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Radar Altimeter Interference Contextualization

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16. Abstract

This document presents a comprehensive assessment of the compatibility between 5G systems operating in the 3700–4200 MHz band and radio altimeters (RAs) operating in the adjacent 4200–4400 MHz band. The report includes background information and describes relevant 5G emitter and RA parameters necessary to determine compatibility in the context of a limiting close encounter scenario.

This report evaluates interference mechanisms arising from both fundamental and unwanted emissions of 5G base stations and user equipment. The worst-case close encounter scenario is proposed to reflect aviation safety requirements, including minimal spatial separation, maximum transmitter power, and adverse operational conditions. Analysis of this scenario demonstrates that existing and proposed regulations limiting in-band (fundamental) 5G emissions to 65 dBm/MHz Effective Isotropic Radiated Power (EIRP) are compatible with proposed Radio Frequency Interference (RFI) tolerance requirements for future Radar Altimeter (RA) systems expressed as an interference tolerance mask (ITM). However, unwanted emissions from 5G base stations potentially pose a risk to RA performance. Results indicate that existing and proposed regulations limiting 5G conducted unwanted emissions to -13 dBm/MHz can lead to radiated emissions that exceed the exposure limit defined by the ITM. However, maximum radiated unwanted emissions limited to -30 dBm/MHz EIRP are found to be compatible with the proposed ITM.

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Acronyms

Acronym	Definition
5G	Fifth generation technology standard for broadband cellular networks
AAS	Active Antenna System
AD	Airworthiness Directive
AGL	Above Ground Level
ASM	Aviation Safety Margin
AVSI	Aerospace Vehicle Systems Institute
BS	Base Station
BW	Bandwidth
CFR	Code of Federal Regulations
dB, dBi, dBm	Decibels, Decibel-isotropic, Decibel-milliwatt
DPD	Digital Predistortion
ECC	Electronic Communications Committee of the European Conference of Postal and Telecommunications Administrations (CEPT)
EIRP	Effective Isotropic Radiated Power
EUROCAE	Formerly known as The European Organization for Civil Aviation Equipment
FAA	U.S. Federal Aviation Administration
FCC	U.S. Federal Communications Commission
FDD	Frequency Division Duplex
FDR	Frequency-Dependent Rejection
FMCW	Frequency Modulated Continuous-Wave
FSPL	Free Space Path Loss
GDV	Group Delay Variation
GHz	Gigahertz (10^9 Hertz)
HAGL	Height Above Ground Level
ICAO	International Civil Aviation Organization
IF	Intermediate Frequency
IMT	International Mobile Telecommunications
ITM	Interference Tolerance Mask
ITU/ITU-R	International Telecommunications Union/ITU-Radiocommunications
LNA	Low Noise Amplifier
MFCN	Mobile/Fixed Communications Networks

MIMO	Multiple Input Multiple Output
MOPS	Minimum Operational Performance Standard
MPS	Minimum Performance Specification
MHz	Megahertz (10^6 Hz)
MSD	Minimum Separation Distance
NPRM	Notice of Proposed Rulemaking
OCS	Obstacle Clearance Surface
OFDM	Orthogonal Frequency-Division Multiplexing
OOB	Out-of-Band
PA	Power Amplifier
PANS OPS	Procedures for Air Navigation Services – Aircraft OPerationS
PFD	Power Flux Density or Power Flux Spectral Density
PSD	Power Spectral Density
PUSCH	Physical Uplink Shared Channel
RA	Radar Altimeter; also commonly referred to as Radio Altimeter, Low Range Radar Altimeter (LRRA), RALT, and RADALT
RF	Radio Frequency
RFI	RF Interference
RMS	Root Mean Square
ROC	Required Obstacle Clearance
RR	Radio Regulations (ITU-R)
RTCA	RTCA, Inc. (formerly Radio Technical Commission for Aeronautics)
Rx	Receive or Receiver
SPR	Source-Path-Receiver
TDD	Time Division Duplex
TERPS	Terminal Instrument Procedures
TRP	Total Radiated Power
TSO	Technical Standard Order
Tx	Transmit or Transmitter
UC/UC<n>	Usage Category / Usage Category 1, 2, or 3
UE	User Equipment
WBB LMP	Low/Medium Power Wireless Broadband networks
WRC	World Radiocommunication Conference (ITU-R)

Executive summary

This report is intended to contextualize new radio frequency interference (RFI) tolerance requirements being developed for future radio altimeters (RAs) considering changes to the electromagnetic spectrum in frequency bands adjacent to the 4200–4400 MHz band used by RAs. Worldwide allocations of C-band frequencies in the range 3700–4200 MHz for use by International Mobile Telecommunications (IMT) systems created a potential risk of harmful interference to currently installed RA models. The aviation community responded by initiating development of new regulations and standards that define RFI tolerance requirements for future equipment and developing interim solutions to enable compatibility with new flexible-use licenses granted in the 3700–3980 MHz frequency band (Lower C-band) in the United States. Contextualization includes descriptions of the susceptibility of RAs to interference leading to these new requirements, the sources of interference, and the encounter scenarios that drive the safety case for determining compatibility between RAs and specific external sources of RFI.

The latest generation of IMT systems (5G) are highly complex, with dynamic time-frequency channel allocations, power control, and massive multiple-input multiple-output beam-steering active antenna systems. RAs are highly sensitive radars that are optimized to provide accurate and timely height information over the range of flight dynamics, terrain below the aircraft, and weather conditions encountered in flight. The radio frequency (RF) interaction between these systems in an encounter scenario bringing an aircraft into proximity with a 5G emitter is thus highly complex and dynamic. As the only sensor on board an aircraft that provides height above terrain and obstacles information, RAs improve pilot situational awareness and are integrated with on-board safety systems and controls that are critical to the safety of the flight. The safety case for RA fault tolerance is commensurately stringent, leading to the adoption in this report of a worst-case approach based on regulated limits of interaction parameter values to bound the conditions that prevent harmful interference to RAs from 5G systems, rather than a probabilistic analysis based on stochastic models of the interaction parameters leading to estimate the probability of harmful interference.

This report does not provide detailed descriptions of the design and performance of 5G and RA systems. Instead, it seeks to provide enough background information to identify the salient interaction parameters and describe their limits. In the context of a source-path-receiver interference model, this report first describes the elements of 5G base stations that produce both intentional and unintentional signals that can propagate to the input of an RA receiving antenna. Detailed characterization of the generation and propagation of unintentional signals from 5G

base stations that fall in the RA band between 4200–4400 MHz is shown to be of particular concern given that telecom industry understanding of these details is incomplete.

While RAs have contributed to the success of on-board safety systems for decades, existing RA models were largely designed when the RF environment in adjacent frequency bands consisted of low-power satellite services and RA minimum performance standards did not include explicit interference tolerance requirements. This report discusses the development of tolerance requirements leading to an interference tolerance mask (ITM) proposed by the FAA for future RAs, which represents a significant improvement in interference tolerance of RA systems over the typical tolerance prior to 2022. This report also describes limitations to increasing tolerance, while maintaining the RA's intended function and performance requirements, that is achievable with current technology, noting that there is a fundamental tradeoff between system accuracy and the amount of out-of-band rejection implemented in the RA system.

This report describes key elements of interaction scenarios and relates these to regulated parameters to show that the limiting case for a compatibility analysis consistent with aviation safety is a close-encounter scenario that places the RA receiving antenna 35 ft from a 5G emitter. This removes dynamical considerations from the analysis to find that a regulated bounding value of 65 dBm/MHz EIRP for the fundamental 5G emissions in the frequency band 3700–4160 MHz is compatible with the proposed ITM in the context of the close-encounter scenario described herein. The report further finds that for unwanted emissions falling in the frequency band 4200–4400 MHz, the maximum conducted level of -13 dBm/MHz for flexible-use services operating in the frequency band 3700-4160 MHz is not compatible with the proposed ITM in the context of the close-encounter scenario. However, limiting unwanted emissions falling in the 4200–4400 MHz RA band to a maximum of -30 dBm/MHz EIRP ensures compatibility with the proposed ITM in the context of the close-encounter scenario.

1 Introduction

Changes in the use of electromagnetic spectrum in frequency bands near the 4200–4400 MHz frequency band used by radio altimeters (RAs) have raised concern that new broadly deployed, high-power services operating in adjacent bands might cause harmful interference to RAs. Following rulemaking activity in 2020 that included commentary from communications and aviation industry stakeholders,[1] the United States Federal Communications Commission (FCC) issued a Report and Order that allocated the frequency band 3700–3980 MHz (Lower C-band) for flexible use, including technical rules that allowed up to 65 dBm/MHz equivalent isotropic radiated power (EIRP) for fundamental emissions and up to -13 dBm/MHz conducted unwanted emissions (Federal Communications Commission, 2020). This led to the United States Federal Aviation Administration (FAA) to issue Notices to Airmen (NOTAMs) at airports supporting CAT II/III instrument approach procedures (IAPs) concerning unreliable RA operation putting such flight operations at unacceptably high risk of potentially catastrophic failure. These were followed by new Airworthiness Directives (ADs) for fixed-wing and rotorcraft that mandated improved radio frequency interference (RFI) tolerance over that of existing deployed RAs for certain aviation operations (Federal Aviation Administration, 2023a) (Federal Aviation Administration, 2023b). The combination of the aviation industry's rapid response with solutions for improving the RFI tolerance of existing RA models, and the wireless industry's voluntary agreements with the FAA to limit conducted unwanted emissions to -48 dBm/MHz and to limit emissions for elevation angles above horizontal (AT&T Services, Inc., T-Mobile, UScellular, Verizon, 2023), enabled 5G to be deployed in the contiguous 48 United States in the Lower C-band while managing the risk of harmful interference to RAs.

Subsequent to the FCC rulemaking and wireless industry rollout of 5G in the Lower C-band, the United States Congress passed the One Big Beautiful Bill Act that included a requirement for the FCC to auction at least 100 MHz of C-band spectrum between 3980–4200 MHz (Upper C-band) for full-power commercial licensed use cases (One Big Beautiful Bill Act, 2025). This was signed into law in July 2025 and set a deadline to complete the auction by July 2027. The FCC responded by issuing a Notice of Inquiry (NoI) seeking input from stakeholders on how to repurpose the Upper C-band while protecting RAs (Federal Communications Commission, 2025). This was followed by the FCC issuing a Notice of Proposed Rulemaking (NPRM) (Federal Communications Commission, 2025) that sought input on the proposed changes to the Upper C-band.

[1] See for example, FCC GN Docket No. 18-122 (Federal Communications Commission (FCC), 2018).

The FAA issued a separate but related NPRM (Federal Aviation Administration, 2026) seeking input on proposed rules mandating improvements to RA RFI tolerance necessary to maintain aviation safety given the changes to the adjacent spectrum mandated by the new law. The NPRM proposes an ITM that represents a significant improvement over the tolerance exhibited by current RAs, even after improvements required for compliance with the 2023 FAA Airworthiness Directives issued in response to the new flexible-use services in the Lower C-band. It specifies the level of RFI in the frequency band 3000–5600 MHz that RA systems must be able to tolerate while meeting all other performance requirements, expressed in terms of a power flux spectral density (PFD) in dBW/m^2/MHz referenced to the input to the RA system's receiving (Rx) antenna mounted on the fuselage of the aircraft. In other words, the NPRM specifies the level of RFI in which the RA system must be able to operate with no impact to safety.

The ITM is a characteristic of RA equipment, i.e., it is an equipment requirement for which compliance with regulation must be demonstrated to gain or maintain the certification basis of the equipment. As such, the specific interference tolerance of RA systems is the concern of the RA equipment manufacturers that design the equipment, who must demonstrate compliance with regulation to obtain a Technical Standard Order (TSO) that authorizes the manufacture of compliant equipment. The interference tolerance of the installed RA system is also the concern of aircraft manufacturers that must install RA systems on aircraft, integrate them with other aircraft systems, and certify the integrated aircraft by demonstrating that the equipment and systems perform as intended under the aircraft's operating and environmental conditions (Equipment, systems, and installations, 2024).

RFI is a component of environmental conditions and can be radiated by both intentional and unintentional emitters. In the case of intentional emitters, compatibility between two RF systems is established by regulating the use of the electromagnetic spectrum nationally by spectrum regulation administrations and internationally by the International Telecommunications Union – Radiocommunications (ITU-R). To gain license to use a given frequency band, new RF systems must typically demonstrate that the technical conditions proposed for the new system (e.g., the radiated power and necessary bandwidth) will not cause harmful interference to both incumbent systems that already use the same frequency band and existing systems that operate in adjacent frequency bands. Compatibility studies are performed to estimate the potential for interference using established/accepted system parameters, established protection criteria for the existing systems, and the scenarios that reflect the conditions in which the systems can interact. These scenarios define the coupling between the RF systems that must be managed by regulation.

This report is intended to describe the 5G and RA system equipment parameters and interaction scenarios that are necessary to determine compatibility between these systems given the proposed changes to the Upper C-band. In this case, the scenarios that must be considered are those that are governed by rules concerning aviation safety, as established over decades of improvement that has led to the establishment of aviation as the safest mode of motorized passenger transportation (National Safety Council, 2026).

2 Compatibility studies

Chapter 1 of International Civil Aviation Organization (ICAO) Doc. 9718 Volume 2 (ICAO, 2022) lays out a general methodology for performing studies of compatibility with aviation radio services that is based on various guidance documents published by the ITU-R. Services are compatible if the normal operation of one service does not cause harmful interference in the other service. Both "interference" and "harmful interference" are defined in the ITU-R Radio Regulations (RR) (International Telecommunication Union, 2024, pp. RR1-16):

> 1.166 *interference*: The effect of unwanted energy due to one or a combination of *emissions*, *radiations*, or inductions upon reception in a *radiocommunication* system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy.
>
> 1.169 *harmful interference*: *Interference* which endangers the functioning of a *radionavigation service* or of other *safety services* or seriously degrades, obstructs, or repeatedly interrupts a *radiocommunication service* operating in accordance with Radio Regulations (CS).

Interference can come from signals that intentionally operate in a shared frequency band, or from signals that operate in adjacent frequency bands. In the latter case, the RR define unwanted emissions to characterize the leakage of energy outside of a service's assigned frequency band:

> 1.144 *out-of-band emission*: Emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process but excluding spurious emissions.
>
> 1.145 *spurious emission*: Emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions.

1.146 *unwanted emissions*: Consist of spurious emissions and out-of-band emissions.

1.146A *out-of-band domain* (of an emission): The frequency range, immediately outside the *necessary bandwidth* but excluding the *spurious domain*, in which *out-of-band emissions* generally predominate. *Out-of-band emissions*, defined based on their source, occur in the out-of-band domain and, to a lesser extent, in the *spurious domain*. *Spurious emissions* likewise may occur in the out-of-band domain as well as in the *spurious domain*. (WRC-03)

1.146B *spurious domain* (of an emission): The frequency range beyond the out-of-band domain in which spurious emissions generally predominate. (WRC-03)

Both types of unwanted emissions are referenced to the edge of the fundamental emission's assigned band in terms of the necessary bandwidth, which is defined by RR 1.152:

1.152 *necessary bandwidth*: For a given *class of emission*, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions.

These are shown schematically in Figure 9 of ICAO (2018), reproduced in Figure 1 below.

Compatibility is generally described in terms of a source-path-receiver (SPR) model that incorporates the essential elements necessary to determine how much interference energy emitted from one service is received by another. This includes:

- **Source of emissions**: the source of interfering emissions that are transmitted to the receiver (victim). The important parameters of the transmitter include the amount of power radiated by the transmitting antenna (Tx), the gain pattern or directivity of the antenna, the center frequency and bandwidth of the emissions, and the power and frequency dependence of unwanted emissions radiated in the direction of the receiving antenna (Rx), and polarization.
- **Transmission path**: the path that energy takes from the source Tx antenna to the victim Rx antenna. This can be complex for certain scenarios, including effects of transmission through a lossy medium such as fading, clutter, and multipath. Standard propagation models are provided in ITU-R documents such as Recommendation ITU-R P.528-5 (ITU-R, 2021). However, the shortest line-of-sight path, or free-space path loss (FSPL) is often considered as a simplifying assumption for compatibility studies involving smaller separation distances, which only consider the effects of the RF energy at a given frequency spreading out as it propagates.

- **Receiver**: The receiver subject to RF interference (victim) is characterized by parameters that affect its ability to detect and process desired signals in the presence of external interference and noise. These include the Rx antenna gain, polarization, installation losses (such as cable losses), filtering, noise figure, and processing gain.

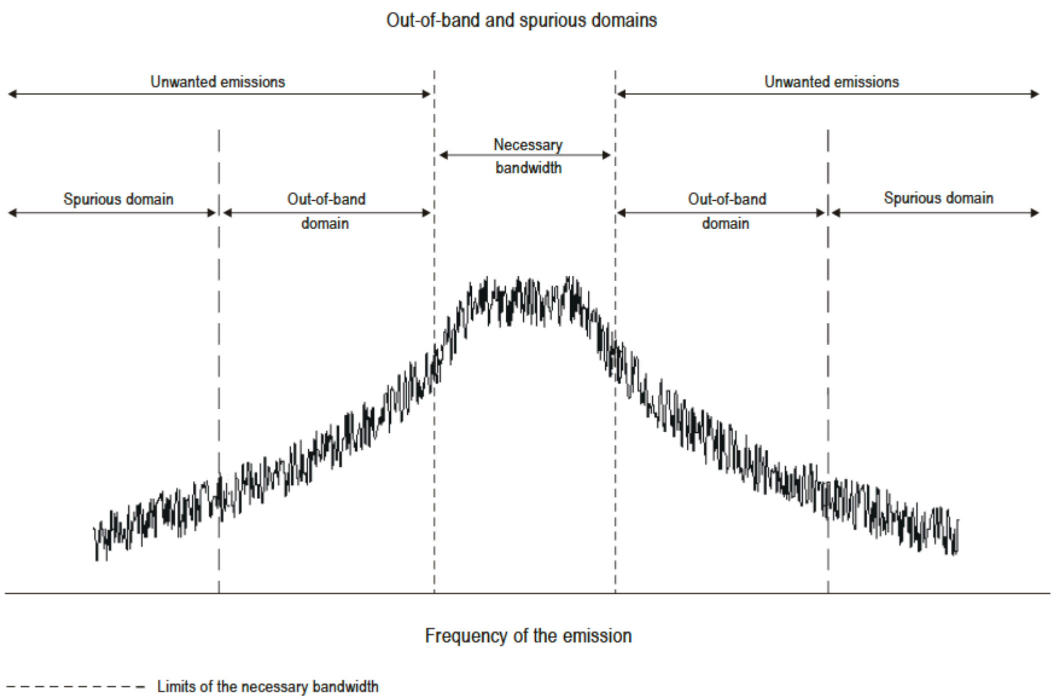


Figure 1. Illustration of unwanted emissions

Figure 2 illustrates the basic components of the SPR model for the case of an aircraft in proximity to a cell phone tower emitting RF energy. The figure shows the relationship between the transmission, propagation, and receiving parameters. Considering free-space transmission of the RF energy, the SPR model parameters are related according to the Friis transmission equation for the power received by a receiving antenna:

$$P_R = \frac{P_T \, G_T \, G_R \, c^2}{(4\pi R f)^2} \qquad 1$$

where

- P_T is the power transmitted from a given emitter antenna in W,
- P_R is the interference power received by the receiving antenna in W,
- $G_{R,T}$ are the receive/transmit (Rx/Tx) antenna frequency-dependent gains along the line connecting their phase centers,

- c is the speed of light in m/s,
- R is the distance (range) between the Tx and Rx antennas in m, and
- f is the frequency of the transmission in Hz.

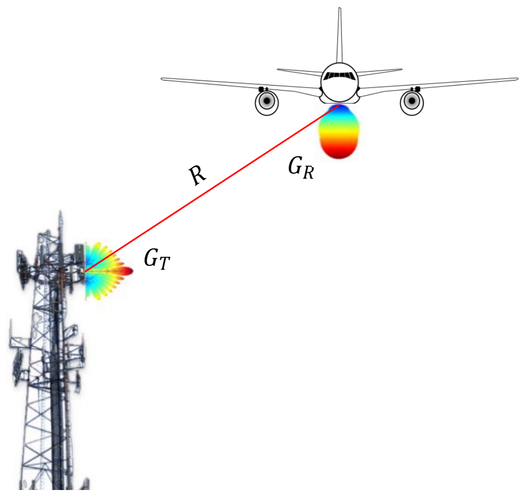


Figure 2. SPR model for an aircraft in proximity to a source of RF emissions

This is often expressed as either a power spectral density (PSD) for transmit/receive powers (P_T, P_R) in W/MHz or a power flux density (PFD) in W/m^2/MHz. To obtain a received power PFD value, the received power or PSD is divided by the effective aperture (A_e) of the receive antenna:

$$A_e = \frac{\lambda^2}{4\pi} G_R = \frac{c^2}{4\pi f^2} G_R \quad 2$$

and given that $P_T\, G_T$ is the EIRP from the transmitter, Equation 1 can be written

$$P_R = \frac{P_{T,EIRP}}{(4\pi R^2)} A_e \quad 3$$

$$\frac{P_R}{A_e} = P_{R,PFD} = \frac{P_{T,EIRP}}{4\pi R^2} \quad 4$$

or in decibels

$$P_{R,PFD,dB} = P_{T,EIRP,dBW} - 10 \log_{10} 4\pi - 20 \log_{10} R \quad 5$$

The characteristics of the source of RF emissions are contained in the $P_{T,EIRP,dBW}$ term, including the directivity of the emissions due to the antenna gain pattern. Often, emissions are specified in units referenced to milliwatts rather than Watts. This requires subtracting 30 dB from the right side of Equation 5 to convert dBm to dBW.

Note that many compatibility analyses compute a power or PSD referenced to the input of the receiver rather than the PFD at the antenna aperture. However, given the range of RA designs, installation conditions, and encounter geometries, using the PFD of the interfering signal at the RA Rx antenna input allows decoupling of the transmitter and receiver design details and enables use of a system-level protection criterion for RAs defined by an ITM referenced to the RA Rx input, which is described in section 4.5. The ITM incorporates RA system considerations such as antenna gain and frequency selectivity, installation losses, and RA receiver parameters.

Intuitively, the duration of an exposure to RFI above the tolerance limit should have some effect on the ability of the RA system to operate properly before, during, and after the exposure. For example, one would expect that a one picosecond pulse above the ITM level could potentially have a different effect than a one second exposure. The dynamics of an interference encounter include both the time dependence of the source transmissions, the received signal processing in the RA transceiver, and the aircraft dynamics. Time dependence would thus involve such parameters as aircraft dynamics, including

- aircraft ground speed,
- changes in aircraft trajectory and attitude (pitch and roll),
- changes in height above ground level (HAGL) and obstacles.

Time-dependent source transmission parameters would include

- Time Division Duplex (TDD) uplink/downlink scheduling,
- network load factor,
- Active Antenna Systems (AAS) beam steering based on number of concurrent user equipment (UE) devices serviced per sector and relative motion between the base station and the UEs.

Time-dependent design features of the RA receiver would include

- chirp rate for frequency modulated continuous wave (FMCW) RAs,
- baseband sampling frequency,
- output time constant (filtering),
- time to detect operating conditions that prevent computation of a valid HAGL,

- maximum allowable time to reacquire a valid signal when operating conditions return to acceptable limits,
- coasting time allowed by system integration considerations.

The methodology in Recommendation ITU-R M.2101 "Modelling and simulation of IMT networks and systems for use in sharing and compatibility studies" (ITU-R, 2017) is based on Monte Carlo analysis that considers 5G source dynamics. However, note that Equation 5 is time independent (ignoring the implied RMS averaging of the signals during the source transmission period). This basic model is used to determine the worst-case exposure to interference, not typical or average over a time period that is much greater than the duration of the encounter between the source and receiver. Given potential for impacting flight safety, compatibility is achieved by preventing unwanted RF energy from causing harmful interference to RA systems by defining an ITM that sets an absolute maximum exposure that RA systems must tolerate to be compatible with known RF emission environments.

The time dependence of RA receiver parameters and aircraft dynamics are not considered in the analysis of compatible levels of RFI. These effects are already incorporated in the determination of the RA system-level ITM, since the ITM defines the maximum RFI level that an RA can tolerate while still meeting performance requirements in all operating conditions.

3 Source: C-band mobile telecommunications emissions

The introduction of International Mobile Telecommunications (IMT) in the Lower C-band in the United States stimulated investigations into possible interference to RAs. This included testing and analysis based on publicly available information characterizing the wanted and unwanted emissions from commercial IMT systems operating in this band. This section considers the emission parameters that impact compatibility with RA systems installed on aircraft.

IMT models suitable for ITU-R compatibility studies are provided in ITU-R recommendations such as "Modelling and simulation of IMT networks and systems for use in sharing and compatibility studies" (ITU-R, 2017). This document describes a Monte Carlo-based "methodology for modelling and simulation of IMT networks for use in sharing and compatibility studies between IMT and other systems and/or applications" (ITU-R, 2017, p. 1) and includes a model for computing the gain of AAS active array antennas. References therein, additional supporting ITU-R documents, and industry standards provide additional guidelines.

Recommended IMT characteristics were updated for compatibility studies leading to World Radio Conference 2023 (WRC-23) that included study of the frequency band 3600–3800 MHz.

The June 2021 Working Party 5D Chairman's Report (ITU-R, 2021) provided updated tables of IMT parameters for rural, urban/suburban macro, urban small cell (outdoor)/micro cell, and indoor (small cell) deployments, including an extension of the AAS model in Recommendation ITU-R M.2101-0 (ITU-R, 2021, p. 28).

3.1 Base station considerations

IMT networks interface with user equipment like cell phones through Radio Access Networks (RANs) that control the communication protocols and over-the-air RF emissions. Rizk, et al. (2025) provide a simplified block diagram identifying the components that can contribute to RFI that is reproduced in Figure 3.

The primary components affecting compatibility are the digital predistortion (DPD) block, the output cavity filter, the power amplifier (PA), and the AAS antenna. Note that these architectural elements are standardized, but typically not regulated. That is, the specific components are chosen for interoperability and optimized service to UEs, not for compatibility with other services, which is generally regulated in terms of power limits for fundamental and unwanted emissions and installation considerations.

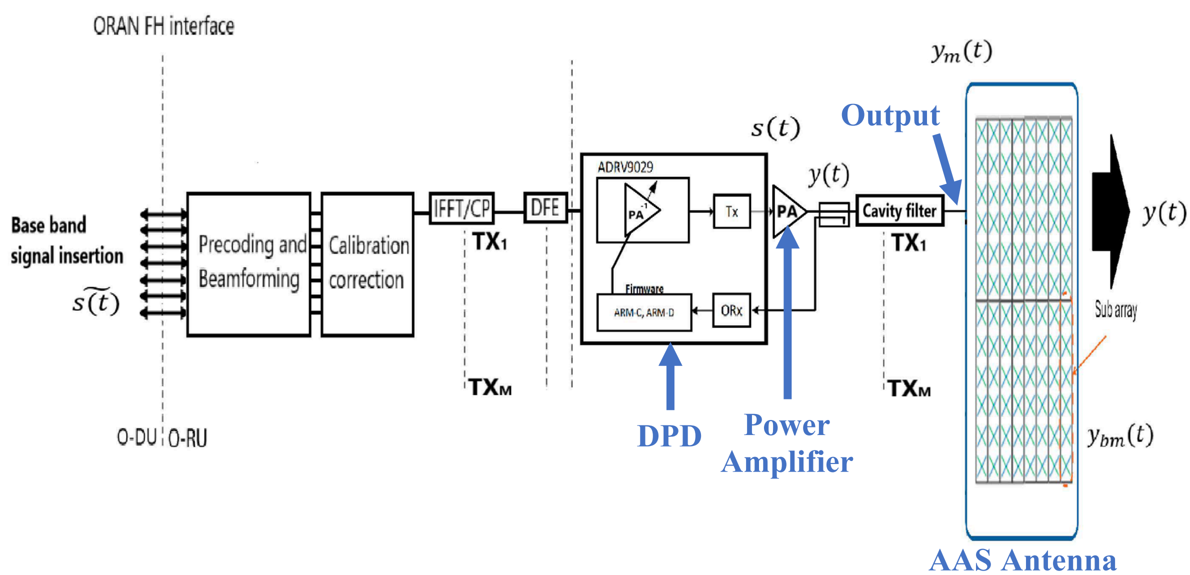


Figure 3. 5G base station elements

3.1.1 Digital predistortion

The modulated 5G carrier signal is typically an Orthogonal Frequency Division Multiplexing (OFDM) employing some coding such as binary or quadrature phase-shift keying on multiple subcarriers within an assigned frequency block. These modulation schemes can have a relatively high peak-to-average power ratio that requires a PA to have a significant amount of head room to avoid saturating the PA output, which can be energy inefficient. DPD is a technique that has been employed to allow base stations to operate more efficiently by compensating for the distortion in the output signal created by the nonlinearity of an amplifier in compression. This can significantly reduce spurious signals such as harmonics and intermodulation products caused by second- and third-order nonlinearities in the PA.

3.1.2 Output cavity filter

A cavity filter is typically used to suppress unwanted emissions to levels below the regulated limit. Such filters provide significant attenuation for out-of-band emissions, but it is important to fully characterize their performance for spurious signals that might fall in adjacent bands, since unwanted emissions are often regulated for conducted levels at the filter output for frequencies beyond the edge of the assigned band.[2]

3.1.3 Power amplifier

The power amplifier is intended to drive the radiating elements of the output antenna with an amplified but otherwise identical signal as provided at the input. As stated in section 3.1.1, the PA is often configured such that it operates in saturation, which must be compensated using DPD to prevent spectral regrowth and spurious signals.

To understand effects of saturation of the PA and the nonlinearity due to signal compression, the PA can be represented using a third-order non-linear model (Hemmi, 2002):

$$v_0 = k_1 v_i + k_2 v_i^2 + k_3 v_i^3 \qquad 6$$

where the input signal v_i is comprised of two tones with differing phased array weighting

$$v_i = A_n \cos(\omega_1 t - n\Delta\phi) + A_n \cos(\omega_2 t - n\Delta\psi) \qquad 7$$

[2] See for example Federal Communications Commission, 2020 at para. 343, which states “Specifically, base stations will be required to suppress their emissions beyond the edge of their authorization to a conducted power level of -13 dBm/MHz.” (Federal Communications Commission, 2020)

This results in an expression for the output signal that identifies the second- and third-order nonlinear components:

$$
\begin{aligned}
v_o = {} & k_2 A_n^2 \\
& + k_2 A_n^2 \cos[(\omega_1 - \omega_2)t - n(\Delta\phi - \Delta\psi)] \\
& + \left(k_1 A_n + \frac{9}{4} k_3 A_n^3\right) \cos(\omega_1 t - n\Delta\phi) \\
& + \left(k_1 A_n + \frac{9}{4} k_3 A_n^3\right) \cos(\omega_2 t - n\Delta\psi) \\
& + \frac{3}{4} k_3 A_n^3 \cos[(2\omega_1 - \omega_2)t - n(2\Delta\phi - \Delta\psi)] \\
& + \frac{3}{4} k_3 A_n^3 \cos[(2\omega_2 - \omega_1)t - n(2\Delta\psi - \Delta\phi)] \\
& + k_2 A_n^2 \cos[(\omega_1 + \omega_2)t - n(\Delta\phi + \Delta\psi)] \\
& + \frac{1}{2} k_2 A_n^2 \cos[2\omega_1 t - 2n\Delta\phi] \\
& + \frac{1}{2} k_2 A_n^2 \cos[2\omega_2 t - 2n\Delta\psi] \\
& + \frac{3}{4} k_3 A_n^3 \cos[(2\omega_1 + \omega_2)t - n(2\Delta\phi + \Delta\psi)] \\
& + \frac{3}{4} k_3 A_n^3 \cos[(2\omega_2 + \omega_1)t - n(2\Delta\psi + \Delta\phi)] \\
& + \frac{1}{4} k_3 A_n^3 \cos[3\omega_1 t - 3n\Delta\phi] \\
& + \frac{1}{4} k_3 A_n^3 \cos[3\omega_2 t - 3n\Delta\psi]
\end{aligned} \tag{8}
$$

The frequencies of the components of the output signal will fall both within the assigned 5G band and outside the assigned frequency band. Considering a 100 MHz OFDM 5G signal centered at 4110 MHz and subcarriers at either end of the assigned band, mixing these two tones would produce the frequencies listed in Table 1. Note that only the third-order difference $2f_2 - f_1$ would produce a signal that would fall within the RA band. As an approximation, an amplifier operating at its 1-dB compression point will typically have second- and third-order intermodulation outputs at 18 to 20 dB below the fundamental. The commercial cavity filter considered in Rizk, et al. shows an attenuation of about 46 dB at 100 MHz above the band edge, as shown in Figure 4 (Rizk, et al., 2025, p. Fig. 1). This indicates that, for a 65 dBm/MHz EIRP fundamental signal without compensation such as crest factor reduction and DPD, the third-order signal reaching the RA band could be as high as

$$
65\ \text{dBm/MHz} - 18\ \text{dB} - 46\ \text{dB} = 1\ \text{dBm/MHz} \tag{9}
$$

Clearly this is above the Lower C-band regulated limit of -13 dBm/MHz. However, it illustrates the effect of PA nonlinearity on compatibility and the need for techniques such as DPD.

Table 1. Two-tone third-order nonlinearities

Description	**Frequency**	**Frequency Value (MHz)**
Fundamental #1 (also 2nd and 3rd harmonics)	f_1 $(2f_1, 3f_1)$	4060 (8120, 12180)
Fundamental #2 (also 2nd and 3rd harmonics)	f_2 $(2f_2, 3f_2)$	4160 (8320, 12480)
Third-Order Difference	$2f_1 - f_2$ $2f_2 - f_1$	3960 4260
Difference	$\|f_1 - f_2\|$	100
Sum	$f_1 + f_2$	8220
Third-Order Sum	$2f_1 + f_2$ $2f_2 + f_1$	12280 12380

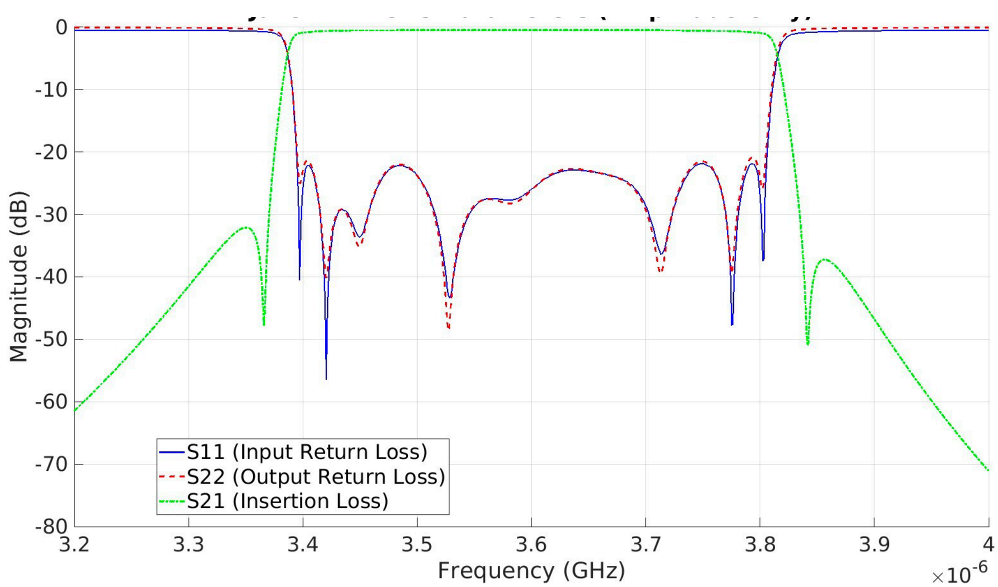


Figure 4. Commercial cavity filter S-parameters

3.1.4 Antennas

While 5G networks can be implemented using legacy sectoral antennas, C-band networks are expected to largely be deployed using AAS antenna technology to exploit the high gain, beam forming, and massive Multiple Input Multiple Output (MIMO) capability they possess. IMT antennas are considered in more detail in section 3.3.

3.1.5 Base station parameters for compatibility studies

The characteristics of IMT base stations (BSs) that are recommended for compatibility studies within the ITU-R are summarized in Appendix A for non-AAS (Table A- 1) and AAS (Table A-2) base station implementations.

As an aviation safety service, compatibility conditions for RAs are determined by considering the worst-case exposure to RFI that an RA can experience anywhere in the aircraft's operational envelope. As a result, many of the deployment parameters in Table A- 1 and Table A- 2 are not considered in determining C-band 5G – RA compatibility conditions. Note also that the values in Table A- 1 and Table A- 2 are based on industry standards for use in compatibility studies; they are not necessarily regulated values. For example, Table A- 1 specifies antenna height, but the FCC Lower C-band Report and Order ("R&O") does not restrict antenna heights beyond current aviation obstacle restrictions (Federal Communications Commission, 2020, p. para 351). Aviation safety analyses must necessarily consider limits established by either physical limitations or regulation, not typical values.

The FCC Lower C-band R&O regulates flexible use services operating in the 3700–3980 MHz frequency band in the contiguous United States to the values listed in Table 2 (Federal Communications Commission, 2020).

Table 2. Lower C-Band technical rules in the United States

	Non-rural	**Rural areas**	**User Equipment**
Fundamental Emissions Power Levels EIRP (Note 1)	1640 W/MHz (62 dBm/MHz)	3280 W/MHz (65 dBm/MHz)	1 Watt (30 dBm)
Out-of-band Emissions (Note 2)	-13 dBm/MHz (1)	-13 dBm/MHz (1)	-13 dBm/MHz (1)
Antenna Height Limits (Note 3)	not restricted	not restricted	N/A

Notes:

1. Power limits apply to the aggregate power of all antenna elements in any given sector of a base station.
2. Conducted power level beyond the edge of their authorized frequency band.
3. Beyond any requirements necessary to ensure physical obstructions do not impact air navigation safety.

In addition to the flexible use already authorized for the 3700–3980 MHz, similar frequency bands near the RA band are authorized for use by IMT in other countries. For example, the frequency band 3400–3800 MHz is authorized for mobile/fixed communication networks (MFCN) in Europe with no specific maximum EIRP power levels for fundamental emissions

(ECC, 2018). Canada authorizes the use of 3450–3900 MHz for flexible use subject to EIRP limits of 61 dBm/MHz for signals with a channel bandwidth less than 5 MHz and 68 dBm/5 MHz for broader channels, with reductions based on height above average terrain exceeding 305m.

As mentioned above, the 3980–4200 MHz band adjacent to the RA band (Upper C-band) is being considered for flexible use in the contiguous United States with a preference to harmonize technical conditions for flexible use across the Lower and Upper C-band. In Europe, the 3800–4200 MHz band is currently authorized by ECC Decision (24)01 (ECC, 2024) for shared access by low/medium power terrestrial wireless broadband systems (WBB LMP) providing local-area network connectivity. Table 3 and Table 4 reproduce the power limits specified in the Decision for fundamental and unwanted emissions.

Table 3. Recommended EIRP limits for WBB LMP operating in 3800–4200 MHz in Europe

Category	**EIRP per cell (Note 1 and Note 2)**
Low power base station	≤ 24 dBm/channel for BW ≤ 20 MHz ≤ 18 dBm/5 MHz for BW > 20 MHz
Medium power base station	≤ 44 dBm/channel for BW ≤ 20 MHz ≤ 38 dBm/5MHz for BW > 20 MHz
Note 1: In a multi-sector site, the value per 'cell' corresponds to the value for one of the sectors. Note 2: Higher EIRP levels may be authorized by national administrations in exceptional and duly justified cases, provided that protection of FSS receiving earth stations and FS links (where appropriate nationally) in the band as well as MFCN below 3.8 GHz and radio altimeters above 4.2 GHz is ensured, taking into account their future development, including in the neighboring countries. Coverage shall remain local, i.e. no nationwide networks.	

Table 4. Recommended unwanted emission limits above 4200 MHz for WBB LMP in Europe

Frequency range	**Non-AAS base station EIRP limit dBm/5 MHz per cell (Note 1)**	**AAS MP base station TRP limit dBm/5 MHz per cell**
4200-4205 MHz	11	1
4205-4240 MHz	8	-3
Note 1: In a multi-sector site, the value per 'cell' corresponds to the value for one of the sectors.		

3.2 User equipment

User equipment originally referred to mobile handsets, but the definition now encompasses any device capable of terminating the 3GPP radio interface and accessing network services such as Internet of Things (IoT) devices and data modems (hotspots). Table A- 3 in Appendix A reproduces the UE parameters recommended for sharing studies for bands between 3 and 6 GHz.

RTCA Paper No. 274-20/PMC-2073, "Assessment of C-Band Mobile Telecommunications Interference Impact on Low Range Radar Altimeter Operations," found that while UEs on the ground did not cause harmful interference, UEs on board aircraft can cause interference for the ITM levels considered in the report (RTCA, Inc., 2020). [3]

The assessed aggregate interference levels of fundamental emissions with a peak power of 30 dBm EIRP from multiple UEs was compared to interference tolerance thresholds in Table 10-1 of the report (reproduced in Table 5 below). It was noted that "In all cases, the aggregate interference exceeds the Rec. ITU-R M.2059 protection criterion. Further, for Usage Category 2 and Usage Category 3, the computed aggregate interference far exceeds the tolerance thresholds, even before accounting for the safety margin. Unlike the case of 5G UEs operating on the ground, the exceedance of the safe interference limit for Usage Category 2 and Usage Category 3 is significant enough that it is not expected that transmit power control employed by the UEs will be sufficient to prevent harmful interference." (RTCA, Inc., 2020, p. 86) *Usage categories* were defined in this report to group RAs based on both their intended and actual use on different types of aircraft. These were defined as:

- Usage Category 1, covering commercial air transport airplanes, both single-aisle and wide-body;
- Usage Category 2, covering all other fixed-wing aircraft not included in Usage Category 1, including regional, business aviation, and general aviation airplanes; and
- Usage Category 3, covering both transport and general aviation helicopters.

---

[3] The RTCA Report computed ITMs based on empirical measurements of a sample of commercial RA models in service prior to the report's publication. See (RTCA, Inc., 2020) and references therein.

Table 5. RFI from UEs onboard aircraft for 5G fundamental emissions in 3700–3980 MHz

Usage Category	Aggregate UE Interference (dBm/MHz)	RTCA Report Overall ITM Minimum (dBm/MHz)	Rec. ITU-R M.2059 Receiver Overload Protection Criterion (dBm/MHz)
1	-70.8	-56	-73
2	-60.8	-94	
3	-47.8	-94	

Note that the power spectral density (PSD) values in dBm/MHz in Table 5 are referenced to the input port of the RA receiver. To compare this to ITM values at 3980 MHz proposed for future RAs, which are specified in terms of PFD in dBW/m^2/MHz referenced to the input of the RA Rx antenna, the effective aperture, cable loss, and aviation safety margin must be included:

$$ITM_{RA,PSD} = ITM_{Rx,PFD}(f) + 30 + A_{e,dB}(f) - L_c - ASM = 7 \text{ dBm/MHz} \qquad 10$$

where

$f = 3980$ MHz,

$ITM_{Rx,PFD}(f) = 9.5$ dBW/m^2/MHz,

$G_{RA} = 10$ dBi,

$A_{e,dB}(f) = 10 \log_{10}\left(\frac{c^2}{4\pi f^2} G_{RA}\right) = -23.45$ dB,

Cable loss $L_c = 3$ dB, and

$ASM = 6$ dB is the aviation safety margin.

In this case, we assume a tolerance PFD level at 3980 MHz according to that proposed in the FAA NPRM (Federal Aviation Administration, 2026, p. Table 3) as described in section 4.5.2. This illustrates that improvements in the RA rejection of out-of-band emissions specified by an achievable ITM would effectively prevent harmful interference due to fundamental emissions from UEs on board an aircraft.

Note also that including the ASM in Equation 10 reflects that this assumes that the maximum PFD of the interfering signal that an aircraft will experience anywhere in its operational volume is 6 dB below the maximum interference level in which the RA has demonstrated that it can safely operate. Furthermore, this assumes the maximum RA antenna gain to cover all potential interaction scenarios.

Similar analysis for unwanted emissions from UEs on an aircraft uses the values from the RTCA Assessment Report summarized in Table 6. In this case,

$f = 4300$ MHz,

$ITM_{Rx,PFD}(f) = -82$ dBW/m^2/MHz, and $A_{e,dB} = -24.13$ dB yielding

$ITM_{RA,PSD} = -85$ dBm/MHz.

As for the fundamental emissions, the proposed ITM also prevents harmful interference from unwanted emissions from UEs on board an aircraft based on the RTCA assumption of a peak spurious PSD for UEs defined by the 3GPP standard value of -34 dBm/MHz EIRP (RTCA, Inc., 2020, p. 30).

Table 6. RFI from UEs onboard aircraft for 5G unwanted emissions in 4200–4400 MHz

Usage Category	**Aggregate UE Interference (dBm/MHz)**	**RTCA Report Overall ITM Minimum (dBm/MHz)**	**Rec. ITU-R M.2059 Protection Criteria (dBm/MHz)**	
			False Altitudes	**Receiver Desensitization**
1	-114.8	-107	-103	-117
2	-104.8	-119		
3	-91.8	-119		

3.3 International Mobile Telecommunications antennas

IMT networks are implemented using phased-array AAS and non-AAS sectoral antennas. The recommended non-AAS antenna parameters provided in Table A- 1 applied to the pattern described in Recommendation ITU-R F.1336-5 produce the pattern shown in Figure 5 (ITU-R, 2019).

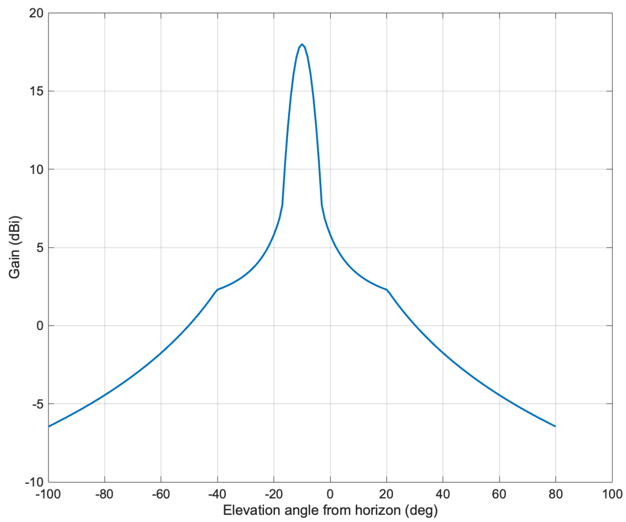


Figure 5. Elevation cut of non-AAS antenna pattern with 10º downtilt

AAS antennas are phased-array antennas that incorporate massive MIMO and beamforming to increase network capacity. The configuration that is recommended for compatibility studies is a 4-row by 8-column array with each element made up of a 3-row by 1-column subarray of ±45º cross-polarized radiating elements. This is shown schematically in Figure 6 along with the pattern computed using the equations in Table 7 for the Extended AAS model and the recommended parameters in Table A- 2 transcribed from the WP5D Chairman's Report (ITU-R, 2021, p. 28).

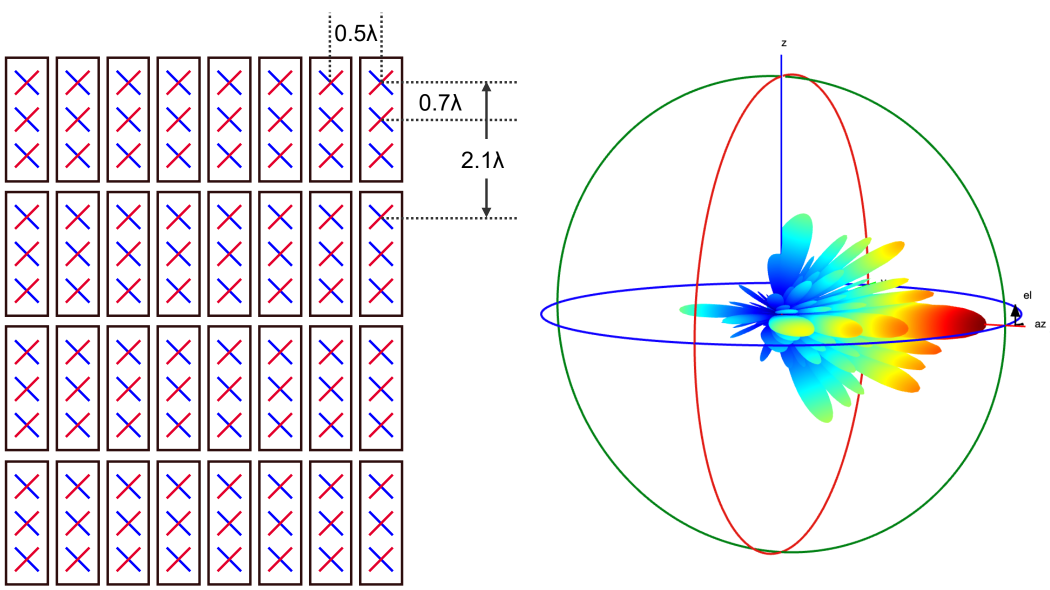
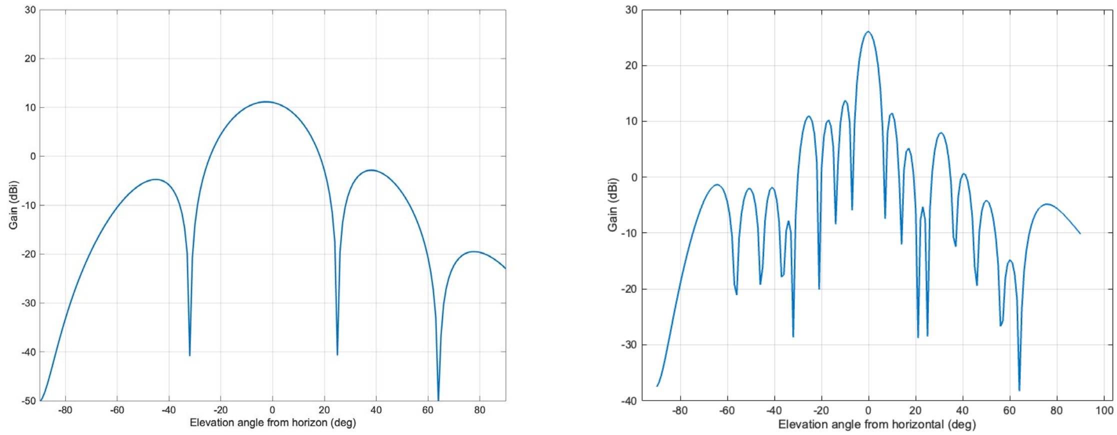


Figure 6. 4 x 8 x 3 AAS antenna and pattern

Table 7. Extended AAS model

Description	Equation
Peak normalized element radiation pattern	$A(\theta,\varphi) = -\min\left[-\left(-min\left[12\left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_m\right] - min\left[12\left(\frac{\theta-90}{\theta_{3dB}}\right)^2, SLA_v\right]\right), A_m\right]$
Peak gain normalized element radiation pattern	$A_E(\theta,\varphi) = G_{E,max} + A(\theta,\varphi)$
Sub-array excitation	$w_m = \frac{1}{\sqrt{M_{sub}}}\exp\left(j2\pi(m-1)\frac{d_{v,sub}}{\lambda}sin(\theta_{subtilt})\right)$
Sub-array radiation pattern	$A_{sub}(\theta,\varphi) = A_E(\theta,\varphi) + 10\log_{10}(\left\|\sum_{m=1}^{M_{sub}} w_m v_m\right\|^2)$, where $v_m = \exp\left(j2\pi(m-1)\frac{d_{v,sub}}{\lambda}cos(\theta)\right)$
Array excitation	$w_{m,n} = \frac{1}{\sqrt{MN}}\exp\left(j2\pi\left((m-1)\frac{d_v}{\lambda}sin(\theta_{etilt}) - (n-1)\frac{d_h}{\lambda}cos(\theta_{etilt})sin(\varphi_{escan})\right)\right)$ Where M and N is corresponding to (Row × Column) in Table 21, row 1.6.
Composite array radiation pattern	$A_A(\theta,\varphi) = A_{sub}(\theta,\varphi) + 10\log_{10}\left(\left\|\sum_{m=1}^{M}\sum_{n=1}^{N} w_{m,n}v_{m,n}\right\|^2\right)$, where $v_{m,n} = \exp\left(j2\pi\left((m-1)\frac{d_v}{\lambda}cos(\theta) + (n-1)\frac{d_h}{\lambda}sin(\theta)sin(\varphi)\right)\right)$ Where M and N is corresponding to (Row × Column) in Table 21, row 1.6.

Elevation cuts of the 3 x 1 subarray and the composite array signal at 0° azimuth are provided in Figure 7 for comparison of the features in the AAS antenna pattern with the non-AAS antenna pattern shown in Figure 5. Previous studies employed the original AAS model in ITU-R M.2101, which does not include the subarray modeling (RTCA, Inc., 2020, p. 22). However, the current recommendation is to use the subarray pattern in the Extended AAS model. For the individual element gain of 6.4 dBi specified in Table A- 2, the peak subarray gain is approximately $6.4 + \log_{10}(3) = 11$ dBi.



(a) (b)

Figure 7. Elevation cuts of AAS (a) subarray and (b) composite array antenna patterns

Note that ITU-R M.2101 recommends that for IMT unwanted emissions falling in an adjacent frequency band, the antenna pattern for the unwanted emission can be assumed to have a similar antenna pattern as a single antenna element (Table 7, row 2) (ITU-R, 2017, p. 26). This assumes that signals outside the operating bandwidth of the AAS array rapidly decorrelate with increasing distance from the operating band edge. This may be a valid assumption for previous studies of unwanted emissions from Base Station (BS) operating in the Lower C-band with 200 MHz of separation of the AAS array operating bandwidth and the 4200–4400 MHz RA band. However, for the smaller frequency separation of an AAS array operating in the 3980–4200 MHz Upper C-band, this has not been demonstrated to be true for unwanted emissions above 4200 MHz. Since the subarray excitation only includes a static electrical downtilt and does not contribute to vertical or horizontal electronic steering, the subarray pattern (Table 7, row 4) is the appropriate pattern for spurious emissions using the Extended AAS model.

The effects of detuning the radiated signal from the designed operating bandwidth of the AAS antenna on the array factor can be illustrated by considering the term $d_{v,sub}/\lambda$ in the expressions for the subarray excitation and radiation pattern in Table 7. This is the ratio of the vertical separation between radiating elements in the three-element subarray to the wavelength of the radiated signal, which Table A- 2 indicates is nominally 0.7. Assuming the separation distance is fixed for a given AAS design, the separation implemented in hardware would be the wavelength at the center frequency of the designed AAS operating band. Higher and lower frequencies will thus have higher and lower ratios and affect the subarray radiation pattern. Figure 8 illustrates this effect for a range of frequencies in the C-band below 4200 MHz, assuming a designed center frequency of 3950 MHz and other parameters, as listed in Table A- 2. Note that this shows only the effect of detuning on the array factor for the subarray pattern. It does not include other considerations such as changes to the radiating element pattern and impedance matching. Figure 8 shows that effects of detuning on the radiation pattern increase away from boresight.

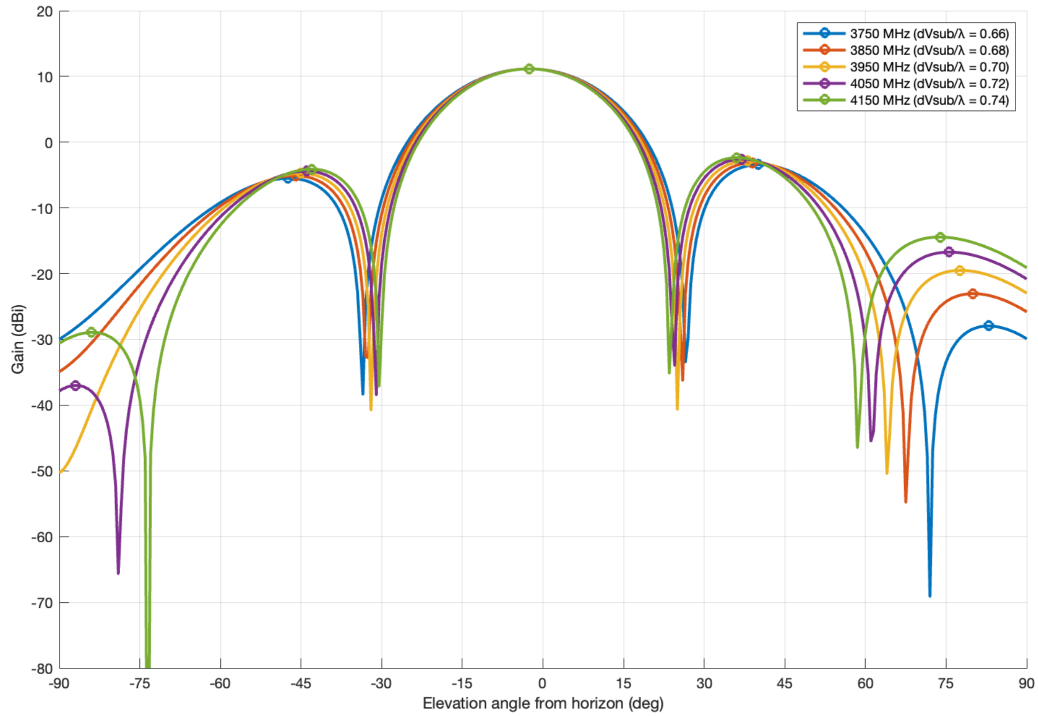


Figure 8. AAS subarray pattern for multiple radiating frequencies

The third-order intermodulation example in section 3.1.3 further illustrates the potential for directed unwanted emissions. For the two-tone input signal represented by Equation 7, the expression for the distorted output signal in Equation 8 shows that the harmonics are co-bore sighted with the fundamental, and the second- and third-order intermodulation products are offset by a predictable beam angle. The simple analysis, however, does not consider dispersive elements in the signal chain, such as the DPD and cavity filter elements shown in Figure 3, which would be expected to contribute to decorrelation of unwanted emissions. The Rizk study of a commercial AAS antenna array demonstrated that for a PA operating in the nonlinear regime without DPD, "OOB emissions become spatially coherent and are beamformed in the same direction as the desired signal, leading to an increased risk of interference" (Rizk, et al., 2025, p. 7). Measurements demonstrated that this is mitigated by applying DPD.

It is important to note that the application of DPD is not mandated by regulation, only the unwanted emission levels outside the operating bandwidth. Given the complexity of AAS antenna systems, unwanted emission limits have typically been specified in terms of conducted or total radiated power (TRP). Such specification creates challenges for determining compatibility of RAs with AAS base station unwanted emissions, since the EIRP level necessary to determine how much RF energy is directed from the AAS antenna to the RA Rx antenna is not regulated, is implementation dependent, and is not exhaustively characterized for all commercial AAS antennas.

The other major difference between the AAS and non-AAS patterns is the presence of significant sidelobes in the AAS pattern. Figure 7b shows that the peak value at the horizontal (for an un-steered beam with no mechanical downtilt) is about 26 dBi, and with a sidelobe at 10º above the horizontal 14.5 dB down at 11.5 dBi. Electrical steering of the beam affects the magnitude of the sidelobes, as shown in Figure 9. When the beam is electrically steered downward by 15º, the main lobe is 23.25 dBi, and the sidelobe at 11º above the horizontal is only 1.75 dB down at 21.5 dBi. Implementing sidelobe suppression can reduce the impact, but again, this is an implementation detail that is not regulated except in cases where the AAS emissions are subject to a vertical EIRP mask.

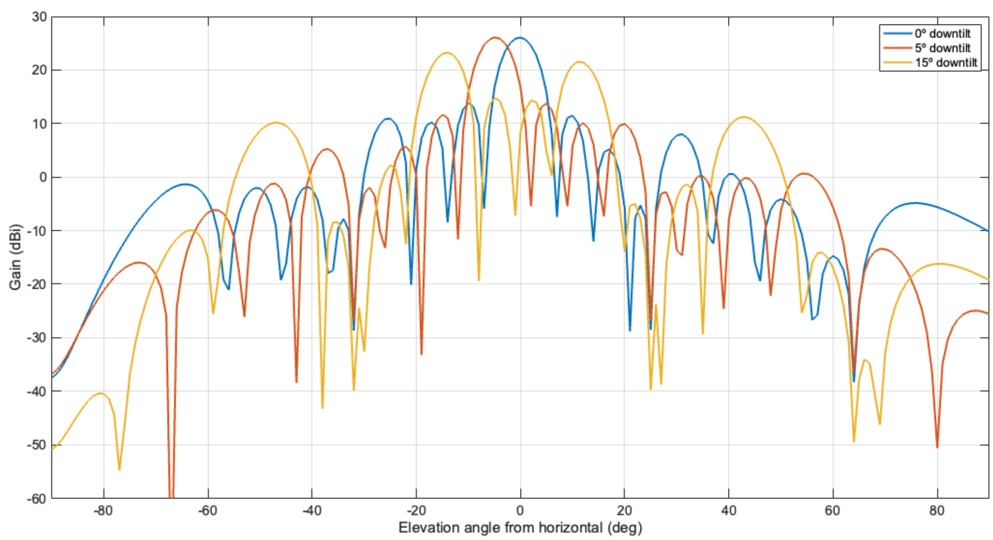


Figure 9. AAS composite pattern for several electrical downtilt angles

Note that the full composite patterns in Figure 7b and Figure 9 require correlated signals and are representative of the pattern for fundamental emissions. As discussed above, the subarray pattern in Figure 7a can be used for frequencies well outside the AAS operating bandwidth.

4 Receiver: RA parameters

RAs are downward-looking radars that are the only sensors on board aircraft that provide a direct measurement of the clearance height above the terrain and any obstacles below the aircraft. As such, RAs provide critical HAGL inputs to multiple safety systems integrated on aircraft and situational awareness to pilots operating RA-equipped aircraft. Multiple sources have described the importance of RA integrity, availability, and continuity on the safe operation of aircraft, especially in low-visibility landing conditions (Federal Aviation Administration, 2026, p. 465 §IV.D; RTCA, Inc., 2020).

RA systems are typically comprised of separate Tx and Rx antennas, a transceiver unit, RF cabling connecting the antenna and transceiver, and some type of display as shown in Figure 10, though other system architectures are possible. Linearly polarized microstrip patch antennas are most common for all applications. Most commonly, Tx/Rx antenna pairs are mounted fore/aft with the H-plane coupling, i.e., with the H-plane along the longitudinal axis of the aircraft. Installation requirements determined by the RA system manufacturing specify minimum isolation between Tx/Rx pairs in the range 75–100 dB. Losses in the RF cable connecting the antennas to the transceiver can range from 2 to 5 dB for a single path (i.e., antenna to transceiver) (Frick, 2021).

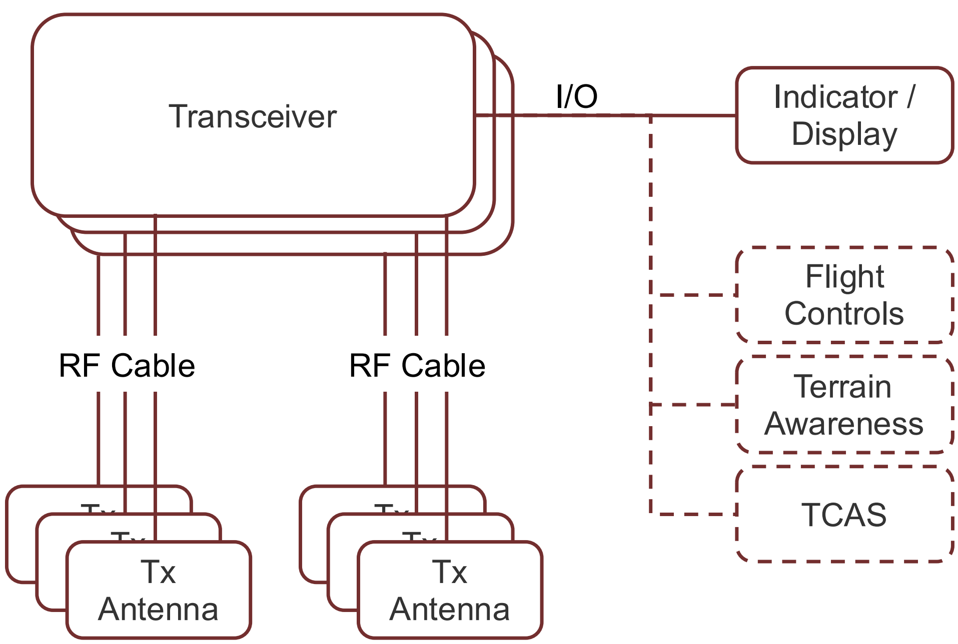


Figure 10. RA system elements

Figure 10 also illustrates that RAs are typically integrated with other aircraft systems and functions, which can impose specific integrity, availability, and continuity requirements on the RA system output. In some cases, multiple redundant RA systems may be necessary to meet these requirements, which is often the case for large commercial transport airplanes on which duplex or triplex systems may be installed. Multiplex installations impose additional requirements for isolation between Tx/Rx pairs of the independent RA systems. Table 8 lists typical RA system characteristics.

Table 8. Typical RA system parameters

Parameter	**Typical Value**
Maximum Reported Altitude	2,500 – 7,500 ft
Altitude Accuracy	±1.5 ft to 3 ft up to 100 ft AGL 2% to 3% from 100 to 500 ft AGL ±2% to 5% above 500 ft AGL
Aircraft Pitch and Roll Angles	±20º to ±40º
Operating Temperature	-55 ºC to 40 ºC min +70 ºC max
Loop Sensitivity	Depends on terrain backscatter, antenna patterns, pitch/roll requirements, and RF cable losses

The loop sensitivity of an RA is one of the most critical performance characteristics, as it defines the maximum loop loss at which the RA can still meet its intended function. As stated in the table, it depends on the amount of energy from the transmitted signal that is scattered back to the receive antenna, which is determined by such considerations as the type of terrain, terrain features, antenna patterns, aircraft attitude, and RF cable losses. This is discussed further in section 4.4.2.

Commercial RAs can be implemented using pulsed modulation or FMCW. FMCW implementations are more common for civil and commercial aviation. Figure 11 illustrates the components of a representative homodyne FMCW RA system. The Rx antenna and Rx front-end filter are key components for determining compatibility and are considered in more detail in section 4.3 and 4.4. The Tx synthesizer generates a linear frequency modulated chirped signal that has a characteristic slope and period. The chirp is typically a sawtooth or triangular wave, as shown in Figure 12.

The figure identifies the sweep bandwidth (F2-F1) and the sweep period (2*T). The figure also shows the return signal (Rx) as a copy of the transmit signal that has a time delay directly proportional to the baseband signal frequency (f_b):

$$\text{Chirp Rate: } K = ((\text{Sweep Bandwidth}))/((\text{Sweep Time})) = \frac{(F_2 - F_1)}{T} \quad 11$$

$$f_{TX}(t) = F_1 + Kt \quad 12$$

$$f_b = F_{TX} - F_{RX} = f_{TX}(t_{RX}) - f_{TX}(t_{RX} - \frac{2R}{c}) = K\,\frac{2R}{c} \quad 13$$

where R is the one-way range and c is the speed of light. The Rx waveform is also shifted due to Doppler, but triangle FMCW waveforms, with both upward and downward frequency sweeps, allow for range-Doppler decoupling. Typical transceiver characteristics for FMCW RAs are provided in Table 9.

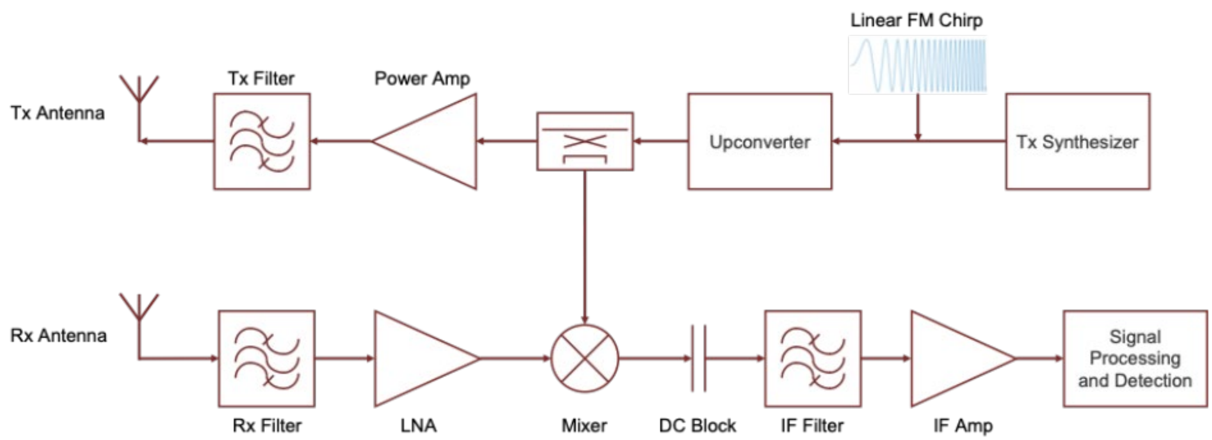


Figure 11. Representative FMCW homodyne RA implementation

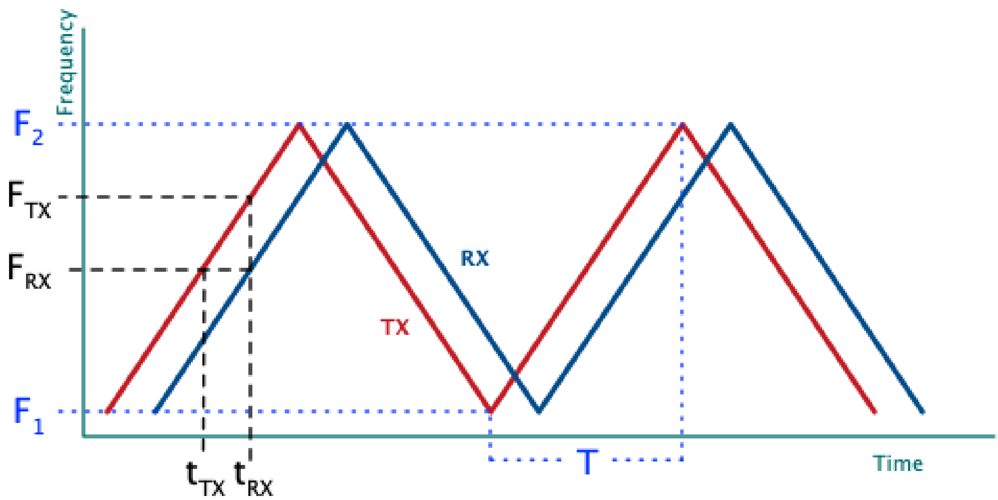


Figure 12. Triangular wave FMCW signal

Table 9. Typical FMCW Transceiver Parameters

Parameter	**Typical Value (FMCW)**
Transmitter	
Peak TX Power	0.05 – 2 W
Sweep Bandwidth	100 – 180 MHz
Sweep Period	0.2 – 10 ms
Receiver	
IF Bandwidth	0.2 to 2 MHz (single-sided)
Detector Bandwidth	0.1 – 10 kHz

As described in section 2, compatibility studies investigate the possibility that a system transmitting RF energy creates harmful interference, i.e., seriously degrades, obstructs, or repeatedly interrupts another RF system (victim), and to determine conditions that prevent such interference. The metrics that determine when the victim system's operation is compromised are defined by system performance requirements, and the conditions that prevent compromised operation are defined by protection criteria established within the ITU-R based on the victim system's receiver parameters. For RAs, performance requirements are defined in minimum performance standards EUROCAE ED-30 (EUROCAE, 1980) and RTCA DO-155 (RTCA, Inc., 1974), and protection criteria are defined in in Recommendation ITU-R M.2059 (ITU-R, 2014).

4.1 RA system minimum performance standards

To gain FAA approval through the TSO process, RA manufacturers must demonstrate compliance with the performance requirements specified in the applicable Minimum Performance Specification (MPS) or equivalent. Given the rigor of the aviation regulatory approval processes, avionics systems have relatively long lifecycles compared to commercial electronics. Thus, there are currently deployed RA models that received FAA approval under both the current TSO-C87a, which recognizes the EUROCAE ED-30 MPS released in 1980, and the earlier TSO-C87, which includes requirements from the RTCA DO-155 MPS released in 1974, though the performance requirements are largely the same.

Both documents describe performance requirements and test methods required to demonstrate compliance with them. Performance specifications include:

- the in-flight conditions, such as the range of horizontal/vertical velocity and pitch/roll angles over which the RA must meet all its other performance requirements,
- accuracy, provided as a function of HAGL,
- noise in the HAGL indication output from the RA, and
- time constant of the output for abrupt changes in height above the terrain below the aircraft.

It is important to note that, as these are minimum standards, there are many parameters that are not specified, including the level of interference tolerance. While additional requirements govern the development of some RA models (e.g., aircraft manufacturer specifications), existing RAs were designed to meet integrity, availability, and continuity requirements in an RFI environment that, before 2020, reflected satellite operations and other relatively low-powered services in the frequency bands adjacent to the RA band.[4] Thus RA systems have performed reliably for multiple decades based on the current performance requirements and approval basis. However, recognizing that improvements in RF tolerance were necessary to achieve compatibility with the post-2020 RFI environment, RTCA, Inc. and EUROCAE have been engaged in an effort to develop an updated Minimum Operation Performance Standard (MOPS) that not only includes new requirements for interference tolerance, but also provides a much more comprehensive set

[4] As illustrated in the FAA NPRM, “previous low-powered satellite services were limited such that their signals were no greater than roughly -99 decibel-milliwatts (dBm) per MHz (dBm/MHz) at the Earth’s surface, where current Lower C-band wireless base stations can transmit up to 65 dBm/MHz,” or about 100 million times stronger signal at the Earth’s surface (Federal Aviation Administration, 2026, p. 463).

of performance requirements that clarifies the capabilities and constraints for future RA system development.[5] This new standard is anticipated to be published in early 2027.

Again, these requirements define the baseline performance necessary for proper operation of RA systems. The criteria necessary to protect RA systems from performance degradation due to RFI are defined in Recommendation ITU-R M.2059.

4.2 RA system protection criteria

Recommendation ITU-R M.2059 describes the operational characteristics, technical characteristics, and protection criteria that should be used for RAs when conducting compatibility studies within the ITU-R. Technical characteristics are anonymously presented for a representative mix of 10 digital/analog and pulsed/continuous wave (FMCW) RA models that were in use at the time the document was developed. These characteristics include RA transmitter, receiver, and antenna/installation parameters. Protection criteria are defined using receiver parameters for three failure modes that may be caused by RF interference: (1) receiver front-end overload, (2) receiver desensitization, and (3) false altitude reports. Table 10 summarizes these criteria.

[5] This effort is organized under the RTCA, Inc. Special Committee 239 (SC-239) (see https://www.rtca.org/sc-239/) and the European Organisation for Civil Aviation Equipment (EUROCAE) Working Group 119 (WG–119) (see https://www.eurocae.net/working-group/wg-119/).

Table 10. Recommendation ITU-R M.2059 Protection Criteria

Protection Criterion	ITU-R M.2059 Definition (Annex 3)	Worst-Case Tolerance Thresholds Based on ITU-R M.2059 Parameter Values
Front End Overload	$I\_RF \leq P_{T,RF}$ where I_{RF} is the total peak interference power at the receiver input and $P_{T,RF}$ is the input power threshold at which receiver front-end overload occurs.	-53 dBm
Receiver Desensitization	$I/N = -6$ dB where I is the interference power and $N = -114\ \text{dBm/MHz} + 10\log_{10}(B_{R,IF}) + N_F$ is the thermal noise within IF bandwidth of the RA receiver with a noise factor N_F.	-102 dBm -117 dBm/MHz
False Altitude Reports (FMCW RAs only)	$I_D < I_{T,FA}$ where $I_{T,FA} = -143$ dBm/100 Hz following the instantaneous altimeter local oscillator.	-103 dBm/MHz

Front-end overload occurs when an interfering signal saturates the front-end of an RA receiver. For this to occur, the interfering signal must be received through the RA Rx antenna, propagate through the antenna cabling, and pass through the RA's front-end filter. Thus, determining compatibility with the ITU-R M.2059 front-end overload protection criterion requires knowledge of the RA receiver, antenna, and installation parameters as a function of frequency outside the RA band. As pointed out in the Recommendation, RAs at the time generally had modest front-end selectivity[6] and thus these RAs are susceptible to front-end overload from interference frequencies both within its operational swept bandwidth as well as from outside this bandwidth.

Desensitization occurs when the total power of the interfering signals falling within the RA receiver IF bandwidth raises the noise floor by 1 dB. Thus, this failure mode is applicable to interference from unwanted emissions falling within the RA band. The interference signal must be received by the RA Rx antenna and propagate to the RA transceiver, but given that the signal falls within the RA band, it is not attenuated by the front-end filter.

[6] ITU-R M.2059 Table 3 suggests a representative frequency-dependent rejection of 24 dB/octave to a maximum of 40 dB above and below the RA band edges.

The third column reproduces tolerance thresholds from the RTCA Assessment Report, which were computed using RA receiver parameters in Tables 1 and 2 of ITU-R M.2059 assuming an 5G interference signal centered at 3850 MHz and the Frequency Dependent Rejection provided in Table 3 of ITU-R M.2059 (RTCA, Inc., 2020, pp. 16, Table 6-1). These values represent the worst-case values for each failure mode from among the thresholds computed for each RA model reported in Tables 1 and 2 of ITU-R M.2059.

4.3 RA antennas

RA antennas are often specified by the RA system designer and then developed and manufactured by an antenna supplier to meet the design specification. Thus, RA antenna requirements are not specified in ED-30 or DO-155, and there is no standard specification or MOPS that provides definitive performance parameters for all commercial RA antennas. Table 11 summarizes typical parameter values for currently deployed RA antennas (Frick, 2021).

Table 11. Typical RA antenna parameters

Parameter	**Typical Value**
Antenna Type	Linearly polarized microstrip patch
Form factors	4” x 4” square or ~6” diameter circle
Peak gain @ 4300 MHz	7–13 dBi (10–11 dBi is most common)
3 dB beamwidth @ 4300 MHz	±20º to ±45º
TX-RX separation distance	18” to 48”
TX-RX isolation	75–100 dB (85–90 dB is most common)
Cross-system isolation in multiplex installations	60–90 dB
Installation orientation	Typically H-plane along the aircraft longitudinal axis and E-plane along the lateral axis (H-plane coupling for fore/aft installed Tx/Rx antenna pairs)

As mentioned above, RA antennas are typically linearly polarized microstrip patch antennas. The gain and half power beamwidth are engineered to allow detection of radar return signals for the conditions listed in Table 8 while meeting loop sensitivity and installation isolation requirements. Note that Tx/Rx isolation requirements also lead to antenna pairs being installed with H-plane coupling along the nose-to-tail longitudinal axis with the generally wider E-plane antenna pattern along the wing tip-to-wing tip lateral axis.

As there is no standard specification for the gain pattern of RA antennas, patterns vary for different commercially available RA antenna models. Furthermore, the parameters in Table 11 have typically been specified over the 4200-4400 MHz RA band without defining requirements for frequencies outside the RA band. For compatibility studies, the gain patterns over the range of frequencies being studied are needed to determine the term G_R in Equation 1, which becomes

$$G_R = G_R(\theta, \varphi, f) \quad 14$$

Earlier ITU-R compatibility studies assumed a circular-symmetric representative gain pattern for a microstrip patch antenna described by

$$G_{RA,dB}(\phi) = -\frac{12}{\phi_{3dB}^2}\phi^2 + G_{RA,dBi} \quad 15$$

where ϕ is a single incident angle that represents the combination of azimuth and elevation due to the assumed circular symmetry, ϕ_{3dB} is the specified 3 dB beamwidth, and $G_{RA,dBi}$ is the specified maximum gain (ITU-R, 2014). Figure 13 illustrates this representative pattern.

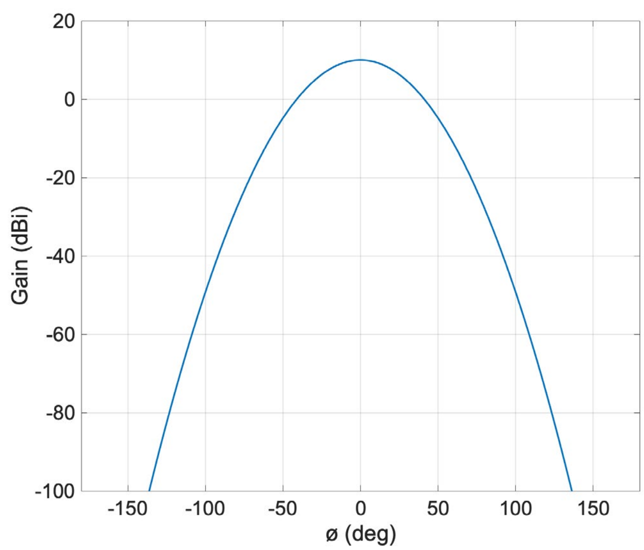


Figure 13. Representative RA Antenna Gain from ITU-R M.2319

The RTCA Assessment Report considered RA antenna gain in more detail, noting that the pattern in ITU-R M.2319 is defined based on the assumed or observed characteristics of altimeter antennas in the RA band only and that a simple frequency-dependent rejection (FDR) factor cannot be used for frequencies outside the band, since the shape of the pattern changes with frequency and the peak gain can be reduced (RTCA, Inc., 2020, p. 31). The RTCA Assessment Report combined patterns from limited measurements of commercially available RA antennas using the procedure described therein to produce empirical reference patterns for frequencies within the RA band and for frequencies in the Lower C-band for use in the RTCA study, which are reproduced in Figure 14 below (RTCA, Inc., 2020, p. 32).

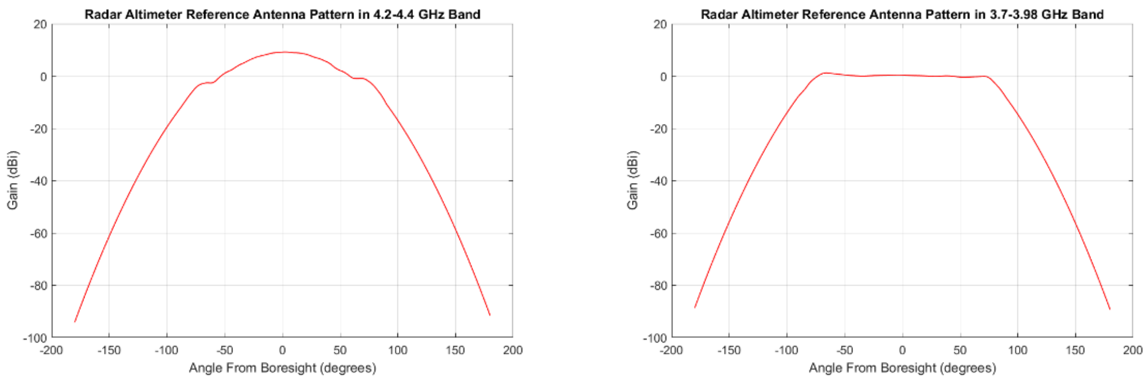


Figure 14. Empirical reference patterns from the RTCA Assessment Report

The in-band pattern is roughly parabolic, though broader than that in Figure 13 and demonstrates a shoulder of constant gain approximately 60º–75º from boresight. The out-of-band pattern exhibits a relatively constant gain out to approximately ±75º that is about 10 dB from the maximum in-band gain. The RTCA Assessment Report further considered the boresight gain for frequencies across the C-band relative to the maximum gain at 4300 MHz, as reproduced in Figure 15 below (RTCA, Inc., 2020, p. 132).

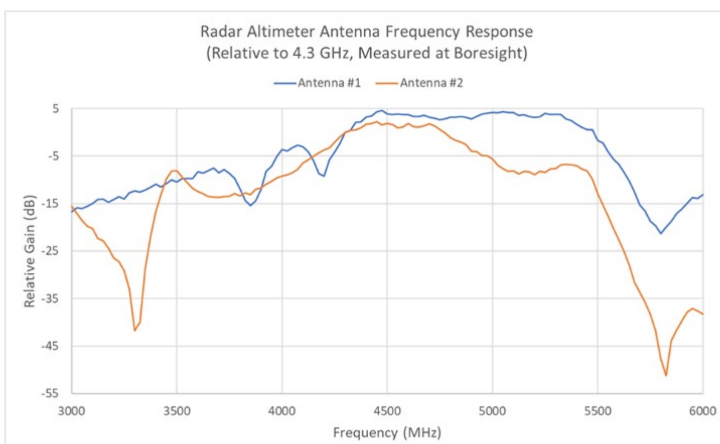


Figure 15. Measured RA antenna frequency response from the RTCA Assessment Report

These data are from a very limited set of measurements. However, they indicate that an RA antenna can have significant gain for frequencies above the RA band and that the gain rolls off between 3500–4200 MHz is gradual. Since the RTCA Assessment Report publication date in October 2020, additional characterization of RA antenna patterns has been performed, though no additional data has been put in the public domain. Given that the commercial RA antennas considered in the RTCA Assessment Report are still currently deployed models, the patterns in Figure 14 may still be valid for current compatibility studies.

One significant omission in the RTCA Assessment Report is the effect of the ground plane on the gain pattern for installed RA antennas.[7] Ground plane effects can have a significant impact on the antenna pattern depending on the shape and extent of the conductive plane around the antenna. Given the wide variety of installations on aircraft of different shapes and sizes, from large transport aircraft to light helicopters, it is not possible to define a standard installed ground plane, and compliance of an installed RA system with performance requirements must be demonstrated by the aircraft integrator. However, traceability between the designed performance and the installed performance can be aided by defining consistent test conditions for pattern measurement of the RA antenna, including a standard ground plane. This can be specified in new industry standards recognized in a new TSO for RA antennas, as was indicated in the FAA NPRM (Federal Aviation Administration, 2026, p. 471).

Given the lack of a standard specification for the in-band and out-of-band gain profiles for RA antennas, the relative insensitivity of existing antenna gain to variations in angle of arrival as shown in Figure 14, and the variation in the ground plane effects for installed antennas, the appropriate approach to ensure the safety of aircraft in the presence of RFI is to decouple the safety requirement from detailed performance parameters of the RA antenna. This is the approach adopted in the FAA NPRM, which specifies a tolerance requirement based on the interference signal PFD at the aperture of the RA Rx antenna, regardless of the angle of arrival (Federal Aviation Administration, 2026, p. 467).

4.4 RA receivers

Compatibility studies in the ITU-R typically use agreed receiver parameters to compare potential interference with agreed protection criteria. As described above, ITU-R M.2059 published accepted receiver parameters for 10 analog and digital RA models, which are reproduced in Table 12.

The parameters in Table 12 represent a survey of models that were deployed at the time ITU-R M.2059, which are models that are still currently deployed. Thus, the values reflect current RA receiver performance. As shown in Figure 11, the wanted and unwanted signals received by the RA Rx antenna and propagated to the Rx input of the transceiver pass through the front-end filter prior to amplification by the low-noise amplifier (LNA). The front-end filter for the models listed in Table 12 are assumed to have a gradual roll-off described by ITU-R M.2059.

[7] The RTCA Assessment Report was not intended to be exhaustive but was the most comprehensive assessment available at the time of its publication to inform the proceedings in the Lower C-band. See §4 of the RTCA Assessment Report, p. 8.

Table 12. RA receiver parameters from ITU-R M.2059

a. Analog RA models

	A1	**A2**	**A3**	**A4**	**A5**	**A6**	**Units**
Sensitivity (Note 1)	-120	< -113	≤ -120	-95	-95	-95	dBm
Noise Figure	10	6	6	10	10	10	dB
$P_{T,RF}$ Input Power 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	16	MHz
Note 1. For some of the radio altimeters listed above, the receiver noise power level, calculated based upon IF bandwidth and noise figure, is higher than the receiver sensitivity level. In these cases, the detector bandwidth of the radio altimeter, which is generally lower than the IF bandwidth, determines the receiver sensitivity level.							

b. Digital RA models

	D1	**D2**	**D3**	**D4**	**Units**
Sensitivity (Note 1)	< -114	< -125	≤ -120	-95	dBm
Noise Figure	8	9	8 to 12	10	dB
$P_{T,RF}$ Input Power Threshold Receiver Overload	-30	-43	-53	-40	dBm
–3 dB Intermediate Frequency (IF) bandwidth	0.312 (Note 2)	1.95	0.1 to 2.0	30	MHz
1. For some of the radio altimeters listed above, the receiver noise power level, calculated based upon IF bandwidth and noise figure, is higher than the receiver sensitivity level. In these cases, the detector bandwidth of the radio altimeter, which is generally lower than the IF bandwidth, determines the receiver sensitivity level. 2. Low pass filter – single sided.					

4.4.1 Front-end filter

The gradual roll-off of the front-end filter for existing RAs was confirmed in testing performed by the Aerospace Vehicle Systems Institute (AVSI) in 2020 that demonstrated that multiple RA models showed degraded performance for interference signals well below the RA band edge at 4200 MHz (AVSI, 2020). This testing was performed to characterize currently deployed RAs for assessment of the potential for harmful interference due to proposed licensing of the Lower C-band for flexible use, including 5G cellular communications. The resulting test data was provided to RTCA, Inc. as input to the development of the RTCA Assessment Report, which presented the empirical data as a series of interference tolerance masks (ITMs) that were plotted as a function of altitude for three 100-MHz sub-bands within the 3700–3980 Lower C-band (RTCA, Inc., 2020, p. 49). These ITMs were preferentially used in the assessment instead of ITU-R M.2059 protection criteria, since the protection criteria do not completely characterize RA behavior and susceptibility to RF interference. As outlined in §6.2.2 of the report (RTCA, Inc., 2020, p. 17), the protection criteria do not exhaustively consider all possible failure modes and interference mechanisms, are defined statically without consideration of altitude-dependent performance characteristics, and are derived from a list of unspecified RA models without consideration of installation platforms or operational scenarios. The AVSI empirical "black-box" data was determined from observed performance criteria that intrinsically depend on all possible interference mechanisms that might degrade a given RA model's performance and do not require any specific determination of interference mechanisms in the receiver.

The results of the assessment indicated that the RAs would sustain harmful interference from the Lower-C band under the technical conditions proposed by the FCC (RTCA, Inc., 2020, p. 87). As a result of the risk identified in the RTCA Assessment Report and the technical conditions in FCC Lower C-band R&O, the FAA issued ADs defining new interference tolerance requirements for existing RAs (Federal Aviation Administration, 2023a) (Federal Aviation Administration, 2023b). This in turn led the aviation industry to execute a rapid retrofit campaign to improve the front-end filtering of susceptible RAs.

It is important to note that the amount of additional filtering that can be added to an existing RA receiver design is limited by engineering trade-offs in the design of the receiver and signal processing. Furthermore, the amount of filtering that is necessary depends on both the power of the interfering signal and the frequency separation between the interfering signal and the RA band edge. This can be challenging for high-power, broadly deployed services, such as 5G emissions, located in frequency bands adjacent to the RA band. A filter with an arbitrarily steep roll-off outside the RA passband is not possible. Flexible use in the 3700–3980 MHz Lower C-band provided a 220 MHz frequency separation in which to implement filtering for existing RA designs.

A primary concern with addition of dispersive elements in the signal path between the RA Rx antenna and the receiver mixer is the introduction of group delay variation (GDV) in the RA passband. Ripple or variation in total group delay from all dispersive elements in the signal path across the RA passband results in phase modulation of the baseband or IF signal in the radar altimeter receiver for any implementations using coherent detection (including FMCW designs). This causes distortion in the detected signal that cannot be compensated by signal processing and can lead to degraded range resolution and the possibility of false target detections. The magnitude of the variation created by a front-end filter increases with the steepness of its roll-off, as illustrated in Figure 16 (Robin, 2026).

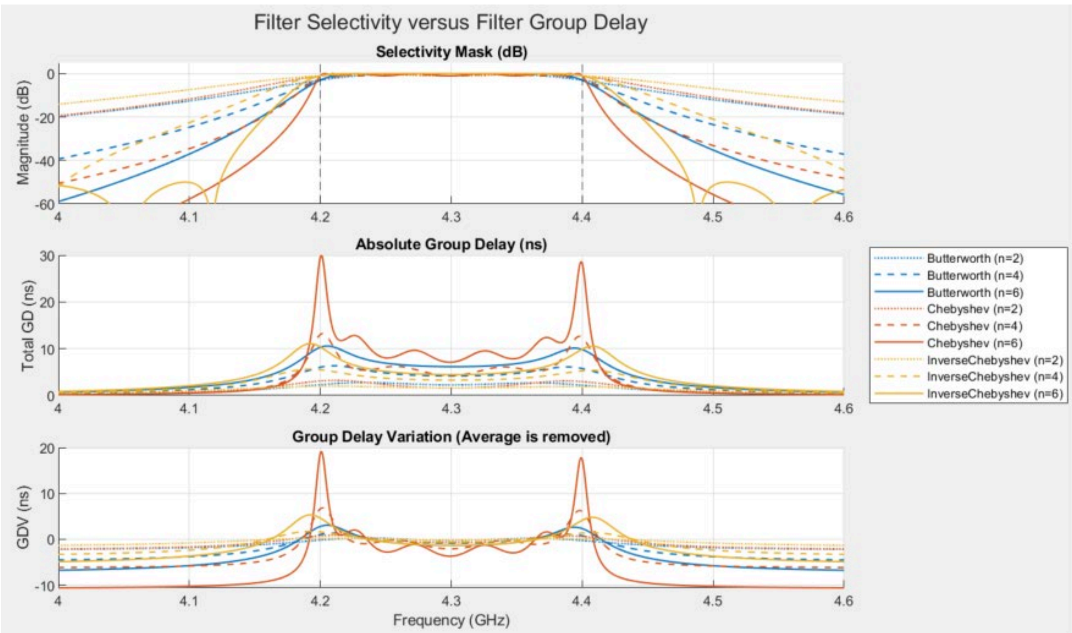


Figure 16. GDV imposed by filters of different order

The figure illustrates that the amount of GDV in the passband can be controlled by choosing an appropriate filter design. It also suggests that the magnitude of the variation could be decreased by locating the filter poles outside the passband, thereby pushing the large peaks outside the passband. However, this solution is not consistent with spectrum management practice, thus the amount of attenuation achievable close to the band edge is limited by the impact of GDV on RA performance.

This also explains why existing RA designs with an existing TSO authorization cannot be retrofitted with arbitrarily steep bandpass filters. The GDV in the RA passband is due to the cumulative effect of dispersive elements in the RF signal path, including frequency selectivity of the RA Rx antenna. Existing system designs have receivers/detectors that have been optimized to meet performance requirements given the total GDV in the system. Changes to these designs are subject to validation such that the additional filtering does not negatively impact compliance with performance requirements.

For this reason, retrofitting existing RAs with additional filtering as the sole mitigation to meet new ITM requirements necessary to achieve compatibility with Lower C-band 5G emissions in the United States was determined to be insufficient. Continued safe operation of aircraft in all-weather operations also required the telecommunications industry to enter into voluntary agreements with the FAA to constrain Lower C-band emissions around certain airports to levels that were compatible with the new ITM requirements issued by the FAA (AT&T Services, Inc., T-Mobile, UScellular, Verizon, 2023). Limits on the additional filtering that is achievable with existing RA designs thus required constrained 5G emissions below 3980 MHz to achieve compatibility. However, significantly higher levels of FDR are achievable using existing technology, albeit with more extensive modifications to the RA system design, and these improvements will be incorporated in future RA systems.

4.4.2 Receiver sensitivity

In normal operation, an FMCW RA transmits a continuous beam from the RA Tx antenna to the ground below the aircraft, where it scatters off the terrain and any features that are within the beam. The amount of return power received by the RA Rx antenna relative to the transmitted power is known as the *external loop loss*, which is determined by factors such as the height of the aircraft above the scattering surface; the relative angle of the normal axis of the antenna and the terrain below (which depends on both the aircraft attitude and variations in the terrain); the gain of the RA Rx antenna (as a function of azimuth and elevation angle); and the electromagnetic backscattering characteristics of the terrain surface. This last parameter, the terrain backscatter coefficient $\sigma_0(\theta, \varphi)$, depends on the presence of vegetation, water/snow/ice, and any features on the terrain surface illuminated by the Tx beam. Thus, an RA's relatively low-power transmitted signals experience significant variation in loop loss (and thus received signal levels), which requires RAs to accurately process and track signals over a dynamic range well beyond 100 dB. Because the biggest contributor to this dynamic range is the increasing loop loss with increasing HAGL, the entire dynamic range does not need to be instantaneous or available for signals at every altitude. Therefore, most RAs will have sensitivity characteristics that are highly dependent on the range/altitude of the received signal. In FMCW RAs, sensitivity vs. altitude is set primarily by tuning the baseband frequency response to provide more gain at higher frequencies (i.e., larger delays between the Tx and Rx signals mixed in the homodyne receiver) to enable more sensitivity for higher altitudes.

The dynamic range is closely related to loop sensitivity, one of the most critical system-level RA performance characteristics. It defines the maximum loop loss at which the RA can still meet its intended function. Loop sensitivity can be specified in terms of "acquisition/make track" sensitivity, or "tracking/break track" sensitivity. Make track sensitivity is the maximum loop loss (and thus lowest Rx power level) at which the RA can first acquire and begin tracking a target signal at a particular altitude, starting from a non-tracking state. Break track sensitivity is the maximum loop loss (and thus lowest RX power level) at which the RA can continue tracking a signal at a particular altitude, while in a tracking state. Break-track sensitivity is typically a few dB higher than make-track sensitivity, providing hysteresis to avoid oscillations at the sensitivity limit.

4.5 System ITM

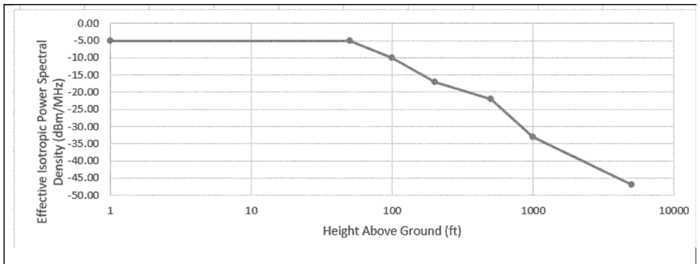
The definition of a system-level ITM for the full RA system simplifies compatibility analyses by grouping the antenna, installation, and receiver parameters that determine the system's tolerance to RFI in a single system performance parameter measured at the input to the RA Rx antenna. As described in section 4.2, compatibility studies in the context of the ITU-R rely on representative parameters, protection criteria, and scenarios published in approved ITU-R documents. The fidelity of ITU-R studies thus depends on how closely the agreed parameters reflect deployed systems. In the case of ITU-R M.2059, RA transmitter, receiver, and antenna parameters are sampled from a limited set of RA models, and protection criteria are estimated from typical values and basic receiver principles for specific designs choices. As discussed in section 4.3 that antenna parameters that are useful for determining compatibility with receiver-specific protection criteria are not considered.

Specifying a system-level ITM in regulation establishes certainty in the level of exposure to RFI in which RA systems will continue to operate according to their requirements. Safety is assured provided the aggregate interference PFD (dBW/m^2/MHz) measured at the input to the RA Rx antenna is at or below the ITM level throughout the volume of airspace that an aircraft can operate. Compatibility is then achieved by establishing emissions parameters in regulation that prevent new potential sources of interference from exceeding the ITM level.

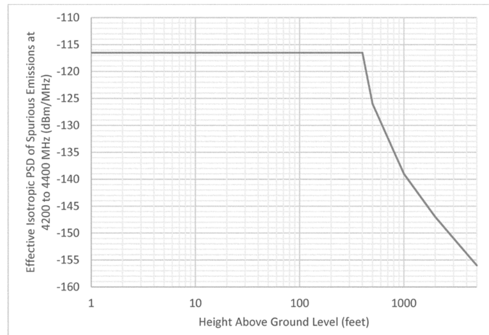
4.5.1 Lower C-band ITMs

Following the release of the FCC Lower C-band R&O and subsequent licensing of Lower C-band spectrum, the FAA established that the new FCC rules for Lower C-band 5G emissions increased the risk of RA interference and entered into temporary voluntary agreements with the 21 wireless service license holders, effective through January 1, 2028, to coordinate emitted power levels. These agreements included an attenuation mask defined as a function of angle above the horizon and limits on conducted unwanted emissions into the RA band from Lower C-band operations to -48 dBm/MHz. The FAA further issued AD 2023-10-02 for transport and commuter category airplanes (Federal Aviation Administration, 2023a) and AD 2023–11–07 for various helicopters (Federal Aviation Administration, 2023b) that defined new ITMs for existing

RAs specified as EIRP PSD values as a function of altitude. Figure 17 and Figure 18 show the tolerance levels for Lower C-band fundamental emissions and spurious emissions defined by the ADs.

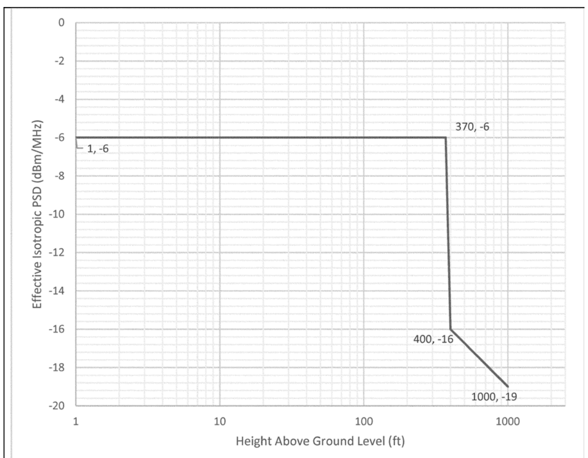


Height above ground (ft)	Effective Isotropic PSD (dBm/MHz)
Airplanes on the ground	-5
50	-5
100	-10
200	-17
500	-22
1000	-33
5000	-47



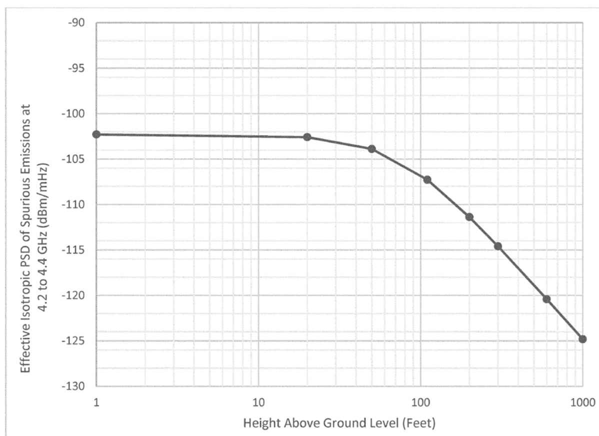
Airplane Altitude (ft AGL)	Effective Isotropic PSD (dBm/MHz)
1	-116.50
400	-116.50
500	-126.00
1000	-139.00
2000	-147.00
3000	-151.00
5000	-156.00

Figure 17. Fundamental and spurious ITMs for transport and commuter category airplanes



*The notch that occurs in the curve between 370 ft AGL to 1000 ft AGL is due to the impact of the Nationwide EIRP Elevation Mask, 75 ft horizontal minimum separation distance (MSD), and 50 ft vertical MSD for a 5G tower at 350 ft AGL.

Height above ground (ft)	Effective Isotropic PSD (dBm/MHz)
1	-6
370	-6
400	-16
1000	-19



Height above ground (ft)	Effective Isotropic PSD (dBm/MHz)
1	-102.3
20	-102.6
50	-103.9
110	-107.3
200	-111.4
300	-114.6
600	-120.4
1000	-124.8

Figure 18. Fundamental and spurious ITMs for various helicopters

It is important to note that these ITMs effectively limit interference to RAs only in conjunction with the limits on Lower C-band emissions included in the voluntary agreements between the FAA and the Lower C-band licensees. The FAA highlighted this fact in their recent NPRM addressing potential risks posed by FCC proposed changes to the Upper C-band by stating that "no existing civil equipment can tolerate wireless services aligned with FCC's Lower C-band technical rules in the 100 MHz (or more) of the spectrum to be auctioned above 3.98 GHz. Allocating even 20 MHz of additional spectrum to rural or nonrural wireless services would be incompatible with the current Lower C-band tolerant RAs and would require more than 45% of Lower C-band tolerant RAs to be modified or replaced" (Federal Aviation Administration, 2026, p. 466). Thus, compatibility with the mandated allocation of at least 100 MHz in the frequency band 3980–4200 MHz will require new RA solutions.

4.5.2 ITMs for C-band compatibility

The FAA NPRM proposes an ITM that defines required tolerance levels for C-band frequencies between 3000–5600 MHz for all RA-equipped aircraft operating between 0-500 ft HAGL under 14 CFR Part 91, as captured in Table 13 (Federal Aviation Administration, 2026, pp. 468, Table 3). The interference environment is specified as the RMS PFD from all sources measured at the surface of the aircraft RA Rx antenna in $dBW/m^2/MHz$, so the RA system compliance includes the maximum directional gain of a linearly polarized RA antenna. Figure 19 provides a plot of the requirement specified by Table 13 for frequencies between 3800 and 4800 MHz.

Table 13. Proposed ITM for all RA-equipped Part 91 aircraft

Frequency Range (MHz)	**Power flux density single polarization, RMS, 0–500 ft HAGL ($dBW/m^2/MHz$)**	**Anticipated Environmental Limit ($dBW/m^2/MHz$)**
$3000 \leq f < 4000$	9.5	3.5
$4000 \leq f < 4100$	9.5	3.5
$4100 \leq f < 4150$	9.5	3.5
$4150 \leq f < 4160$	6.5	0.5
$4160 \leq f < 4170$	-1	-7
$4170 \leq f < 4180$	-7	-13
$4180 \leq f < 4190$	-17	-23
$4190 \leq f < 4200$	-34	-40
$4200 \leq f \leq 4400$	-82	-88
$4400 < f \leq 4410$	-33	-39
$4410 < f \leq 4430$	-21	-27
$4430 < f \leq 4440$	-8	-14
$4440 < f \leq 4450$	-1	-7
$4450 < f \leq 4460$	6.5	0.5
$4460 < f \leq 4500$	9.5	3.5
$4500 < f \leq 4600$	9.5	3.5
$4600 < f \leq 5600$	9.5	3.5

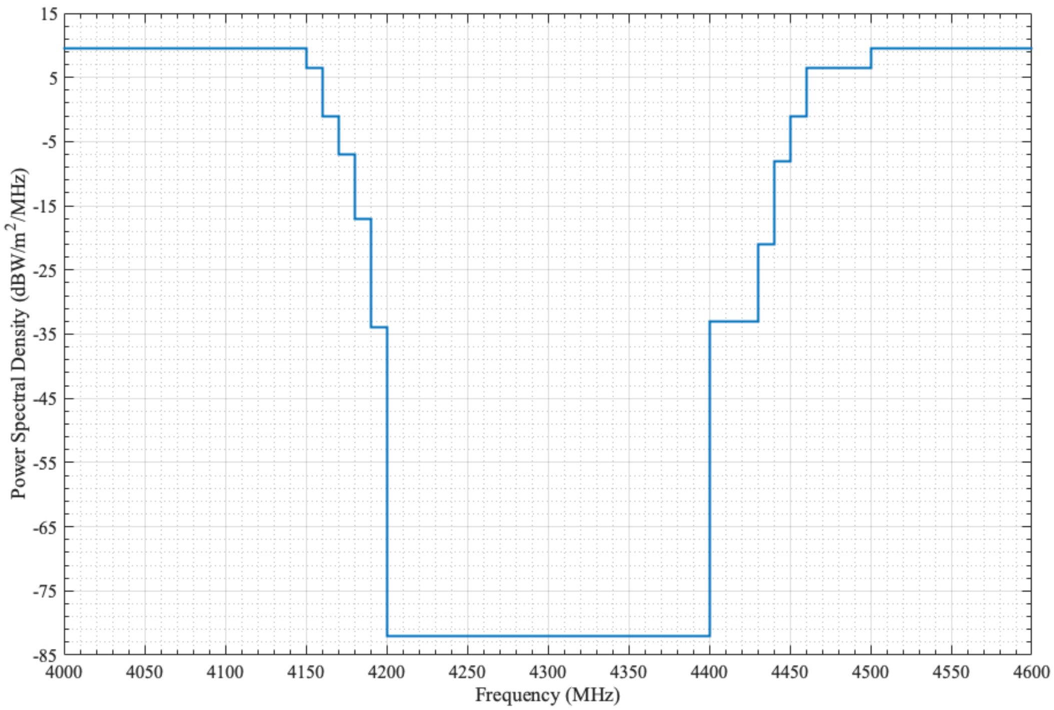


Figure 19. Detail of proposed ITM for all RA-equipped Part 91 aircraft

Note that the values in Table 13, column 2 are the maximum interference power above which RAs may not be able to maintain compliance with performance requirements. To ensure this level is not exceeded, column 3 lists the maximum exposure level of the RFI environment anticipated between 0–500 ft HAGL. This value is 6 dB lower than the ITM limit to account for the safety margin recommended for aeronautical safety services in the ICAO Handbook on Radio Frequency Spectrum Requirements for Civil Aviation (ICAO, 2018, pp. 9-8).

The minimum interference tolerance requirements in Table 13 reflect the best achievable interference rejection using current technology without compromising RA system performance. Thus, compatibility between tolerant RA systems compliant with this ITM and other sources of RFI can only be achieved by controlling emissions from the sources of RFI and/or by imposing aviation operational restrictions that prevent unacceptable risk of exposure to RFI above the ITM level.

Spectrum regulators typically seek the least restrictive rules for licensees when determining technical conditions for new service allocations. It should be noted that the ITM in Table 13 represents a significant improvement over the interference tolerance of existing RA systems. Table 14 compares tolerance values derived from ITU-R M.2059, AVSI empirical measurements, the ITMs in AD 2023–10–02 and AD 2023–11–07, and the ITM proposed in the

FAA NPRM. To compare values, empirical values use the minimum interference tolerance across all altitudes, and a 100 MHz bandwidth is assumed to convert PSD values to dBm for interference signals in the 3700-3980 MHz Lower C-band. The proposed NPRM ITM shows significant improvement over existing tolerance for both the Lower C-band fundamental and spurious signals.

Table 14. Comparison of RFI tolerance

Frequency Range (MHz)	**fc**	**From ITU-R M.2059 Protection Criteria**	**From AVSI**	**AD 2023–10–02** **AD 2023–11–07**	**FAA NPRM IMT (500') (dBm/ MHz)**
3000 ≤ f < 4000	3500	-53 dBm	-36 dBm (UC1) -74 dBm (UC2,3)	-20 dBm (UC1) +1 dBm (UC2,3)	38.163 (dBm)
4000 ≤ f < 4100	4050				16.895
4100 ≤ f < 4150	4125				16.736
4150 ≤ f < 4160	4155				13.673
4160 ≤ f < 4180	4170				6.142
4180 ≤ f < 4190	4185				-9.890
4190 ≤ f < 4200	4195				-26.910
4200 ≤ f ≤ 4400	4300	-103 dBm/MHz -117 dBm/MHz	-107 dBm/MHz (UC1) -119 dBm/MHz (UC2,3)	-156 dBm/MHz (UC1) -124.8 dBm/MHz (UC2,3)	-75.125
4400 < f ≤ 4410	4405				-26.335
4410 < f ≤ 4430	4420				-14.364
4430 < f ≤ 4440	4435				-1.394
4440 < f ≤ 4450	4445				5.587
4450 < f ≤ 4460	4455				13.067
4460 < f ≤ 4500	4480				16.019
4500 < f ≤ 4600	4550				15.884
4600 < f ≤ 5600	5100				14.893
4400 < f ≤ 4410	4405				-26.335

Figure 20 compares the FDR in ITU-R M.2059 superimposed on the proposed ITM to illustrate the significant improvement near the edges of the RA band. It shows that within 100 MHz of the RA band edge at 4200, the interference tolerance of future compliant RAs increases by 91.5 dB, whereas the attenuation of unwanted emissions according to the FDR suggested in Table 3 of ITU-R M.2059 is only about 1.1 dB. ITMs depend on RA front-end FDR and other receiver considerations, and are thus not the same quantity as the FDR in ITU-R M.2059 Table 3. Nonetheless, this illustrates the improvement in selectivity of future RAs that are compliant with the new ITM.

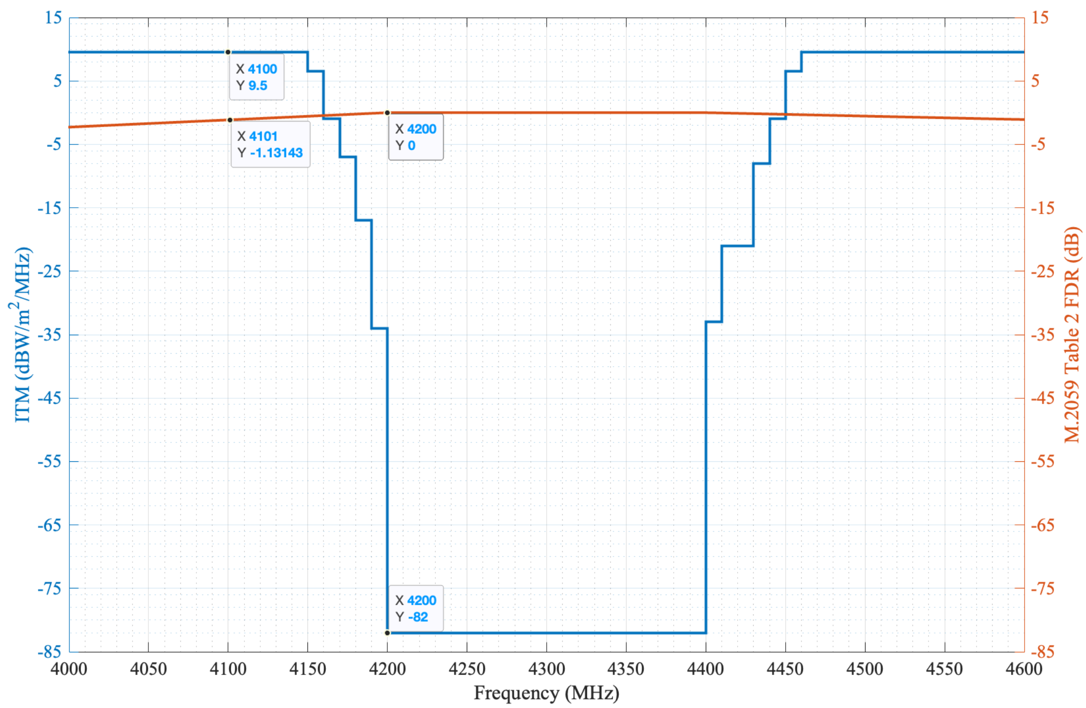


Figure 20. Comparison of proposed ITM with ITU-R M.2059 FDR

5 Path: Interference encounter scenarios

The interaction between a ground-based RF emitter (such as a 5G AAS antenna mounted on a pole or building) and an RA installed on an aircraft depends on locations in space where antennas are allowed to be located and where aircraft can be located on or above the surface of the Earth. While 5G cellular communications operate in the Mobile Service, high-power base stations are fixed with antennas mounted at elevated locations designed to service the maximum number of cell phone customers. However, aircraft move and can be located anywhere on or above the surface of the Earth. The points in space at which aircraft are allowed to normally operate are constrained by FAA operational rules, but the physics of a flying aircraft and the conditions in which it flies determine the actual location of the aircraft when in an abnormal state. Thus, the evaluation of compatibility in a given scenario must consider the possible locations of the source and the receiver and the propagation of the RF energy along the path connecting them.

The general approach for determining compatibility between RAs and C-band 5G sources starts with the basic equations in section 2 and adds specific details for the source, path, and receiver that are characteristic of the encounter scenario. The logical steps of the analysis include:

1. Step 1: Computation of the minimum distances between aircraft and emissions source(s) (excluding physically unrealizable configurations) for the scenario being studied, $\mathrm{R_{min}} = \sqrt{\mathrm{X_{min}^2} + \mathrm{Z_{min}^2}}$, where R is the range, X_{min} is the minimum possible horizontal distance and $\mathrm{Z_{min}}$ the minimum possible vertical distance between the phase centers of the RA Rx antenna and the emission source antenna
2. Step 2: Computation of the interference power received at the RA Rx antenna face (i.e., at the fuselage) caused by all emissions source(s) in the encounter scenario ($\mathrm{PFD_{Rx}}$)
3. Step 3: Computation of the HAGL below the aircraft, since the RFI tolerance can change with altitude as described in section 4.4.2, to deduce the RFI tolerance thresholds ($\mathrm{PFD_{RA}}$) at the RA Rx antenna face
4. Step 4: Computation of the margin existing between $\mathrm{PFD_{Rx}}$ and $\mathrm{PFD_{RA}}$.

The methodology does not depend on knowledge of the latitude, longitude, or height above mean sea level (MSL) of specific emissions source locations (neither horizontally nor vertically), only the relative geometries between the source(s) and an aircraft, which can generally be specified (at least to bound the worst-case limits) based solely on aircraft operational constraints and protections designed to prevent collisions with terrain and physical obstacles.

5.1 Control of obstructions to air navigation

In the United States, control of obstacles that could be considered a hazard to aviation is prescribed by federal law in 14 CFR Part 77. This code defines conditions and reporting requirements for the construction or modification of physical structures that could pose a risk of collision with aircraft. 14 CFR 77.17 defines the criteria by which an obstacle is considered to be an obstruction to air navigation:

- The obstacle’s height is greater than 499 ft AGL at the site of the object.

- The obstacle's height is greater than 200 ft AGL, or above the established airport elevation, whichever is higher, within 3 nautical miles of an airport with a runway more than 3,200 ft long. The maximum height increases 100 ft for each additional nautical mile from the airport, up to a maximum of 499 ft.
- The obstacle's height is greater than a height within a terminal obstacle clearance area which would result in the vertical distance between any point on the object and an established minimum instrument flight altitude within that area or segment to be less than the required obstacle clearance.
- The obstacle's height is greater than the surface of a takeoff and landing area of an airport or any imaginary surface established under § 77.19, 77.21, or 77.23.

In addition to these criteria, 14 CFR 77.9 specifies criteria that trigger mandatory notification of any plans to construct or modify a structure that exceeds certain maximums defined by its distance to a runway. Beyond these simple reporting requirements, 14 CFR 77.19 defines imaginary surfaces around runways at civil airports that determine the height thresholds at which obstacles are considered to pose a risk to aviation, as summarized in Table 15 for runways supporting precision approaches that rely on proper operation of RAs.

Table 15. Civil airport imaginary surfaces for precision approach

Surface	**Description**
Horizontal Surface	A horizontal plane 150 ft above the established airport elevation, the perimeter of which is constructed by swinging arcs of a specified radii from the center of each end of the primary surface of each runway of each airport and connecting the adjacent arcs by lines tangent to those arcs. The radius of each arc is 10,000 ft precision approach runways.
Conical surface	A surface extending outward and upward from the periphery of the horizontal surface at a slope of 20 to 1 for a horizontal distance of 4,000 ft.
Primary surface	A surface longitudinally centered on a runway. When the runway has a specially prepared hard surface, the primary surface extends 200 ft beyond each end of that runway; … The width of the primary surface is: … 1,000 ft for a non-precision instrument runway having a non-precision instrument approach with visibility minimums as low as three-fourths of a statute mile, and for precision instrument runways.

Surface	Description
Approach surface	A surface longitudinally centered on the extended runway centerline and extending outward and upward from each end of the primary surface. An approach surface is applied to each end of each runway based upon the type of approach available or planned for that runway end. (1) The inner edge of the approach surface is the same width as the primary surface, and it expands uniformly to a width of: … (vi) 16,000 ft for precision instrument runways. (2) The approach surface extends for a horizontal distance of: … (iii) 10,000 ft at a slope of 50 to 1 with an additional 40,000 ft at a slope of 40 to 1 for all precision instrument runways.
Transitional surface	These surfaces extend outward and upward at right angles to the runway centerline and the runway centerline extended at a slope of 7 to 1 from the sides of the primary surface and from the sides of the approach surfaces. Transitional surfaces for those portions of the precision approach surface which project through and beyond the limits of the conical surface, extend a distance of 5,000 ft measured horizontally from the edge of the approach surface and at right angles to the runway centerline.

The FCC Lower C-band R&O chose not to restrict antenna heights for 3.7-3.98 GHz band operations beyond any requirements necessary to ensure physical obstructions do not impact air navigation safety, referencing FCC rules for antenna structures in 47 CFR 27.56 and 47 CFR 17 (which aligns with the FAA reporting rules in 14 CFR 77.9) (Federal Communications Commission, 2020, p. 2473). Furthermore, the FCC Lower C-band R&O limits only the EIRP PSD of fundamental emissions and conducted PSD for unwanted emissions. It does not restrict antenna orientation or impose a vertical attenuation mask that might constrain emission levels above the horizon. It is also important to note that there is a preference to harmonize the technical conditions governing Lower C-band and Upper C-band flexible-use licenses (Federal Communications Commission, 2025, p. 3).

5.2 Aircraft operational volume

Aviation operations are highly regulated to ensure the safety of the traveling public throughout the National Airspace System (NAS). In the U.S., instrument flight procedures and air traffic control procedures are prescribed by the U.S. Standard for Terminal Instrument Procedures (TERPS) (Federal Aviation Administration, 2024a) and internationally by ICAO Procedures for Air Navigation Services – Aircraft Operations (PANS-OPS) (ICAO, 2020). Encounter scenarios described in terms of TERPS guidance can be extended to those described by PANS-OPS as both regulations aim to regulate the location of aircraft in space under standard (non-emergency) conditions.

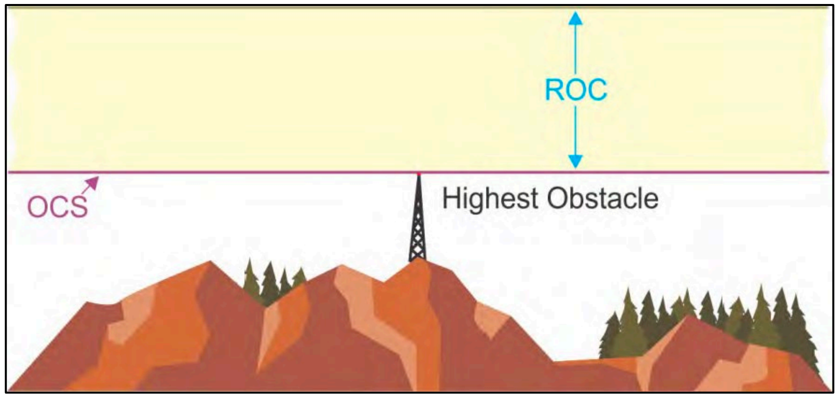
Previous studies have estimated the possibility of an RA encountering harmful interference from 5G base station emitters by considering aircraft takeoff and landing scenarios that reflect these aviation operational rules.[8] This choice of scenarios is motivated by the consideration that they represent the portion of the aircraft flight envelope where both the possibility of an RA system encountering harmful interference from 5G communications is highest and the integrity, availability, and continuity of RA HAGL data is the most critical, especially in low-visibility conditions. However, it is not sufficient to consider only nominal conditions when assessing the potential impact of RFI on the ability of an RA to provide its intended function, since the RA is a critical instrument in assuring that an aircraft and its crew can operate successfully through emergency, off-nominal conditions. Two examples of such emergency conditions are severe convective weather and loss of an engine during takeoff. The International Air Transport Association (IATA) has indicated that windshear is a persistent operational challenge, noting that in 2024 there were 2,259 incidents reported by 116 airlines, while in 2025 there were approximately 1,559 incidents reported by 109 airlines (ITU-R, 2025). Thus, off-nominal conditions must be the baseline safety case in compatibility analyses.

Compatibility of altimeters with terrestrial sources of radio frequency emissions must consider the entire volume of airspace where operations require reliable intended function of the altimeter. For many fixed-wing aircraft, reliable intended function of the altimeter is expected everywhere below the RA's operational altitude (which is generally greater than the maximum reported altitude), and accurate measurements of height above terrain and features when at or below its specified maximum reported altitude. This expectation is embedded into the failure hazard assessments for the altimeter and its integration with many sensors and functions in the aircraft, and therefore the aircraft airworthiness certification. Some categories of aircraft have especially critical hazards in the final phases of both visual and non-visual approach and landing operations. Thus, it is necessary to ensure reliable altimeter intended function to maintain continued operational safety in the volume of space around airports.

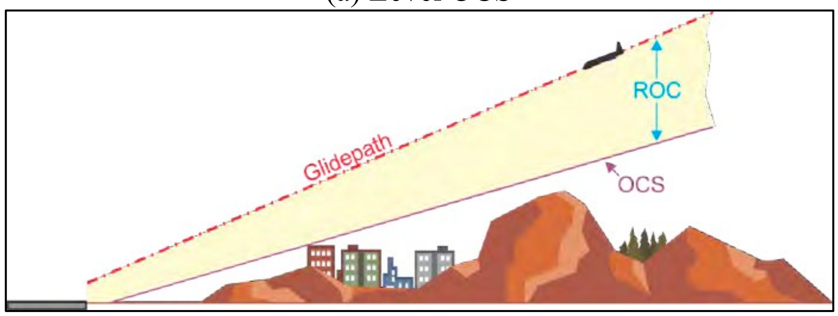
[8] See for example the scenarios described in the RTCA Assessment Report, §8, p. 43. See also ECC Report 362: "Compatibility between MFCN operating in 3400-3800 MHz and wireless broadband systems in low/medium power operating in the frequency band 3800-4200 MHz with Radio Altimeters operating in 4200-4400 MHz," approved 8 November 2024. Available from: https://docdb.cept.org/document/28630.

5.2.1 Obstacle Clearance Surfaces

The risk of an aircraft colliding with an obstacle is controlled using Obstacle Clearance Surfaces (OCS). Just as an RA system is operational through all phases of flight, OCS are defined for different segments of a total flight. The segments are classified as either Level OCS, for "level flight" segments, or Sloping OCS, for segments dedicated to descending on a glidepath or climbing in a departure or missed approach segment. TERPS also specify the Required Obstacle Clearance (ROC), which is the minimum measure of obstacle clearance considered by the FAA to supply a satisfactory level of vertical protection (Federal Aviation Administration, 2024a, pp. 2-1). The clearance criteria assume that aircraft will perform according to their certified performance in normal aircraft operational conditions. Normal aircraft operation means all aircraft systems are functioning normally, all required navigation systems are performing within flight inspection parameters, and the pilot is conducting instrument operations utilizing instrument flight procedures based on the TERPS standard to provide the ROC. Under these assumptions, the safety contribution provided by obstacle clearance standards allow aeronautical navigation in instrument meteorological conditions (IMC) without fear of collision with unseen obstacles. The ROC is provided through application of a level and sloping OCS. The combination of the OCS and the ROC is illustrated in Figure 21 is intended to ensure the risk of collision is acceptably remote (Federal Aviation Administration, 2024a, pp. 2-1).



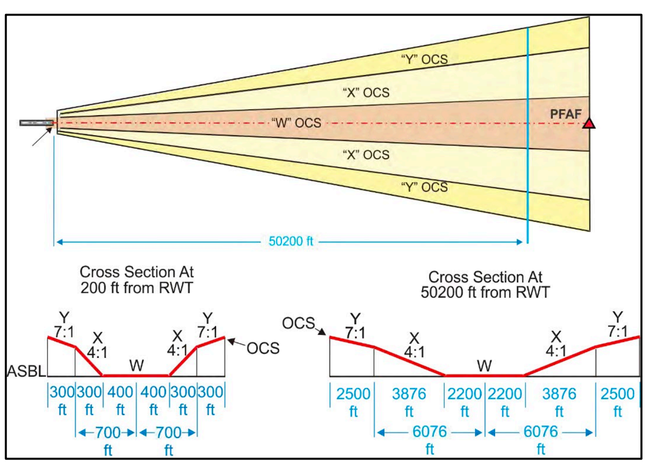
(a) Level OCS



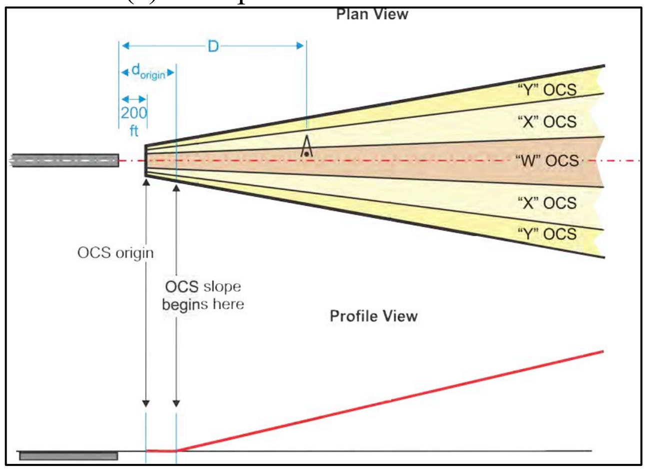
(b) Sloping OCS

Figure 21. TERPS OCS

In general, the OCS around airports is a complex imaginary surface. Section 10-2 of TERPS defines a final approach segment that has areas with differing cross-sectional profiles and slope. Figure 22 (a) illustrates plan and cross-sectional views and (b) shows the slope profile for a Precision Approach and Localizer Type Directional Aids with glide slope (Federal Aviation Administration, 2024a, pp. 10-6). TERPS define minimum values for the computation of OCS surfaces. Similar guidance is applied to helicopter flight profiles in Chapter 12 of the TERPS. Similar concepts are also incorporated in ICAO PANS-OPS.



(a) OCS plan and cross-section



(b) OCS slope

Figure 22. TERPS OCS geometries for precision approach

The OCS surfaces control only the extent of physical structures. Approach procedures based on the performance capabilities of the aircraft and the sensors and systems on board are developed to ensure that the occurrence of a catastrophic failure leading to a collision is extremely improbable. Thus, the OCS regulates only the physical location of 5G emitters mounted on towers and buildings.

5.2.2 Minimum separation distances

While the TERPS define imaginary surfaces that constrain obstacle location around airports to minimize the risk of collision in normal operations (including CAT II/III reduced visibility operations), other regulations define operational and performance requirements for aircraft meant to manage the risk of collusion in abnormal conditions. 14 CFR Part 121.189(d) states the operational requirement for commercial air transport aircraft:

> *(d) No person operating a turbine engine powered airplane may take off that airplane at a weight greater than that listed in the Airplane Flight Manual—*
>
> > *(1) [… snip …]*
> >
> > *(2) In the case of an airplane certificated after September 30, 1958 (SR 422A, 422B), that allows a net takeoff flight path that clears all obstacles either by a height of at least 35 feet vertically, or by at least 200 feet horizontally within the airport boundaries and by at least 300 feet horizontally after passing the boundaries.* (Airplanes: Turbine engine powered: Takeoff limitations)

This clearance requirement must be met even under the one-engine-inoperative emergency conditions, as specified by 14 CFR Part 25.

It should be noted that 14 CFR 121.189, 14 CFR 135.379, and 14 CFR 135.398 regulate operations based on the weight of the airplane, i.e., that the allowable gross weight of the airplane and its contents must be managed based on the local conditions such that the airplane can meet the clearance requirement. This does not guarantee that the risk from all emergency conditions that can affect an aircraft during takeoff are mitigated by these rules. However, the safety case informing the clearance numbers is based on the distances at which the risk of a physical collision between the aircraft and the obstacle become unacceptable.

It should also be noted that the regulation states a vertical clearance of at least 35 ft or a horizontal clearance of 200–300 ft depending on the location of the obstacle. This implies a cylindrical volume whose surfaces represent the minimum separation distance (MSD) between an aircraft and an obstacle below which the risk of collision becomes unacceptable. The MSD volume extends vertically from the ground to 35 ft above the obstacle's physical vertical limit and horizontally at least 200 ft beyond the obstacle's horizontal physical boundary, as illustrated in Figure 23.

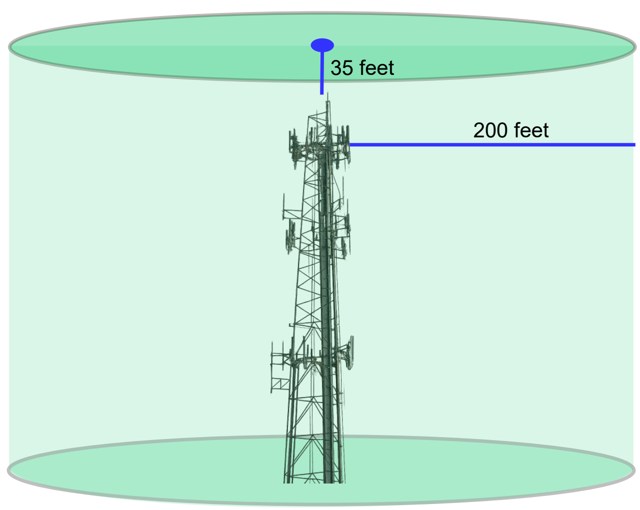


Figure 23. Minimum separation distances from 14 CFR 121.189

Given that the Lower C-Band R&O does not regulate antenna heights beyond the aviation safety requirements in 47 CFR 27.56, and the FCC desires to harmonize rules for the Upper and Lower C-band licenses, the maximum allowable physical height for a structure around airports is limited by the OCS surfaces. Thus, for an AAS antenna located at the physical limit, the volume defined by the MSD will penetrate the OCS, as illustrated in Figure 24 for a building-mounted antenna.

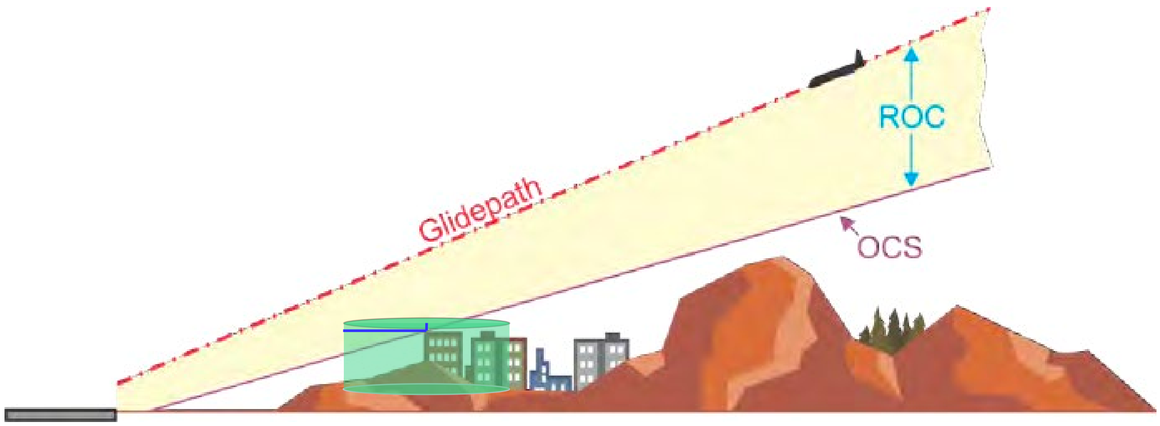


Figure 24. MSD volume penetrating the OCS

This suggests that aircraft locations defined by the OCS+ROC alone may not be the limiting safety case for determining compatibility between sources of RF emissions and RAs. For example, the regulation does not include the climb out of a missed approach during a wind shear event, which could deviate an aircraft's flight path down to the MSD surface. As described above, such convective weather events are not extremely rare, are not always predictable, and are critically dependent on the RA operating according to its integrity, availability, and continuity requirements to enable recovery of the aircraft.

This establishes that the minimum distance to be considered in Step 1 of the general approach (see section 5) is the MSD defined by the obstacle clearance requirements. While Figure 23 suggests that the volume of airspace defined by the MSD surface is cylindrical, practical considerations necessitate consideration of a spherical MSD to cover all aircraft operations and 5G deployment scenarios (see section 6.2).

5.2.3 Source-receiver mutual gain

Step 2 of the general approach involves computing the interference power received at the RA Rx antenna face (i.e., at the fuselage) caused by all emissions source(s) in the encounter scenario (PFD_{Rx}). At the MSD surface, the sources will include all collocated 5G AAS antennas that are servicing a given sector. For fundamental emissions, collocated 5G AAS antennas will not be emitting in the same frequency band at the same time; thus, aggregation of fundamental emissions does not need to be considered, only the maximum power spectral flux density (PFD in $dBW/m^2/MHz$) at the RA Rx antenna surface. However, the PFD of unwanted emissions from all collocated sources must be aggregated, since these generally cover a range of frequencies above and below the fundamental frequency band.

There are no regulations prescribing minimum separation distances between installed 5G AAS antennas, though there are practical limitations and industry guidelines.[9] Minimum vertical separation between antennas is generally established by mechanical concerns such as ice shedding and wind loading. Minimum horizontal separation can vary based on similar mechanical limits and mutual interference considerations. Both can vary between installation sites based on operator-defined requirements.

The Friis Equation (Equation 1) relates the power at the receiver to the emitted power as a function of the range, signal frequency, and gain of both the Tx and Rx antennas. The antenna patterns are a function of spatial angle and frequency

$$\mathrm{G_i} = \mathrm{G_i}(\theta_\mathrm{i}, \varphi_\mathrm{i}, \mathrm{f}), \quad i = T, R \qquad 16$$

which generalizes Equation 14 to indicate that reference frame is defined locally at each antenna. Additionally, both the 5G AAS antenna and the RA Rx antenna are typically linearly polarized, with the AAS antenna radiating on each of two orthogonally polarized emitters for each antenna element in the array such that the power received by the linearly polarized RA Rx antenna depends on the power transmitted by a single polarization of the 5G AAS antenna. Thus, the term $\mathrm{P_{T,EIRP,dBW}}$ in Equation 5 is the power transmitted per polarization (3 dB less than the maximum total EIRP allowed by regulation).

Mutual gain is the product of the 5G AAS antenna gain and the RA Rx gain along a line connecting their phase centers, as shown conceptually in Figure 2. Given that a fixed-wing aircraft is in motion throughout the encounter scenario, the mutual gain will generally be time-dependent of the form:

$$\mathrm{G_M}(\mathrm{t}, \mathrm{f}) = \mathrm{G_T}(\theta_\mathrm{T}(\mathrm{t}), \varphi_\mathrm{T}(\mathrm{t}), \mathrm{f}) * \mathrm{G_R}(\theta_\mathrm{R}(\mathrm{t}), \varphi_\mathrm{R}(\mathrm{t}), \mathrm{f}) \qquad 17$$

or in dB as

$$\mathrm{G_M}(\mathrm{t}, \mathrm{f}) = \mathrm{G_{T,dBi}}(\theta_\mathrm{T}(\mathrm{t}), \varphi_\mathrm{T}(\mathrm{t}), \mathrm{f}) + \mathrm{G_{R,dBi}}(\theta_\mathrm{R}(\mathrm{t}), \varphi_\mathrm{R}(\mathrm{t}), \mathrm{f}) \text{ (dBi)}. \qquad 18$$

5.2.4 Terrain considerations

As described in section 4.4.2, RA sensitivity characteristics are highly dependent on the HAGL of the aircraft. Thus, the local terrain and features around an antenna installation must also be considered. Figure 25 illustrates the case in which the ground is sloping down away from a

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[9] See for example, Telecommunications Industry Association, ANSI/TIA-222-I, "Structural Standard for Antenna Supporting Structures, Antennas and Small Wind Turbine Support Structures," Sept. 2023. Available from: https://store.accuristech.com/standards/tia-ansi-tia-222-i?product_id=2592271.

tower-mounted base station. As an example, a terrain slope of 55º creates a condition that the HAGL at which the RA is operating is 50 ft more than the height of the phase center of the antenna above the base of the tower. Figure 26 shows the same for a cylindrical MSD.

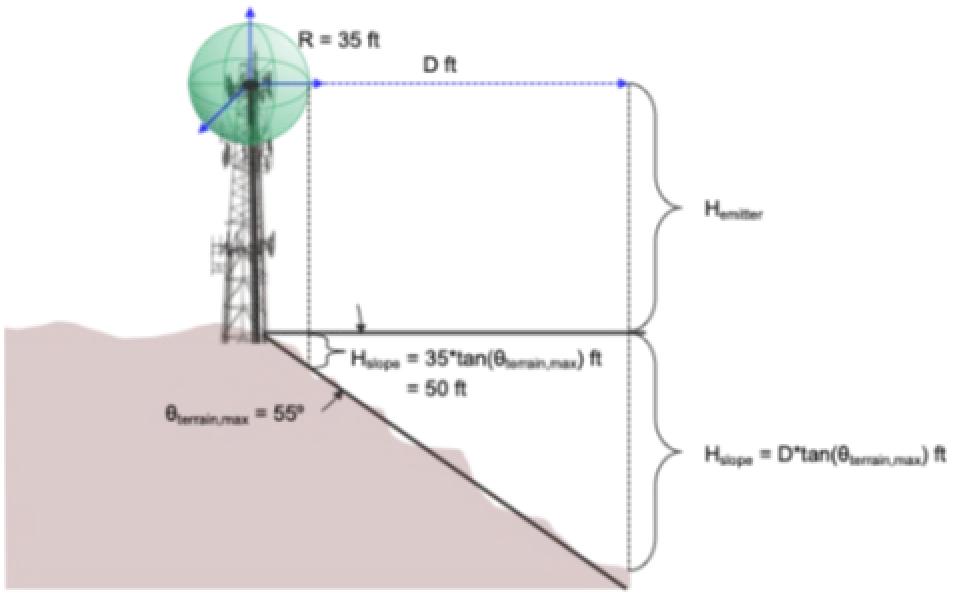

Figure 25. Tower mounted antenna near sloping terrain for spherical MSD

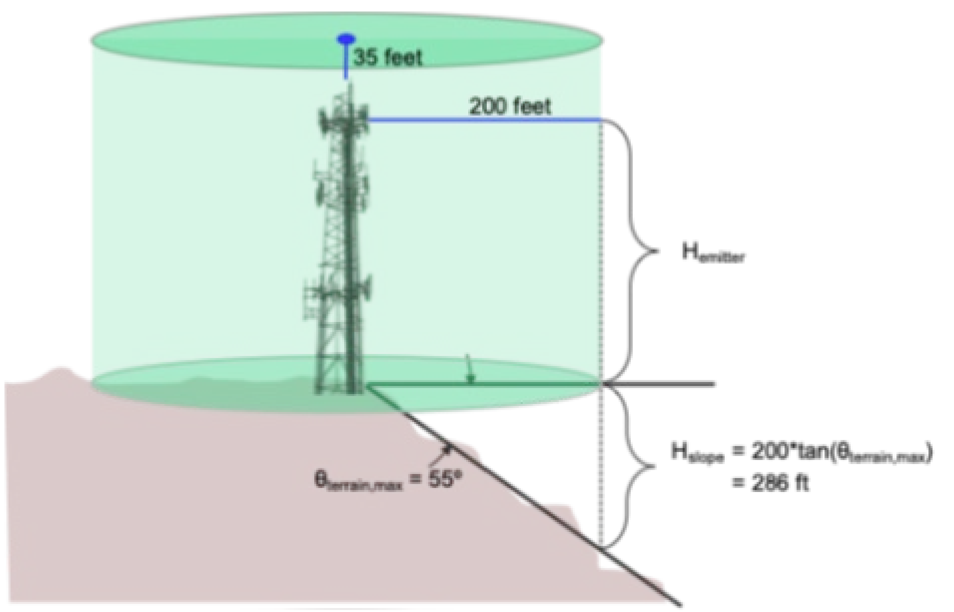

Figure 26. Tower mounted antenna near sloping terrain for cylindrical MSD

This is important when considering the maximum allowed installation height for a 5G base station. An installation that has a maximum tower height nominally defined by an OCS surface will need to account for this additional RA HAGL to be compatible with an RA ITM defined for a specific range of HAGL. The maximum HAGL of the phase center of 5G antenna should be such that (H_{slope}+$H_{emitter}$+35 feet) ≤ 500 ft for the ITM defined in section 4.5.2.

6 RA/5G compatibility analysis

6.1 Parameters for compatibility analyses

The logical steps of a compatibility analysis described in section 5 require a set of input parameters that define the characteristics of the emitter and the encounter scenario to compute the margin of the PFD of the interference signal at the input to the RA Rx relative to the ITM value defined at that reference point. These parameters are summarized in Table 16, which indicates the step in the general process that these are considered.

Table 16. Compatibility analysis input parameters

Parameter	**Analysis Step**	**Description**
Emitter Height	Step 1	The emitter height above the local ground level. For flat terrain, this would be the same as the RA Rx HAGL but could different if the emitter is mounted on sloped or irregular terrain. The emitter height includes the height of any structures on which the antenna is mounted (towers, buildings, etc.)
Vertical/Horizontal MSD	Step 1	The vertical and horizontal MSDs that define the volume surrounding the emitter outside of which, including the surface, the RA performance must meet its specified requirements. See section 5.2.2.
Horizontal Separation Distance	Step 1	This is the horizontal distance between the emitter and the RA Rx antenna.
Frequency Band	Step 2	This is a frequency band of interest outside of the 4200–4400 MHz RA band defined in Table 13. Each of these bands is characterized by a single ITM level value (in dBW/m^2/MHz). For emissions that cover multiple ITM frequency bands, the band closest to the RA band edge (and hence lowest ITM value) determines the band of interest.
Peak Fundamental EIRP	Step 2	The maximum EIRP of the emitter within its tuned fundamental frequency band. This is typically specified as a PSD in dBm/MHz.

Parameter	Analysis Step	Description
Peak Unwanted EIRP	Step 2	The maximum EIRP of the emitter within the 4200–4400 MHz RA band. Since the peak unwanted emissions are typically specified in terms of conducted levels, assumptions must be made about the directivity of unwanted emissions from AAS antennas for frequencies outside their tuned operating bandwidth, as discussed in section 3.3.
Fundamental/unwanted emissions polarization	Step 2	This indicates whether the emitter's specified fundamental emissions limit applies to a single transmitted polarization or is a total that is split evenly between two orthogonal polarizations. If the latter, then the assumed maximum EIRP within each polarization is approximately 3 dB less than the peak fundamental EIRP specified.
Fundamental/Unwanted EIRP Elevation Mask	Step 2	See discussion in section 6.2.
RA Height, HAGL Offset, or Average Terrain Slope	Step 3	The RA Height is the height of the RA Rx antenna above the local terrain below the aircraft. The HAGL Offset is the difference between the RA Height and the Emitter Height. The Average Terrain Slope is an approximation obtained from the slope of the line connecting the emitter to the point on the ground directly below the RA Rx antenna. Since RAs adjust their dynamic range based on HAGL and the tolerance to RFI changes with these adjustments, the measured HAGL must be known in addition to the slant range to the emitter (which can be determined from the Emitter Height, one of these parameters, and the horizontal separation distance).
RA ITM	Step 4	The interference tolerance mask for RAs operating up to the specified operating limit.

Step 2 nominally computes the PFD of the interference signal at the input to the RA Rx antenna, since that is where the RA system-level ITM is defined. This simplifies the ITM requirements for RA systems, allowing flexibility in the design of RA equipment and decoupling compatibility from detailed characterization of the RA system elements. However, interference effects manifest in the RA receiver, so some analyses may consider parameters characterizing the RA Rx antenna gain, installation cable loss, RA transceiver FDR, etc., to evaluate interference signals in the RA receiver detector against protection criteria such as those defined in Rec. ITU-R M.2059. The risk with such an analysis is that RA system parameters that are used in the analysis that are not bound by standards or regulations may not be representative of the breadth of RA systems that are in service.

For aviation services, compatibility analyses must balance fidelity and risk to achieve estimates that minimize the risk of safety escapes while not being overly conservative to the point of preventing efficient use of spectrum. Aviation safety analyses that inform compatibility studies must be conservative as mandated by law due to the risk of loss of life in the event of catastrophic failures in safety-critical aviation systems. Such failures must be shown to be extremely improbable, which is generally accepted to mean that they have an average probability of occurrence per flight hour on the order of 10^{-9}, for an aircraft to be certificated (Federal Aviation Administration, 2024b). However, certification does not require a quantitative safety analysis demonstrating compliance to this probability. Thus, for aviation safety services such as RAs, it is important to drive the compatibility analysis from the perspective of (at least) preserving the level of safety exhibited prior to the introduction of changes to the spectral environment that might pose a risk of harmful interference to the safety-critical system. For RAs, this safety case drives the approach to be used in compatibility analyses to consider static worst-case conditions, i.e., coupling between the RFI emitter and the RA receiver with a free-space separation of 35 ft for the maximum mutual gain between the emitter antenna and the RA Rx antenna at any point in time.

6.2 Fundamental/unwanted EIRP elevation masks

In addition to simplifying the compatibility assessment by employing an RA ITM defined at the RA Rx aperture, a vertical mask that limits EIRP emissions levels as a function of elevation angle can be employed to control fundamental and unwanted emissions from the emitter to achieve compatibility with RAs. Typical AAS antenna installations have a fixed mechanical downtilt of 3º–10º below horizontal and electrical steering 0º–10º below horizontal (see Table A-2). It is important to note that these are typical and not regulated values. The elevation mask is typically defined as an attenuation from the base station maximum EIRP for any elevation angle above the horizontal at the phase center of the base station antenna. Thus, it can be used in place of specific 5G antenna radiation patterns to determine the amount of power directed toward an RA Rx antenna in a given scenario, allowing a compatibility analysis to consider only the propagation losses and the ITM.

Examples of elevation masks that have been deployed in the U.S. are the temporary masks defined in C-band operator Voluntary Agreements (AT&T Services, Inc., T-Mobile, UScellular, Verizon, 2023). The agreements specify an EIRP mask for specific airports and a nationwide EIRP mask for all other airports that are effective until the January 1, 2028 sunset date of the agreement. The mathematical definition for each mask is summarized Table 17, and these definitions are illustrated graphically in Figure 27.

Table 17. Voluntary EIRP elevation mask definitions in the U.S.

Coverage	**Mask**
C-Band Mitigated Airports	Attenuation = min [0, -14 + 20 * log10 (1/sin(Θ+11.5))] dB
Nationwide	Attenuation = min [0, -14 + 20 * log10 (1/sin(Θ))] dB

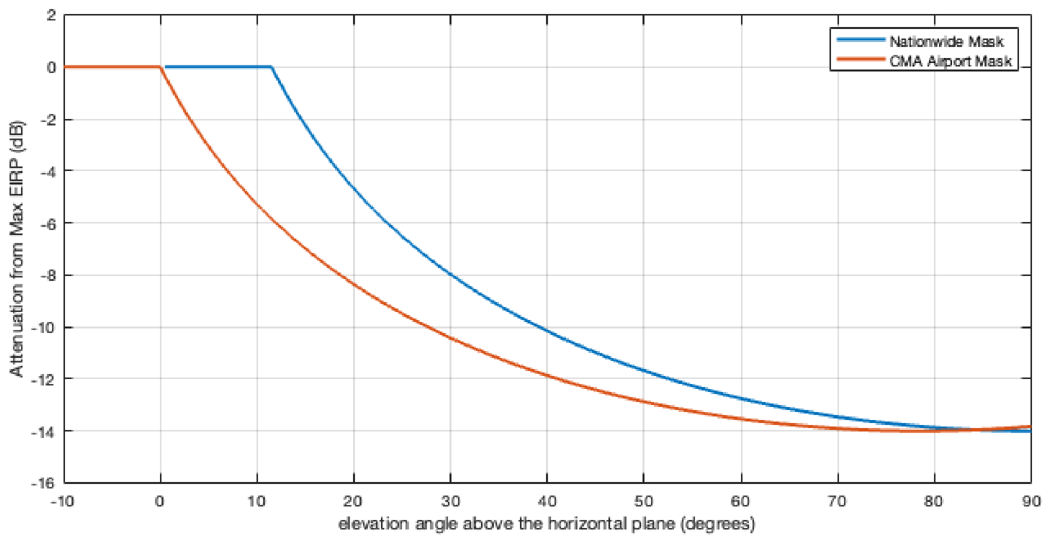

Figure 27. Plot of EIRP elevation masks in voluntary agreements

Canada similarly deployed a nationwide elevation mask in their rollout of Lower C-band services that expired January 1, 2026, while an elevation mask defined for specific airports and frequency bands will continue to apply through 2027 (Innovation, Science and Economic Development Canada, 2023).

These elevation masks are defined with the simple equations in Table 17 as informed by the operators' understanding of achievability given existing 5G base station performance.

Neither the Lower C-band R&O in the U.S. nor similar European regulations specify any restriction on the orientation of 5G antennas. Without regulatory control of the orientation of the emissions from a base station, it must be assumed that the peak EIRP for both fundamental and unwanted emissions can occur in any direction around the base station antenna. This implies that the limiting scenario that must be considered is that of the spherical MSD, as illustrated in Figure 25, for which the peak EIRP can occur at any point on the surface of the MSD.

6.3 Compatibility in the context of a spherical MSD

As established above, the limiting scenario driving the safety case for assessing the compatibility of C-band 5G emitters and RAs is the one illustrated in Figure 28.

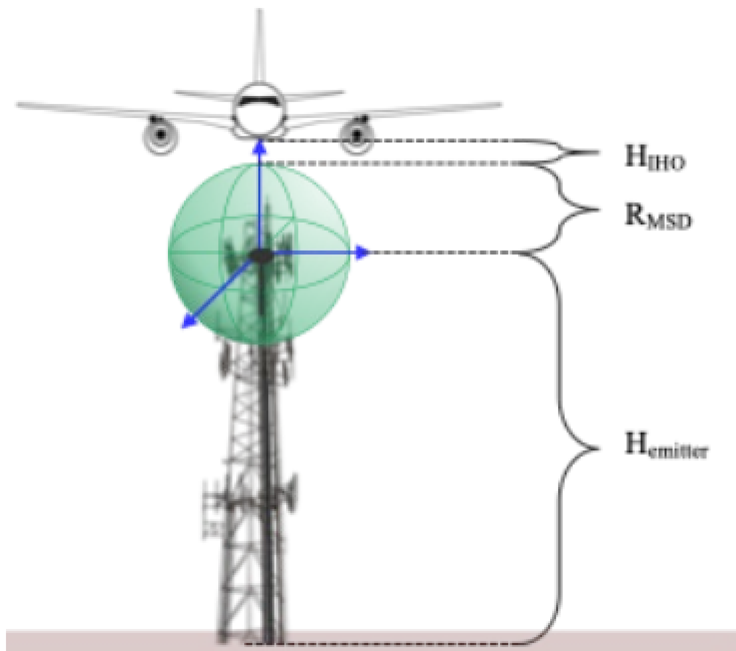

Figure 28. Close encounter scenario

Table 18. Close encounter scenario compatibility parameters

Parameter	Value	Description
Emitter Height	$H_{emitter}$ = 450 ft	HAGL of the phase center of the 5G antenna in feet
MSD	R_{MSD} = 35 ft	radius of spherical MSD
Horizontal Separation Distance	0 ft	(Note 1)
Frequency Band	4060–4160 MHz	(Note 2)
Peak Fundamental EIRP	$P_{T,\mathrm{F}}$ = 65 dBm/MHz	Aggregate power of all antenna elements in any given sector of a base station.

Parameter	Value	Description
Peak Unwanted Emissions (conducted)	$P_{T,\text{U.E.}}$ = -13 dBm/MHz	Limit for emissions beyond the edge of a base station's authorized band
Fundamental/unwanted emissions polarization	Dual	Total power split equally between two cross-polarized elements
Fundamental/Unwanted EIRP Elevation Mask	None	
RA Height	$H_{emitter}$+R_{MSD}+H_{IHO} (ft) H_{IHO} = 0 ft	(Note 3)
RA ITM	6.5 dBW/m²/ MHz	(Note 4)
Note 1: Aircraft flies over the emitter such that the phase centers of the emitter and RA Rx antenna align, creating maximum mutual gain Note 2: The fundamental interference signal is assumed to occupy a 100 MHz band with the upper edge at 4160 MHz. Note 3: The obstacle clearance regulations pertain to the lowest point on the aircraft, which is typically the bottom of the landing gear in a takeoff or landing scenario. The offset between this point and the face of the RA Rx antenna represents a fixed installation height offset that is compensated in the height reported by the RA. Note 4: While the ITM level varies with frequency across the assumed band, the signal must be at or below the ITM at all frequencies to ensure proper operation of the RA. Since we assume a constant PSD across the interference signal bandwidth, the lowest ITM value in the occupied band is the limiting case.		

This scenario is the limiting case consistent with aviation safety requirements and current or proposed regulatory controls based on the known performance characteristics for existing aircraft, RAs, and 5G emitters. As described in section 5.2, this is justified in part by the non-zero occurrence of off-nominal windshear events and the requirement that failures of the RA equipment are extremely improbable.

Adapting the Friis equation (Equation 5) for this scenario yields

$$P_{RA\,Rx} = P_{T,EIRP} - L_P - 10\log_{10}(4\pi) - 20\,log_{10}(R_{MSD} + H_{IHO}) \qquad 19$$

Equation 19 and Table 18 can be used to compute the PFD at the RA Rx antenna, but compatibility is assessed by comparing this value to the maximum level at which an RA continues to meet all its performance requirements, i.e., is free from harmful interference. Additionally, as an aviation safety service, the analysis must include the Aviation Safety Margin (ASM), as recommended by ICAO and discussed in §4.5.2. The compatibility assessment is thus

$$P_{RA\,Rx} \leq ITM(f) - ASM \quad (20)$$

Since the emitter characteristics differ for in-band and out-of-band emissions, these are considered separately.

6.3.1 Compatibility of RAs with fundamental emissions

Fundamental emissions in the assigned bandwidth for a specific base station in a given sector have the advantage of having regulated emission level limits defined in terms of EIRP. Thus, knowledge of the specific maximum gain for a given AAS antenna is not necessary.

All parameters should be traceable to physical or regulatory bounds to establish compatibility. Parameters that are not as traceable should provide justification for the validity of the assumed values. Table 19 and the following paragraphs provides this information for the close encounter scenario.

Table 19. Close encounter emitter parameters

Parameter	**Value**	**Source**
$P_{T,EIRP}$ Fundamental Emissions	3280 W/MHz (65.2 dBm/MHz) EIRP	(Federal Communications Commission, 2020) at 335
$P_{T,\mathrm{EIRP}}$ Unwanted Emissions	-13 dBm/MHz conducted	(Federal Communications Commission, 2020) at 343 (Note 1)
L_P	3 dB	ITU-R, see Table A- 2, line 1.5
R_{MSD}	35 ft	(Federal Aviation Administration, 2026) Table 6
H_{IHO}	0 ft	See below
ITM(f)	Table 13	(Federal Aviation Administration, 2026) Table 3 (Note 2)
ASM	6 dB	(ICAO, 2018, pp. 9-8) (Federal Aviation Administration, 2026) Table 6
Note 1: Since the source document provides a conducted limit instead of an EIRP limit, assumptions must be made concerning the antenna gain at the unwanted emission frequencies. See section 3.3 and section 6.3.2. Note 2: Table 13 represents the ITM proposed in the FAA NPRM, with the exception that the value from 4170–4180 MHz is reduced by 6 dB per comments submitted to FAA docket FAA-2025-5666 by Honeywell Aerospace (Honeywell Aerospace, 2026).		

6.3.1.1 Fundamental emissions power and polarization

The FCC limited the aggregate transmitted power of all antenna elements in any given sector of a base station to 1640 W/MHz EIRP for non-rural areas and 3280 W/MHz in rural areas for emissions in the licensed operating band for Lower C-band services. Furthermore, the FCC has indicated a preference to maintain harmonized technical rules for new services in the Upper C-band (Federal Communications Commission, 2025). 5G antennas employ cross-polarized emitters at ±45º (see Table A- 2, line 1.5) over which the total power is equally distributed, thus the polarization loss for linearly polarized RA antennas is 3 dB.

6.3.1.2 Minimum separation distance

Section 5 laid out the obstacle clearance regulations and off-nominal flight considerations that inform the safety case leading to a minimum separation distance of 35 ft. Since this is the limit below which the risk of physical collision is the primary consideration, the obstacle clearance regulations apply to the part of the aircraft closest to the obstacle. In a landing scenario, this is determined by the type of aircraft, the state of the landing gear, and the attitude of the aircraft.

Every RA has a configurable Installation Height Offset that compensates for the delay of the RA return signal caused by the fixed distance between the RA Rx antenna and the ground when the aircraft is on the ground and the additional delay caused by the RF cable from the RA Rx antenna to the RA transceiver. This allows the reported HAGL to be referenced to the bottom of the landing gear, i.e., the RA reports 0 ft when the aircraft is on the tarmac.

The pitch attitude achievable by a fixed-wing aircraft at takeoff is limited by the tail strike pitch angle. This is the angle of the fuselage relative to the runway when the tail of the fuselage and the rear landing gear are in contact with the ground and can be used to estimate H_{IHO} in Equation 19. The height of the RA Rx above the ground at the tail strike angle depends on where the antenna is mounted on the aircraft, which is often at a location between the forward and rear landing gear. Figure 29 illustrates the geometry and parameters necessary to estimate H_{IHO}.

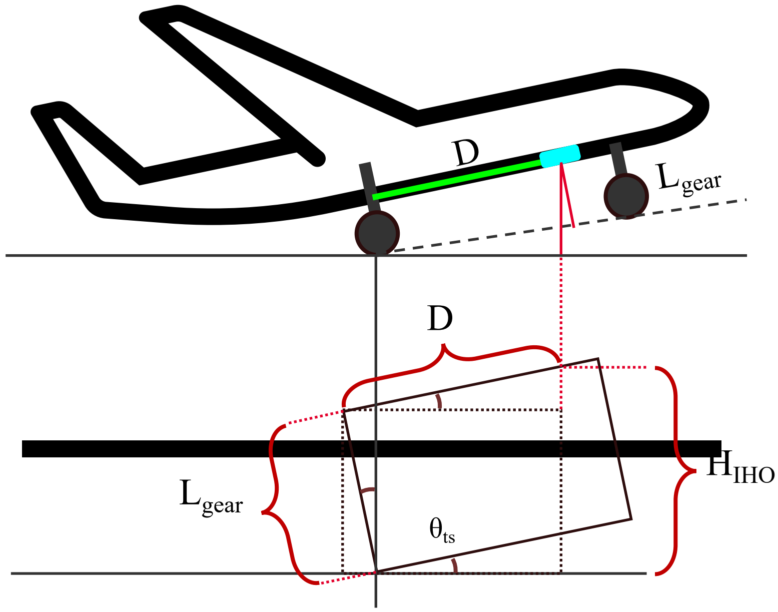

Figure 29. Tail strike geometry

These parameters are highly dependent on the specific aircraft configuration, but values that are representative of a single-aisle commercial transport airplane are D ~ 30ft, L_{gear} ~ 8ft, and θ_{ts} ~ 13º. This gives

$$H_{IHO} = D * \sin(\theta_{ts}) + L_{gear} * \cos(\theta_{ts}) \sim 14.5 \text{ feet.} \qquad 21$$

H_{IHO} will be smaller for aircraft with RAs installed closer to the tail and larger for longer aircraft with RAs mounted closer to the nose. The total attenuation $(20 * \log_{10}(R_{MSD} + H_{IHO}))$ due to propagation for H_{IHO} in the range of 0–20 ft would be 20.6–24.5 dB.

However, the pitch attitude of an aircraft during flight can exceed the tail strike angle, limited by the stall conditions for a specific aircraft. Emergent conditions, such as a wind shear escape, that might bring an aircraft into close proximity to an emitter as described by this close-encounter scenario require extreme handling of the aircraft. Thus, we must assume that $H_{IHO} = 0$ in this analysis.

6.3.1.3 Interference tolerance

As discussed in section 4.5.2, Table 13 provides the proposed aggregate interference levels above which RAs compliant to relevant TSOs are not required to meet all performance requirements. The table specifies PFD values referenced to the input of the RA Rx antenna for bandwidths as small as 10 MHz. However, 5G systems operating under flexible-use rules can operate with much larger bandwidths. The limiting PFD value is thus the lowest PFD value for any frequency in the operational bandwidth of the 5G base station. This is illustrated in Figure 30 for a 5G signal operating in the frequency band 4060–4160 MHz, which shows that the maximum PFD that an RA can tolerate and still meet its performance requirements is 6.5 $dBW/m^2/MHz$, as determined by the ITM value in the frequency band 4150 MHz $\leq f <$ 4160 MHz. The maximum interference signal PFD that can be present at the RA Rx aperture is the one found by applying the ASM, yielding a maximum PFD of 0.5 $dBW/m^2/MHz$, as indicated in the third column of Table 13.

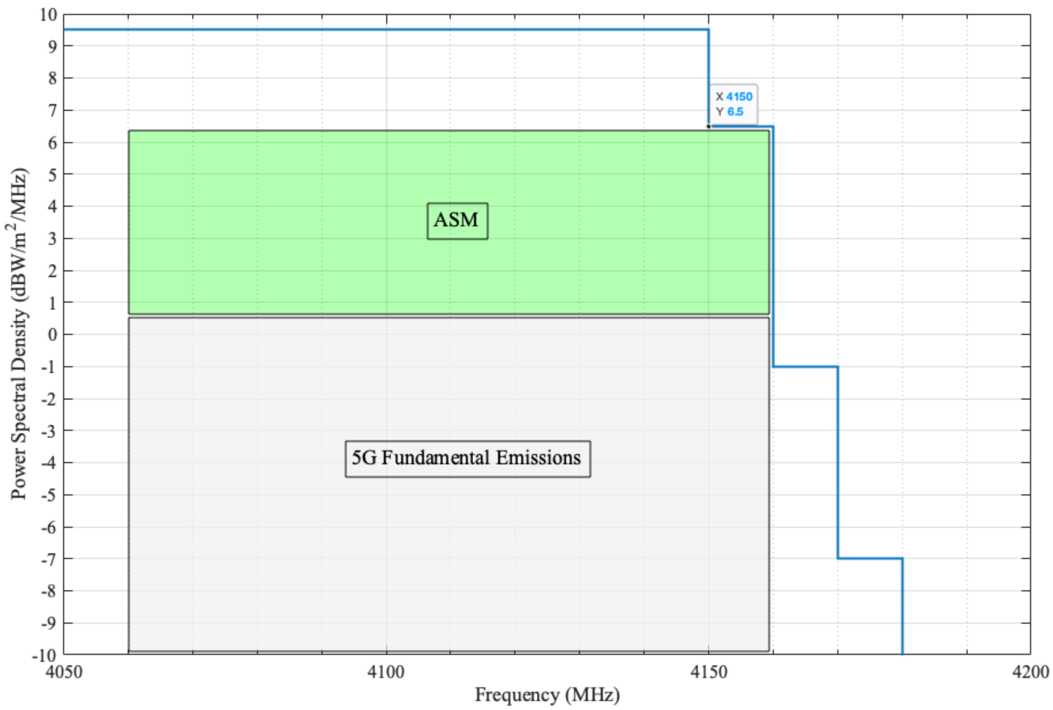

Figure 30. Example of 5G emitter PFD limits for proposed ITM

6.3.1.4 Compatibility evaluation

Applying the parameters values in Table 19 to Equations 19 and 20 yields

$$P_{RA\,Rx} = P_{T,EIRP} - L_P - 10\log_{10}(4\pi) - 20\log_{10}(R_{MSD} + H_{IHO})$$
$$= 0.4\ \text{dBW/m}^2\text{/MHz},$$

and

$$P_{RA\,Rx} \leq ITM(f) - ASM$$
$$0.4 \leq 0.5\ \text{dBW/m}^2\text{/MHz}$$

Thus, fundamental 5G transmissions of 65 dBm/MHz in the frequency band 4060–4160 MHz are compatible with RAs that meet the proposed ITM requirement.

6.3.2 Compatibility of RAs with unwanted emissions

The FCC Lower C-Band R&O specifies that base stations suppress their emissions beyond the edge of their authorization to a conducted power level of -13 dBm/MHz (Federal Communications Commission, 2020). However, compatibility analysis requires quantifying the amount of power radiated in the direction of the RA Rx antenna. Application of Monte Carlo analysis, such as that recommended in Rec. ITU-R M.2101, requires characterization of the emitter antenna gain profile for all frequencies of interest; in this case, for unwanted emissions falling in the 4200–4400 MHz RA band. As discussed in section 3.3, the specific implementation parameters and gain profile for AAS antennas are not regulated, so no standard gain profile can be assumed for unwanted emissions in the RA band for all 5G antenna models/configurations. Thus, it must be assumed in this close-encounter scenario that the maximum EIRP emission level from the emitter in the direction of the phase center of the RA Rx antenna is the regulated conducted power multiplied by the maximum subarray gain pattern of 11.1 dBi. This yields

$$\begin{aligned} P_{T,EIRP} &= P_{T,conducted} + A_{sub,\max} \\ &= -13 + 11.1 = -1.9 \text{ dBm/MHz EIRP} \\ &= -31.9 \text{ dBW/MHz EIRP} \end{aligned} \qquad 22$$

6.3.2.1 Source aggregation

The ITM in section 4.5.2 defines the tolerance for the total RMS power flux density from all sources measured at the RA Rx aperture. 5G networks are configured to avoid self-interference. Thus, an aggregation of fundamental emissions from multiple collocated base stations arriving at the RA Rx antenna at the same instant in time and in the same frequency band does not need to be considered. This is not true for unwanted emissions. The FAA safety case assumes that a limiting aggregation factor of $F_{agg} = 6$ dB is necessary to account for all possible 5G installation conditions (Federal Aviation Administration, 2026, p. 474). This represents a worst case for a tower with four independent AAS antennas mounted in a given cell and equidistant from the RA Rx antenna so that the total interference due to unwanted emissions is the incoherent sum of their nearly equal PFD values at the RA Rx aperture. This may be overly pessimistic, but it provides a bound for the maximum unwanted emission power to which an RA may be exposed. This makes Equation 19

$$P_{RA\,Rx} = P_{T,EIRP} - L_P - 10\log_{10}(4\pi) - 20\log_{10}(R_{MSD}) + F_{agg} \qquad 23$$

6.3.2.2 Compatibility evaluation

Applying the parameter values in Table 19 to Equations 23 and 20 yields

$$P_{RA\,Rx} = P_{T,EIRP} - L_P - 10\log_{10}(4\pi) - 20\log_{10}(R_{MSD}) + F_{agg}$$

$$= -60.5 \text{ dBW/m}^2\text{/MHz}$$

and

$$P_{RA\,Rx} \leq ITM(f) - ASM$$

$$-60.5 \nleq -88 \text{ dBW/m}^2\text{/MHz}$$

Thus, in this scenario conducted, unwanted 5G emissions of -13 dBm/MHz in the frequency band 4200-4400 MHz are not compatible with RAs that meet the proposed ITM requirement, with a negative margin of

$$Margin = ITM(f) - ASM - P_{RA\,Rx} = -27.5 \text{ dB}$$

It is noted that although the regulation of unwanted emissions, which includes both the out-of-band emissions close to the edge of the base station's authorization and spurious emissions at frequencies beyond those, specifies only the conducted level at the edge of the licensed operating frequency band, and that out-of-band emission level are significantly attenuated (see section 3.1.2). However, given that the regulated fundamental power is nearly 150 dB higher than the proposed in-band interference tolerance limit, the EIRP of the 5G unwanted emissions falling in the adjacent RA band must be bound either by physics or regulation to determine the compatibility in Equation 20 using a value for P_T other than that in Equation 22.

The required EIRP to achieve compatibility in this scenario can be estimated by working backwards from the ITM value:

$$P_{T,EIRP} = ITM(@4300\text{MHz})(\text{dBW/m}^2\text{/MHz}) + 30 + L_P + 10\log_{10}(4\pi)$$
$$+20\log_{10}(R_{MSD}) - F_{agg} - ASM \quad (24)$$

This yields a maximum unwanted emission level (spread over two polarizations) of

$$P_{T,EIRP} = -29.4 \text{ dBm/MHz EIRP}$$

Thus, limiting 5G unwanted emissions falling in the 4200–4400 MHz RA band to a maximum of -30 dBm/MHz EIRP will ensure compatibility with the RAs in the context of the close-encounter scenario given then parameter values used in this analysis.

7 Conclusion

While RAs have contributed to the success of on-board safety systems for decades, existing RA models were largely designed when the RF environment in adjacent frequency bands consisted of low-power satellite services, and minimum performance standards did not include explicit interference tolerance requirements. Improvements in RA tolerance to RFI have been rapidly implemented on a temporary basis to provide compatibility between RAs and new IMT services in the Lower C-band in the United States. Further significant improvements have been proposed in the form of an ITM that reflects C-band RFI tolerance that is achievable with existing technology while still meeting performance requirements and the RAs intended function as a critical component of on-board safety systems. Future RA system designs that demonstrate compliance with performance requirements while subject to RFI at the limits described by the ITM will thus define the limit to compatibility with 5G systems that can be achieved solely through RA equipment modification.

The limiting case that bounds the remaining parameters that determine compatibility between 5G systems and RA systems is the close-encounter scenario in which an RA receive antenna flies as close as 35 ft from the 5G emitter. Such an occurrence is remote, but establishing bounding conditions using this scenario is justified by aviation safety regulations that mandate that catastrophic failure conditions must be extremely improbable. Furthermore, aircraft can and do operate outside the regulated operational bounds in emergency conditions, while safety must still be preserved to avoid loss of life. Regulating RA interference tolerance to the proposed ITM in combination with technical rules governing implementation of flexible-use systems in frequency bands adjacent to the 4200–4400 MHz RA band that limit emissions to levels compatible with the ITM in the context of the close-encounter scenario is necessary to support broad deployment of new C-band radiocommunications systems while preserving or improving existing levels of aviation safety. As this represents a worst-case scenario, compatibility conclusions are extensible to other encounter scenarios.

This study finds that radiocommunications systems with fundamental emissions in the frequency band 3700–4160 MHz, limited to a maximum of 65 dBm/MHz EIRP, and unwanted emissions falling in the frequency band 4200–4400 MHz limited to a maximum of -30 dBm/MHz EIRP, are compatible with future RA systems that meet their performance requirements while exposed to RFI at the proposed ITM level.

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A ITU-R IMT Characteristics

The base station parameters recommended for compatibility studies for in the ITU-R are provided in the WP5D Chairman's Report, Table 6-1 (ITU-R, 2021, p. 14) for non-AAS implementations and in Table 9 for AAS implementations (ITU-R, 2021, p. 22). These are reproduced below as Table 20 and Table 21 below. Similarly, Table 22 reproduces the UE parameters for bands between 3 and 6 GHz provided in the WP5D Chairman's Report (ITU-R, 2021, pp. Table 6-2).

Table A- 1. Deployment-related base station parameters for bands between 3 and 6 GHz

	Rural	**Urban/suburban macro**	**Urban small cell (outdoor)/Micro cell**	**Indoor (small cell)**
Base station characteristics/Cell structure				
Cell radius / Deployment density (non-AAS)	1.2 km / isolated BSs or a cluster of four BSs with the density of 0.001-0.006 BSs/km^2 (Note 2)	Typical cell radius 0.3 km urban / 0.6 km suburban	1-3 per urban macro cell <1 per suburban macro site	Depending on indoor coverage/ capacity demand
Cell radius / Deployment density (AAS)	1.6 km / isolated BSs or a cluster of four BSs with the density of 0.001-0.006 BSs/km^2 (Note 2)	Typical cell radius 0.4 km urban / 0.8 km suburban (10 BSs/km^2 urban / 2.4 BSs/km^2 suburban (Note 2))	1-3 per urban macro cell <1 per suburban macro site	Depending on indoor coverage/ capacity demand
Antenna height	35 m	20 m urban / 25 m suburban	6 m	3 m
Sectorisation	3 sectors	3 sectors	Single sector	Single sector

	Rural	**Urban/suburban macro**	**Urban small cell (outdoor)/Micro cell**	**Indoor (small cell)**
Non-AAS BS Downtilt (Note 1)	3 degrees	10 degrees urban / 6 degrees suburban	N/A	N/A
Frequency reuse	1	1	1	1
Non-AAS BS antenna pattern (Note 1)	Recommendation ITU-R F.1336 (*recommends* 3.1) ka = 0.7 kp = 0.7 kh = 0.7 kv = 0.3 Horizontal 3 dB beamwidth: 65 degrees Vertical 3 dB beamwidth: determined from the horizontal beamwidth by equations in Recommendation ITU-R F.1336. Vertical beamwidths of actual antennas may also be used when available	Recommendation ITU-R F.1336 (*recommends* 3.1) ka = 0.7 kp = 0.7 kh = 0.7 kv = 0.3 Horizontal 3 dB beamwidth: 65 degrees Vertical 3 dB beamwidth: determined from the horizontal beamwidth by equations in Recommendation ITU-R F.1336. Vertical beamwidths of actual antennas may also be used when available	Recommendation ITU-R F.1336 (omni: *recommends* 2)	Recommendation ITU-R F.1336 (omni: *recommends* 2)
Antenna polarisation	Linear/±45 degrees	Linear/±45 degrees	Linear	Linear
Indoor base station deployment	N/A	N/A	N/A	100%
Indoor base station penetration loss	N/A	N/A	N/A	Recommendation ITU-R P.2109

	Rural	**Urban/suburban macro**	**Urban small cell (outdoor)/Micro cell**	**Indoor (small cell)**
Below rooftop base station antenna deployment (Report ITU-R M.2292) (Note 1)	0%	Urban: 50% Suburban: 0%	100%	N/A
Non-AAS BS Feeder loss (Note 1)	3 dB	3 dB	3 dB	3 dB
Typical channel bandwidth	40 or 80 or 100 MHz	40 or 80 or 100 MHz	40 or 80 or 100 MHz	40 or 80 or 100 MHz
Maximum Non-AAS BS output power (Note 1)	52 dBm in 40 MHz 55 dBm in 80 MHz 56 dBm 100 MHz	49 dBm in 40 MHz 52 dBm in 80 MHz 53 dBm in 100 MHz	24 dBm in 40 or 80 or 100 MHz	24 dBm in 40 or 80 or 100 MHz
Maximum base station non-AAS antenna gain (Note 1)	18 dBi	18 dBi	5 dBi	0 dBi
Maximum base station output power/sector (e.i.r.p.) (non-AAS BS) (Note 1)	67 dBm in 40 MHz 70 dBm in 80 MHz 71 dBm in 100 MHz	64 dBm in 40 MHz 67 dBm in 80 MHz 68 dBm in 100 MHz	29 dBm in 40 or 80 or 100 MHz	24 dBm in 40 or 80 or 100 MHz

	Rural	**Urban/suburban macro**	**Urban small cell (outdoor)/Micro cell**	**Indoor (small cell)**
Network loading factor (base station load probability X%) (see section 3.4 (ibidem) below and Rec. ITU-R M.2101 Annex 1, section 3.4.1 and 6)	50%	20%, 50%	20%, 50%	20%, 50%
Average Non-AAS BS power/sector (e.i.r.p.) taking into account activity factor (Note 1)	Use Recommendation ITU-R M.2101	Use Recommendation ITU-R M.2101	Use Recommendation ITU-R M.2101	Use Recommendation ITU-R M.2101
TDD / FDD	TDD	TDD	TDD	TDD
BS TDD activity factor	75%	75%	75%	75%
Note 1: This parameter is only applicable for non-AAS base stations. Antenna characteristics for AAS base stations (for frequency bands above 1710 MHz) are provided in Table 9. Note 2: "1 BS" = 1 sector in 3-sector cell.				

Table A- 2. Beamforming antenna characteristics for IMT base stations in 1710-4990 MHz

		Rural macro	**Suburban macro**	**Urban macro**	**Urban small cell (outdoor)/Micro cell**	**Indoor (small cell)**
1	**Base station antenna characteristics**					
1.1	Antenna pattern	Refer to the extended AAS model in Table A of Annex 3			Refer to section 5 of Recommendation ITU-R M.2101	N/A
1.2	Element gain (dBi) (Note 1)	6.4	6.4	6.4	6.4	N/A
1.3	Horizontal/vertical 3 dB beam width of single element (degree)	90º for H 65º for V	90º for H 65º for V	90º for H 65º for V	90º for H 65º for V	N/A
1.4	Horizontal/vertical front to back ratio (dB)	30 for both H/V	30 for both H/V	30 for both H/V	30 for both H/V	N/A
1.5	Antenna polarization	Linear ±45º	Linear ±45º	Linear ±45º	Linear ±45º	N/A
1.6	Antenna array configuration (Row × Column) (Note 2)	4 × 8 elements	4 × 8 elements	4 × 8 elements	8 × 8 elements	N/A
1.7	Horizontal/Vertical radiating element/sub-array spacing, d_h /d_v	0.5 of wavelength for H, 2.1 of wavelength for V	0.5 of wavelength for H, 2.1 of wavelength for V	0.5 of wavelength for H, 2.1 of wavelength for V	0.5 of wavelength for H, 0.7 of wavelength for V	N/A
1.7a	Number of element rows in sub-array, M_sub	3	3	3	N/A	N/A
1.7b	Vertical radiating element spacing in sub-array, $d\_(v,sub)$	0.7 of wavelength of V	0.7 of wavelength of V	0.7 of wavelength of V	N/A	N/A
1.7c	Pre-set sub-array down-tilt, $\theta\_subtilt$ (degrees)	3	3	3	N/A	N/A

		Rural macro	**Suburban macro**	**Urban macro**	**Urban small cell (outdoor)/Micro cell**	**Indoor (small cell)**
1.8	Array Ohmic loss (dB) (Note 1)	2	2	2	2	N/A
1.9	Conducted power (before Ohmic loss) per antenna element/sub-array (dBm) (Note 5, 6)	28	28	28	16	N/A
1.10	Base station horizontal coverage range (degrees)	±60	±60	±60	±60	N/A
1.11	Base station vertical coverage range (degrees) (Notes 3, 4, 7)	90-100	90-100	90-100	90-120	N/A
1.12	Mechanical downtilt (degrees) (Note 4)	3	6	6	10	N/A
1.13	Maximum base station output power/sector (e.i.r.p.) (dBm)	72.28	72.28	72.28	61.53	N/A

		Rural macro	Suburban macro	Urban macro	Urban small cell (outdoor)/Micro cell	Indoor (small cell)
Note 1: The element gain in row 1.2 includes the loss given in row 1.8 and is per polarization. This means that this parameter in row 1.8 is not needed for the calculation of the BS composite antenna gain and e.i.r.p. Note 2: For the small/micro cell case, 8 × 8 means there are 8 vertical and 8 horizontal radiating elements. For the extended AAS model case, 4 × 8 means there are 4 vertical and 8 horizontal radiating sub-arrays. Note 3: The vertical coverage range is given in global coordinate system, i.e. 90° being at the horizon. Note 4: The vertical coverage range in row 1.11 includes the mechanical downtilt given in row 1.12. Note 5: The conducted power per element assumes 8 × 8 × 2 elements for the micro/small cell case, and 4 x 8 x 2 sub-arrays for the macro case (i.e. power per H/V polarized element). Note 6: In sharing studies, the transmit power calculated using row 1.9 is applied to the typical channel bandwidth given in Table 5-1 and 6-1 respectively for the corresponding frequency bands. Note 7: In sharing studies, the UEs that are below the base station vertical coverage range can be considered to be served by the "lower" bound of the electrical beam, i.e. beam steered towards the max. coverage angle. A minimum BS-UE distance along the ground of 35m should be used for urban/suburban and rural macro environments, 5 m for micro/outdoor small cell, and 2 m for indoor small cell/urban scenarios.						

Table A- 3. UE parameters for bands between 3 and 6 GHz

	Rural	Urban/suburban macro	Small cell (outdoor)/Micro cell	Indoor (small cell)
User terminal characteristics				
Indoor user terminal usage	50%	70%	70%	100%
Indoor user terminal penetration loss	Rec. ITU-R P.2109 (traditional building)	Rec. ITU-R P.2109	Rec. ITU-R P.2109	Rec. ITU-R P.2109
User equipment density for terminals that are transmitting simultaneously (Note 1)	3 UEs per sector	3 UEs per sector	3 UEs per sector	3 UEs per sector

	Rural	Urban/suburban macro	Small cell (outdoor)/Micro cell	Indoor (small cell)
UE height (Note 2)	1.5 m	1.5 m	1.5 m	1.5 m
Average user terminal output power	Use transmit power control	Use transmit power control	Use transmit power control	Use transmit power control
Typical antenna gain for user terminals	−4 dBi	−4 dBi	−4 dBi	−4 dBi
Body loss	4 dB	4 dB	4 dB	4 dB
UE TDD activity factor	25%	25%	25%	25%
Transmit power control				
Power control model	Refer to Recommendation ITU-R M.2101 Annex 1, section 4.1			
Maximum user terminal output power, PCMAX	23 dBm	23 dBm	23 dBm	23 dBm
Power (dBm) target value per RB, P0_PUSCH (Note 3)	−92.2	−92.2	−87.2	−87.2
Path loss compensation factor, α (same as "balancing factor" mentioned in Rec. ITU-R M.2101)	0.8	0.8	0.8	0.8
Note 1: UEs share equally the channel bandwidth, i.e. each UE is allocated 1/3 of the channel bandwidth (see Rec. ITU-R M.2101, Section 3.4.1, item 1e-f.). In sharing studies, it is assumed that the AAS BS beamforms towards each UE using the entire array. Note 2: In principle, indoor UEs are distributed over different floors of the building. It should be noted that the number of floors of buildings vary within the environment and among the countries. Moreover, the number of floors of buildings is not related to Macro BS antenna height (parameter given in the Table). In particular in small cities, sub-urban and rural areas, many or most of antennas are installed on masts. Therefore, for outdoor BSs, indoor UEs are assumed to be modelled on the ground floor for the sharing study. Note 3: The target power is defined per Resource Block (RB), considering 180 kHz RB bandwidth corresponding to 15 kHz subcarrier spacing.				