibility and each time step (0.1 s) while the sensor is performing a measurement of the reference area is then computed and compared to the protection criterion of –166 dBW/200 MHz.

$$I = \mathrm{EIRP}(\varphi) + G_{\mathrm{EESS}}(\theta) - LP - 30 \quad \text{(A-6.3)}$$

where:

- I: Interference level generated by one aircraft in the EESS receiver (dBW/200 MHz)
- $EIRP$: WAIC e.i.r.p. density (dBm) defined by Fig. A-1.2 and Table A-1.6
- G_{EESS}: EESS sensor antenna gain into the direction of the aircraft (dBi)
- θ: Offset angle between the sensor pointing direction and the aircraft direction (°)
- LP: Propagation loss (free-space loss) between the aircraft and the satellite (dB)
- φ: Offset angle between the aircraft yaw axis and the point direction of the slant range between aircraft and EESS satellite.

The determination of the angles φ and θ and the separation distance between the satellite and the aircraft while the satellite, the aircraft, and the sensor on board the satellite are moving is complex and requires the development of a simulation tool.

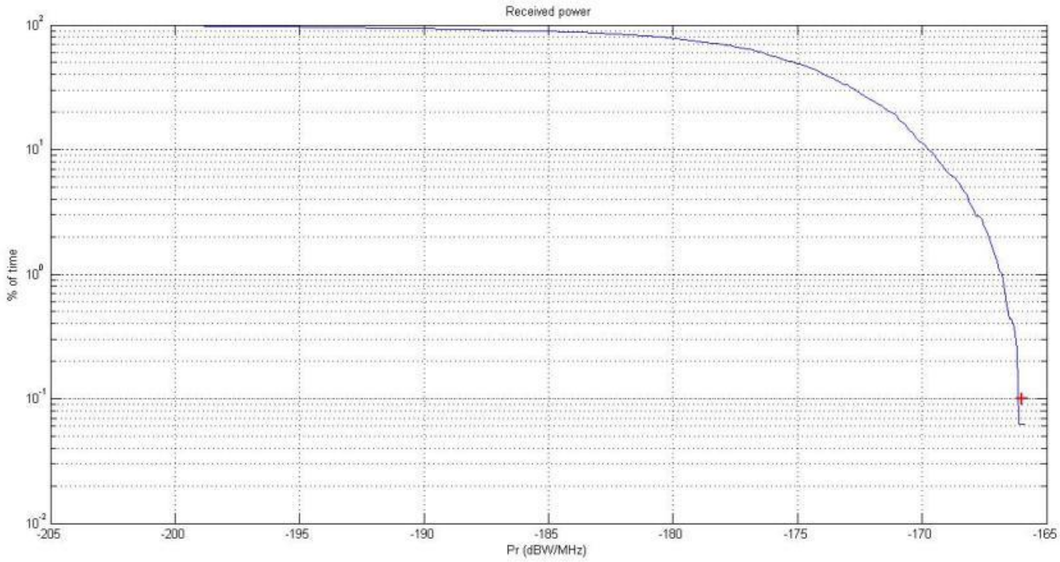
A-6.3.1 Results for low data rate outside and high data rate outside wireless avionics intra-communication systems

The worst-case interference impact arises from WAIC systems located outside the aircraft structure, since their transmit signals are not attenuated through the fuselage or other parts of the aircraft. This study therefore concentrate on high data rate outside and low data rate outside WAIC systems which utilize directional antennas, as described in Annex 1 § A-1.4, in order to reduce the WAIC emissions radiated towards the sky. Figure A-6.5 gives the complementary cumulative distribution function of interference assuming that low data rate outside and high data rate WAIC systems meet the e.i.r.p. mask specified in Fig. A-1.2.

The Figure shows that the protection criterion for EESS (passive) is met.

FIGURE A-6.5

Interference complementary cumulative distribution function for low data rate outside and high data rate outside wireless avionics intra-communication category assuming the e.i.r.p mask in Fig. A-1.2



A-6.4 Conclusions for earth exploration satellite service (passive)

WAIC systems internal to the aircraft (high data rate and low data rate inside) can be introduced in the frequency band while still allowing EESS (passive) sensors authorized in Radio Regulations footnote No. **5.438** on a secondary basis to continue operating in the frequency band 4 200-4 400 MHz.

With regard to WAIC systems outside to the aircraft (high data rate and low data rate outside), the use of the directional antenna concept introduced in Annex 1 § A-1.4 of this Report will also permit EESS (passive) sensors to continue operation in the frequency band 4 200-4 400 MHz.

It should be noted that to date, the frequency band 4 200-4 400 MHz has never been used by any of these EESS (passive) sensors and that no characteristic are available in Recommendation ITU-R RS.1861 for this frequency band.