RTCA, Inc.
1150 18th Street, NW, Suite 910
Washington, DC 20036, USA

Assessment of C-Band Mobile Telecommunications Interference Impact on Low Range Radar Altimeter Operations

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Prepared by: SC-239

Copies of this document may be obtained from:

RTCA, Inc.
1150 18th St. NW, Suite 910
Washington, D.C. 20036, USA

Telephone: 202-833-9339
Facsimile: 202-833-9434
Internet: www.rtca.org

Please call RTCA for price and ordering information.

FOREWORD

This document was prepared by Special Committee 239 (SC-239) and approved by the RTCA Program Management Committee (PMC) on October 7, 2020.

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- coalescing aviation system user and provider technical requirements in a manner that helps government and industry meet their mutual objectives and responsibilities;

- analyzing and recommending solutions to the system technical issues that aviation faces as it continues to pursue increased safety, system capacity and efficiency;

- developing consensus on the application of pertinent technology to fulfill user and provider requirements, including development of minimum operational performance standards for electronic systems and equipment that support aviation; and

- assisting in developing the appropriate technical material upon which positions for the International Civil Aviation Organization and the International Telecommunication Union and other appropriate international organizations can be based.

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EXECUTIVE SUMMARY

The Federal Communications Commission (FCC) has recently taken action to reallocate a portion of the 3.7–4.2 GHz frequency band, making the frequency spectrum from 3.7–3.98 GHz available for flexible use including 5G applications. This spectrum will be auctioned to new licensees beginning in December 2020. The aviation industry noted in the FCC rulemaking process that deployment of 5G networks in this frequency band may introduce harmful radio frequency (RF) interference to radar altimeters currently operating in the globally-allocated 4.2–4.4 GHz aeronautical band. Radar altimeters are deployed on tens of thousands of civil aircraft in the United States and worldwide to support several critical safety-of-life aircraft functions throughout multiple phases of flight. Radar altimeters are the *only* sensor onboard a civil aircraft which provides a direct measurement of the clearance height of the aircraft over the terrain or other obstacles, and failures of these sensors can therefore lead to incidents with catastrophic results resulting in multiple fatalities.

The aviation industry has explained to the FCC that further study was needed to adequately characterize the performance of currently fielded radar altimeters operating in the presence of RF interference from future 5G networks in the 3.7–3.98 GHz band, as well as the risk of harmful interference and associated impacts to safe aviation operations, such that appropriate mitigations could be employed before such 5G networks begin operation. RTCA Special Committee 239 (SC-239) formed a 5G Task Force in April 2020 to lead this study effort as a multi-stakeholder group with open participation from the interested public.

Using technical information supplied by the mobile wireless industry and radar altimeter manufacturers, this report provides a quantitative evaluation of radar altimeter performance regarding RF interference from expected 5G emissions in the 3.7–3.98 GHz band, as well as a detailed assessment of the risk of such interference occurring and impacting aviation safety. This process included testing of many representative radar altimeter models to empirically determine their tolerance to expected 5G interference signals; the development of interference models and assumptions to predict the received interference levels across a wide range of operational scenarios, such that they may be compared to the empirical tolerance limits; and a thorough study of multiple real-world operational scenarios for civil aircraft in which the presence of the expected 5G interference will result in a direct impact to aviation safety.

The results presented in this report reveal a major risk that 5G telecommunications systems in the 3.7–3.98 GHz band will cause harmful interference to radar altimeters on all types of civil aircraft—including commercial transport airplanes; business, regional, and general aviation airplanes; and both transport and general aviation helicopters. The results of the study performed clearly indicate that this risk is widespread and has the potential for broad impacts to aviation operations in the United States, including the possibility of catastrophic failures leading to multiple fatalities, in the absence of appropriate mitigations. The extent of the RF interference is summarized by the worst-case exceedance of the safe interference limit of radar altimeters by expected 5G signals in the 3.7–3.98 GHz band: 14 dB for commercial transport airplanes (as shown in Figure 10-4), 48 dB for business, regional, and general aviation airplanes (as shown in Figure 10-12), and 45 dB for helicopters (as shown in Figure 10-16). Further, the impacts are not only limited to the intentional emissions from 5G systems in the 3.7–3.98 GHz band, but also the spurious emissions from such systems within the protected 4.2–4.4 GHz radar altimeter band directly. In this latter case, the worst-case exceedance of the safe interference limit is 28 dB for business, regional, and general aviation airplanes (as shown in Figure 10-25), and 12 dB for helicopters (as shown in Figure 10-29).

Given the extent to which the safe interference limits are exceeded and the breadth of the impacts to aviation safety, the risk of harmful interference to radar altimeters cannot be adequately mitigated by the aviation industry acting alone. As such, it is envisioned that this report will be useful to those in the aviation industry, the mobile wireless industry, and both aviation and spectrum regulators to understand and take appropriate steps in a timely fashion to mitigate this risk. It is the responsibility of members of all of these groups to work together to ensure that safety-critical aviation systems will continue to be protected for the purposes of public safety.

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1 INTRODUCTION

1.1 Radar Altimeters and Their Usage on Civil and Commercial Aircraft

Radar altimeters (also known as radio altimeters, low range radar/radio altimeters, or by the abbreviations RA, LRRA, RALT, or RADALT) are critical sensors used to enable and enhance several different safety and navigation functions throughout all phases of flight on all commercial aircraft and a wide range of other civil aircraft[1]. Such functions include, but are not limited to, Terrain Awareness Warning Systems (TAWS), Traffic Alert and Collision Avoidance Systems (TCAS) and Airborne Collision Avoidance Systems (ACAS), Wind Shear detection systems, flight control systems, and autoland systems (including autothrottle and automated landing flare and rollout). Radar altimeters are also used on military aircraft, although the use cases and operating requirements for such aircraft vary widely and therefore are not studied here.

Further, as the radar altimeter is the only sensor onboard the aircraft capable of providing a direct measurement of the clearance height above the terrain and any obstacles which may protrude above the terrain, it plays a crucial role in providing situational awareness to the flight crew. The measurements from the radar altimeters are also used by Automatic Flight Guidance and Control Systems (AFGCS) during instrument approaches, and to control the display of information from other systems, such as Predictive Wind Shear (PWS), the Engine-Indicating and Crew-Alerting System (EICAS), and Electronic Centralized Aircraft Monitoring (ECAM) systems, to the flight crew. No other sensor or system is capable of supporting these functions with the same level of integrity, availability, and continuity that is provided by the radar altimeter.

In commercial and civil aviation, the ubiquitous usage of radar altimeters is not solely a matter of convenience. For many types of aircraft operations, such usage is either explicitly or indirectly required by regulations from the Federal Aviation Administration (FAA) or other applicable aviation authority. For example, Title 14 of the Code of Federal Regulations (CFR) § 135.160 states that no person may operate a rotorcraft for compensation or hire unless that rotorcraft is equipped with an operable FAA-approved radar altimeter. In addition, operations such as Category II or Category III Instrument Landing System (ILS) approaches require the use of at least one radar altimeter.

1.2 Radar Altimeter Operational Requirements

Radar altimeters used on civil and commercial aircraft in the United States must be approved by the FAA, either at the equipment level through the Technical Standard Order (TSO) process according to TSO-C87a [1], at the aircraft level through the Type Certificate (TC) process, or both. In either case, the radar altimeter performance must meet the requirements specified in the applicable Minimum Operational Performance Standards (MOPS), or equivalent. Under the most recent and currently active revision of the TSO, the MOPS are specified in EUROCAE ED-30 [2], which was released in 1980. However,

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[1] For the purposes of this report, “commercial aircraft” refers to airplanes and rotorcraft operating under Part 121, Part 129, or Part 135 of the Federal Aviation Regulations (Title 14 of the Code of Federal Regulations, Chapter I). Further, “civil aircraft” refers to airplanes and rotorcraft operating under Part 91 or Part 125 of the Federal Aviation Regulations. The terms “commercial aviation” and “civil aviation” likewise refer to the operations of these respective aircraft.

many currently deployed radar altimeter models received FAA approval under the earlier TSO-C87 [3], which instead directly includes MOPS equivalent to RTCA DO-155 [4] (released in 1974). Nevertheless, the performance requirements listed in both ED-30 and DO-155 are substantially the same.

1.3 Potential for RF Interference

Radar altimeters used in civil and commercial aviation operate using either unmodulated pulse radar or frequency-modulated continuous wave (FMCW) radar technology, with FMCW being far more common among models developed in the last few decades. In either case, the above ground level (AGL) altitude of the aircraft is measured in the radar altimeter by transmitting radio frequency (RF) energy down to the ground and receiving a portion of this energy back through reflection off of the terrain or other obstacles, and determining the round-trip propagation time of the RF energy. The radiated power levels are low, typically on the order of one watt, and thus highly sensitive receivers are required for radar altimeters to function properly. As such, radar altimeters are highly susceptible to RF interference entering the receiver, which can negatively impact their performance.

Radar altimeters operate in an Aeronautical Radionavigation Service (ARNS) spectrum allocation in the 4.2–4.4 GHz band, which is internationally recognized and protected by the International Telecommunications Union (ITU). Radar altimeters may be susceptible to RF interference received either within this band of operation or within adjacent or nearby frequency bands.

2 BACKGROUND

2.1 Brief History

Radar altimeters have successfully operated onboard civil and commercial aircraft since their widespread introduction in the 1970s, without any substantial issues or incidents related to harmful RF interference. This is due primarily to the international protection of the 4.2–4.4 GHz band, along with the adjacent-band RF interference environment being generally benign and compatible with radar altimeter operations, consisting mainly of Fixed Service (FS) and Fixed-Satellite Service (FSS) links. The radar altimeter MOPS did not originally include any specific performance requirements to ensure protection from adjacent-band RF interference, and no updates to the MOPS to include such requirements were considered to be necessary, given the decades of successful operation.

The introduction of mobile telecommunications networks in the 1990s, and their subsequent expansion throughout the 2000s and 2010s, did not initially pose any risk of harmful interference to radar altimeters since the operating frequencies for these networks were all well below the 4.2–4.4 GHz band. However, as the push for extended capabilities of mobile networks has continued, additional spectrum has been identified and made available for commercial mobile use, often through reallocation. In recent years, regulators in the United States and worldwide have worked to make available additional “mid-band” spectrum, including portions of the lower C-band near the radar altimeter ARNS band, to support the development and roll-out of fifth generation cellular networks (5G).

2.2 March 2020 FCC Report and Order

On March 3, 2020, the Federal Communications Commission (FCC) released their Report and Order of Proposed Modification in the matter of Expanding Flexible Use of the 3.7 to 4.2 GHz Band [5]. This Report and Order reallocated the spectrum from 3.7 to 3.98 GHz from FSS and FS to new flexible use licensees. The spectrum will be auctioned beginning in December of 2020, with the intent of supporting 5G telecommunications deployments in the mid-band spectrum ranges. As a result, the incumbent FSS operators in the 3.7 to 4.2 GHz band will be transitioned into the 4.0 to 4.2 GHz band, while FS incumbents will be required to move out of the 3.7–4.2 GHz band entirely.

Several aviation industry stakeholders actively monitored and participated in the FCC rulemaking process by submitting technical reports to the FCC and meeting with FCC technical staff with the intent of ensuring that the risk of potential harmful interference to radar altimeters would be adequately evaluated and considered. These efforts included interference testing and technical analysis conducted by the Aerospace Vehicle Systems Institute (AVSI) [6] [7]. The FCC Report and Order acknowledged that further analysis is warranted to evaluate the potential for interference to radar altimeters.

2.3 Multi-Stakeholder Industry Group

2.3.1 SC-239 5G Task Force

In December 2019, the aviation industry initiated the process of seeking to update the radar altimeter MOPS by receiving approval from the RTCA Program Management Committee (PMC) to form a new Special Committee, SC-239. The updates to the MOPS will primarily be focused on defining additional performance requirements and tests to ensure that new radar altimeter designs can operate in the rapidly changing RF environment around the 4.2–4.4 GHz band with minimal risk of harmful interference. However, as safety is paramount for critical aviation systems such as radar altimeters, the development and implementation of new standards necessarily takes a significant amount of time—several years at a minimum. Further, additional time will be required for new equipment to be designed, certified, and deployed across all civil and commercial aircraft, as typical product lifecycles can span decades.

The FCC Report and Order encouraged interested stakeholders to establish a multi-stakeholder industry group to study and address the complex coexistence issues in the 3.7–4.2 GHz, including with aeronautical services. In order to allow for a suitably rapid reaction from the aviation industry, and to lead the additional analysis needed to fully understand the potential risk of harmful interference to currently-deployed radar altimeters from future 5G operations in the 3.7–3.98 GHz band, SC-239 responded to this suggestion from the FCC by amending its Terms of Reference to establish a multi-stakeholder group referred to as the 5G Task Force. RTCA announced this multi-stakeholder process publicly and invited public participation in late April 2020. RTCA further modified its processes to allow open participation in the SC-239 5G Task Force to those outside of the aviation industry, such that all relevant subject matter experts could contribute and ensure the most thorough analysis possible, conducted as quickly as possible.

2.3.2 Technical Working Group 3

Following the formation and announcement of the RTCA multi-stakeholder group (SC-239 5G Task Force), a separate group contacted RTCA leadership about another multi-stakeholder group being established. This group, called the C-Band Multi-Stakeholder group, established Technical Working Group 3 (TWG-3) to address the issue of coexistence with aeronautical services. While it is understood that TWG-3 does not plan on submitting any technical reports of its own, it has served as a forum for parts of the aviation and mobile wireless industries to better understand the respective industries' operational requirements and technical parameters. This included the facilitation of a technical information exchange (provided in Appendix B). The analysis performed by the RTCA SC-239 5G Task Force and reported here was informed by this technical information exchange.

3 SCOPE OF THIS RTCA ACTIVITY

3.1 Terms of Reference

As stated in Section 2.3.1, RTCA SC-239 was initially chartered to develop updated standards that will form the basis of FAA approvals of radar altimeter equipment. The scope of work for SC-239 was expanded with the generation of the 5G Task Force, and the Terms of Reference [8] now include two items:

1. Produce a report assessing the potential interference impact on radar altimeters of 5G telecommunication signals transmitted on frequencies near the 4200–4400 MHz band (this report); and

2. Update equipment MOPS for Low Range Radar Altimeters to address the robustness of future radar altimeters against the existing and planned future RF environment.

3.2 Assessment Study Objectives

This study is intended to be the most comprehensive assessment to date of the potential risk and operational impacts of interference to radar altimeters that may be caused by 5G telecommunications operations near the 4.2–4.4 GHz band. Accomplishing this task will require two main objectives:

1. Establishing interference tolerance thresholds for radar altimeters throughout different operational scenarios and for different airborne platforms, based upon the types of radar altimeters and their installation characteristics as applicable to each platform; and

2. Determining the operational scenarios for each platform, if any, in which the interference tolerance thresholds may be exceeded by expected 5G telecommunications signals emitted from the following sources:

    - Base stations,

    - User equipment located on the ground, or

    - User equipment located onboard the aircraft.

For each 5G emissions source, the analysis will individually consider both the fundamental emissions—that is, the wanted emissions within the necessary bandwidth of the source—as well as the spurious emissions falling within the 4.2–4.4 GHz band. The fundamental emissions may lead to blocking interference in the radar altimeter receiver, wherein a strong signal outside of the normal receive bandwidth cannot be sufficiently filtered in the receiver to prevent front-end overload or other effects. The spurious emissions, on the other hand, fall within the normal receive bandwidth of the radar altimeter, and may produce undesirable effects such as desensitization due to reduced signal-to-interference-plus-noise ratio (SINR), or false altitude determination due to the erroneous detection of the interference signal as a radar return. The potential combination of the two types of interference emissions is not explicitly considered due to the additional complexity of accurately modeling and analyzing such a scenario. Instead, each type of interference is evaluated individually against the interference tolerance thresholds to identify all possible operating conditions in which harmful interference may occur due to either emissions type.

Both the fundamental and spurious 5G emissions are illustrated pictorially (not to scale) in relation to the radar altimeter band in Figure 3-1.

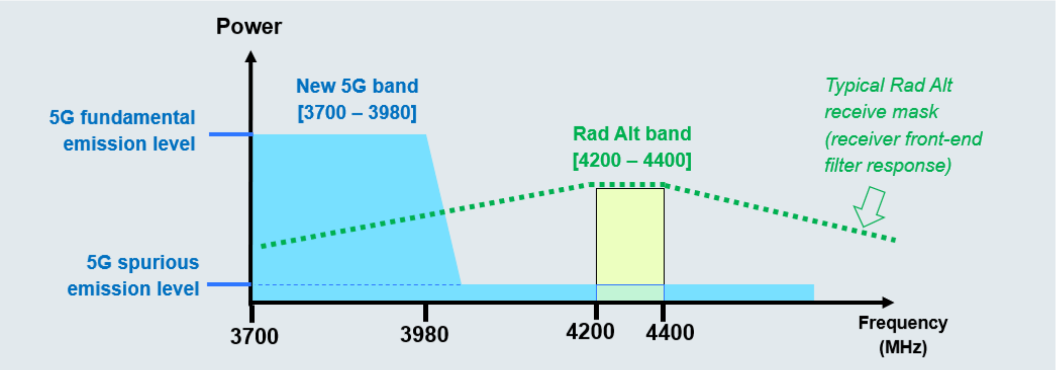

Figure 3-1: Spectrum Illustration Showing 5G Fundamental and Spurious Emissions

In accordance with International Civil Aviation Organization (ICAO) standard practices, the analysis conducted in this report will generally consider all variables at their worst-case limits. This provision is outlined in paragraph 9.4.8 of the ICAO *Handbook on Radio Frequency Spectrum Requirements for Civil Aviation* [17], and has been similarly followed in other assessments of RF interference in aeronautical safety systems caused by telecommunications emissions.

3.3 Assessment Scope

The specific focus of this study is 5G telecommunications operations in the 3.7–3.98 GHz band, which may be encountered in the United States in accordance with the FCC Report and Order. In other regulatory jurisdictions, the specific frequency bands or operational characteristics for 5G deployments in the C-band (or upper S-band) may differ from those laid out by the FCC. However, the reallocation of the 3.7–3.98 GHz band for 5G operations in the United States has led to the most immediate concern in the aviation industry regarding the potential for harmful interference to radar altimeters used on civil and commercial aircraft. Further, the methods, analysis models, operational scenarios, and assumptions outlined in this report provide a foundation for the assessment of the risk and potential impacts of interference to radar altimeters caused by lower C-band (or upper S-band) telecommunications operations in other jurisdictions throughout the world, with adjustment made to these methods and assumptions as necessary. Any consideration of interference impacts from telecommunications systems using substantially different carrier frequencies or modulation schemes than those in this study may also require additional testing of radar altimeters to determine the interference tolerance in these cases.

3.4 Report Organization

The main body of this report is organized into seven major sections, beginning with Section 5, as well as two appendices. Section 5 discusses, in general terms, the potential impacts that could be encountered on an aircraft in the event that the radar altimeter(s) onboard malfunction due to harmful RF interference. Section 6 describes in detail the methods and assumptions used to carry out the interference analysis. Section 7 gives a high-level overview of the empirical testing methods used to determine interference tolerance thresholds. Section 8 provides descriptions of the specific example scenarios based on real-world aircraft operations that are analyzed to give additional context to the extensive parametric interference modeling. Section 9 lists the interference tolerance threshold testing results, while Section 10 lists the subsequent interference analysis results. Finally, Section 11 reviews the key findings and conclusions of the analysis.

Appendix A includes a detailed description of the test setup and methods used by AVSI to determine the empirical interference tolerance thresholds. Appendix B contains the correspondence between the aviation industry and the mobile wireless industry conducted within TWG-3 for the exchange of technical information related to 5G mobile network operations and radar altimeter characteristics. Appendix C documents the public commenting process that was employed for open review of this report, including all comments received and how they were resolved. Appendix D contains the results of additional analysis which was conducted in response to some of the public comments received.

4 RECOMMENDATIONS

4.1 Use of This Report

The primary goal of this report is to provide a quantitative evaluation of radar altimeter performance regarding RF interference from expected 5G emissions in the adjacent band, as well as a detailed assessment of the resulting risk of such interference occurring and impacting aviation safety. As such, it is envisioned that this report will be useful to those in the aviation industry, the mobile wireless industry, and both aviation and spectrum regulators to understand and appropriately account for this risk. It is the responsibility of members of all of these groups to work together to ensure that critical aviation systems will be protected for the purposes of public safety.

4.2 Need for Continued Work and Further Analysis

Although this report is the most comprehensive assessment conducted to date regarding the potential risk of RF interference to radar altimeters caused by 5G telecommunications signals, it is by no means exhaustive. Like any technical analysis, the work described in this report was conducted based upon certain assumptions and parameters that were refined using the best data available at the time. However, the specific implementation of 5G services, operational use cases, industry standards, or government regulations may change in the future and lead to some of these assumptions or parameters no longer being appropriate. As such, this report should not be considered as a definitive one-time assessment, but rather serve as the basis for ongoing work and analysis to continue to ensure that radar altimeters will function as intended to enable continued safe aviation operations. Further dialogue with the mobile wireless telecommunications industry to refine the analysis assumptions for such ongoing work is welcomed.

In addition, the analysis of specific aircraft operational scenarios in this report is somewhat limited, with a greater focus placed on parametric analysis that covers a wider range of operating conditions. Two specific scenarios are analyzed in detail to present an example which may be followed by others, either within or outside of the aviation industry, to consider additional operational scenarios as needed.

5 POTENTIAL IMPACTS TO AIRCRAFT OPERATIONS

5.1 Loss of Situational Awareness

On all types of aircraft, situational awareness of the flight crew is paramount to ensuring safe flight operations, especially flying in busy airspace, close to the ground, or in low-visibility scenarios such as Instrument Meteorological Conditions (IMC). The radar altimeter plays a critical role in providing situational awareness in these operating conditions in particular. Not only do radar altimeters provide a displayed indication of height above terrain to the flight crew, they also form the basis of auditory altitude callouts during terminal landing procedures, as well as TCAS/ACAS and TAWS advisories and warnings.

Erroneous or unexpected behavior of the radar altimeter directly leads to a loss of situational awareness for the flight crew. Not only does this loss of situational awareness present an immediate impact to the ability of the flight crew to maintain safe operation of the aircraft in its own right, it also requires the flight crew to attempt to compensate for the lack of reliable height above ground information using other sensors and visual cues, if available. This further leads to a risk of task saturation for the flight crew, particularly during operations or phases of flight which require continuous crew engagement, such as final approach and landing procedures.

5.2 Controlled Flight into Terrain

In the most extreme cases, loss of situational awareness may lead to an occurrence of Controlled Flight into Terrain (CFIT), which is nearly always a devastating event resulting in aircraft hull loss and a high likelihood of loss of life or severe injuries to the flight crew and passengers. The frequency of CFIT accidents in earlier generations of aircraft operations was unacceptably high[2], providing the key motivating factor for the introduction of radar altimeters in civil and commercial aviation in the 1970s, as well as the subsequent development of TAWS. This implementation has greatly reduced the risk of CFIT, as long as the radar altimeter and associated systems are functioning properly [9].

However, CFIT may still occur in modern aircraft operations due to undetected erroneous output from the radar altimeter(s), which may be considered Hazardously Misleading Information (HMI) during certain phases of flight or operational conditions (such as IMC). If HMI is presented to the flight crew, TAWS, or the AFGCS, it may lead to incorrect and dangerous flight operations, and there may not be sufficient time to correct the error before a catastrophic result such as CFIT occurs.

5.3 Specific Operational Impacts on Commercial Aircraft

On commercial air transport and regional aircraft, high-end business aviation aircraft, and some general aviation aircraft and helicopters, the radar altimeter serves far more purposes than providing situational awareness of the terrain clearance height to the flight crew. In these cases, in addition to providing a displayed indication of the aircraft height above terrain, the radar altimeter will be used as a safety-critical navigation sensor by the AFGCS, and will also feed into systems such as TCAS/ACAS, PWS, and TAWS. This usage by a wide variety of systems onboard the aircraft leads to the possibility of specific operational

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[2] See, for example, TWA Flight 514, which crashed outside of Washington, DC on December 1, 1974 [10].

impacts that go beyond a general loss of situational awareness or risk of CFIT.

Table 5-1 illustrates several specific operational impacts that may be encountered due to undetected erroneous readings or unanticipated loss of output (indicated as a No Computed Data[3], or NCD, condition) from the radar altimeter on commercial or civil aircraft which utilize the radar altimeter for functions such as those mentioned in the preceding paragraph. For each impact, the severity is assessed in accordance with FAA system safety analysis guidelines provided in Advisory Circular (AC) 23.1309-1E [12] for normal category airplanes, AC/Advisory Material Joint (AMJ) 25.1309 (Draft Arsenal version) [13] for transport category airplanes, AC 27-1B [14] for normal category rotorcraft, and AC 29-2C [15] for transport category rotorcraft. Additional guidance may exist for specific aircraft operations rather than for aircraft types, such as AC 120-28D [16] concerning Category III instrument approach procedures. The severity of each condition may be determined to be Minor, Major, Hazardous/Severe Major, or Catastrophic, with each severity classification having its own allowable occurrence rate. The allowable occurrence rate 1 x 10^{-3} per flight hour or less for Minor failure conditions, 1 x 10^{-5} per flight hour or less for Major failure conditions, 1 x 10^{-7} per flight hour or less for Hazardous/Severe Major failure conditions , and 1 x 10^{-9} per flight hour or less for Catastrophic failure conditions.

Table 5-1: Example Aircraft Operational Impacts due to Radar Altimeter Failures

Radar Altimeter Failure	**Operational Impact**	**Flight Phase**	**Severity**
Undetected Erroneous Altitude	Just prior to touchdown, the aircraft performs a flare maneuver to avoid a hard landing. The flare may be performed manually by the flight crew, using auditory callouts of radar altimeter readings, if sufficient visibility is available. In low-visibility conditions, the flare may be controlled by an autoland function. Erroneous radar altimeter readings in either case can result in the potential for CFIT with little or no time for the flight crew to react.	Landing – Flare	Catastrophic
Undetected Erroneous Altitude	Erroneous input to the AFGCS affects aircraft attitude commands and altitude, as well as flight control protection mechanisms	All Phases of Flight	Catastrophic[4]

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[3] The term NCD is used to indicate conditions in which the radar altimeter cannot make an altitude determination (generally due to insufficient receiver SINR), as specified in ARINC 429 [11]. For radar altimeters which do not utilize an ARINC 429 interface to provide altitude output, the MOPS still require that a positive indication of such conditions be provided, for example using a discrete output signal. Throughout this report, “NCD” will be used as a shorthand for such conditions, even if the actual radar altimeter implementation does not follow the ARINC 429 standard.

[4] This situation is considered Catastrophic during landing, Hazardous/Severe Major during approach and takeoff, and Major in cruising flight [49].

Radar Altimeter Failure	Operational Impact	Flight Phase	Severity
Unanticipated NCD	Undetected loss of PWS display to flight crew, preventing awareness of wind shear impact to vertical profile in front of the aircraft	Landing	Hazardous/ Severe Major[5]
Unanticipated NCD	Undetected loss of TCAS/ACAS inhibition near the ground, leading to potential erroneous descent advisory alert and associated possibility of CFIT in low-visibility conditions	Approach, Landing, Takeoff	Hazardous/ Severe Major
Undetected Erroneous Altitude	Erroneous triggering of TAWS reactive terrain avoidance maneuver, forcing mandatory response from flight crew and leading to potential traffic conflicts in surrounding airspace	Approach, Landing, Takeoff	Major
Unanticipated NCD	Aircraft landing guidance flight control laws violated leading to unnecessary missed approach and go-around, jeopardizing safety of surrounding airspace	Approach, Landing	Major
Unanticipated NCD	Loss of capability to perform approach and landing in low-visibility conditions (Category II/III approach), leading to unnecessary diversion and jeopardizing safety of surrounding airspace	Approach, Landing	Hazardous/Severe Major[6]
Unanticipated NCD	Loss of capability to warn flight crew in case of excessive aircraft descent rate or excessive terrain closure rate (TAWS Mode 1 and 2 alert protection not active)	All Phases of Flight	Major
Unanticipated NCD	Loss of capability to warn flight crew of potentially dangerous loss of height after takeoff (TAWS Mode 3 alert protection not active)	Takeoff, Go-around	Major
Unanticipated NCD	Loss of capability to warn flight crew of potentially dangerous aircraft configuration—e.g. landing gear, slats, flaps—based on height above terrain (TAWS Mode 4 alert protection not active)	Landing	Major
Unanticipated NCD	Loss of capability to warn flight crew that aircraft is dangerously below glide path during precision instrument approach (TAWS Mode 5 alert protection not active)	Landing	Major

It is imperative to note that the example operational impacts listed in Table 5-1 are not exhaustive, and other operational impacts which can compromise aviation safety may be encountered. The examples provided are intended to give a general idea of the types of specific impacts that may be experienced and their severity.

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[5] For some aircraft manufacturers, this situation may be considered Major instead of Hazardous/Severe Major.

[6] For some aircraft manufacturers, this situation may be considered Major instead of Hazardous/Severe Major depending on the altitude at which it occurs.

6 INTERFERENCE ANALYSIS METHODOLOGY

6.1 Analysis Approach

6.1.1 Basic Methodology

The interference analysis is conducted in two steps. First, an interference model is used to compute the expected received interference power or power spectral density (PSD) for a given operational scenario based on various assumptions and technical parameters of the interference source and victim radar altimeter. This model is developed in accordance with the standard source-path-receiver model approach described in the ICAO *Handbook on Radio Frequency Spectrum Requirements for Civil Aviation* [17]. Then, the computed interference power or PSD levels are compared to the interference tolerance levels determined for the applicable radar altimeter usage categories (see Section 7.2) to evaluate the likelihood of harmful interference in the given scenario. Harmful interference may be considered likely to occur in any scenarios in which the computed power or PSD level exceeds the tolerance level. Further, in certain operational scenarios which involve potential failure conditions with high severity (e.g. Hazardous/Severe Major or Catastrophic, as described in Section 5.3), the underlying assumptions used in the analysis and determination of interference tolerance levels may not be sufficient to ensure that the likelihood of harmful interference is acceptably low. In such cases, an additional safety margin may be used to further decrease the acceptable interference level below the determined tolerance level. This analysis of computed interference power or PSD levels and comparison to acceptable interference levels is performed in each case considering both the 5G fundamental emissions in the 3.7–3.98 GHz band, and the 5G spurious emissions in the 4.2–4.4 GHz band.

The interference model is described in general terms by Equation 6-1.

$$P_{RX} = P_{source} + G_{source} - L_{prop} + G_{RA} - L_{RX} \tag{6-1}$$

For an interference source with a conducted output power of P_{source} in dBm and antenna gain[7] of G_{source} in dBi, propagation loss from the interference source to the victim aircraft of L_{prop} in dB, and victim radar altimeter with antenna gain of G_{RA} in dBi and receive path cable loss of L_{RX} in dB, the resulting interference power at the altimeter receiver input port is P_{RX} in dBm. This equation can alternatively be expressed in terms of PSD as shown in Equation 6-2, where the interference source has a conducted PSD of PSD_{source} in dBm/MHz, and the resulting interference PSD at the altimeter receiver input is PSD_{RX} in dBm/MHz.

$$PSD_{RX} = PSD_{source} + G_{source} - L_{prop} + G_{RA} - L_{RX} \tag{6-2}$$

In both Equation 6-1 and Equation 6-2, the interference source characteristics (conducted power or PSD and antenna gain) are based on the assumed 5G interference source considered in the analysis as described in Section 6.3.2. Further, the interference source antenna gain may be a function of the azimuth and elevation angles from the antenna phase center to the victim aircraft, the assumed center frequency of the interference signal, and for emissions sources which utilize active beam steering, the commanded beam steering angles. The propagation loss will generally be a function of the interference source and

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[7] The antenna gain term for the interference source is assumed to be net gain, including feeder losses.

aircraft heights above the ground, the horizontal distance between the interference source and the aircraft, and the assumed center frequency of the interference signal. Finally, the radar altimeter antenna gain will be a function of the azimuth and elevation angles from the antenna phase center to the interference source, the aircraft pitch and roll angles, and the assumed center frequency of the interference signal.

6.1.2 Parametric Interference Models

In order to thoroughly examine the risk of potential harmful RF interference to radar altimeters, any scenario analysis which is dependent upon the position or orientation of the victim aircraft relative to the interference source is performed parametrically. This is accomplished using a MATLAB model which computes interference power (or PSD) levels received by the radar altimeter across all combinations of a specified range of aircraft altitudes, lateral distances from the interference source(s), aircraft pitch or roll angles, and base station antenna beam steering angles (as applicable when the interference source considered is a base station with active beamforming). Interference "heatmap" plots can then be generated to quickly illustrate the received power (or PSD) levels across all of these possible operating conditions, with any conditions leading to received interference above the tolerance threshold (or within an applicable safety margin of the tolerance threshold, as discussed in Section 6.3.2) clearly identified.

Figure 6-1 shows a diagram of the interference geometry considered for the parametric analysis.

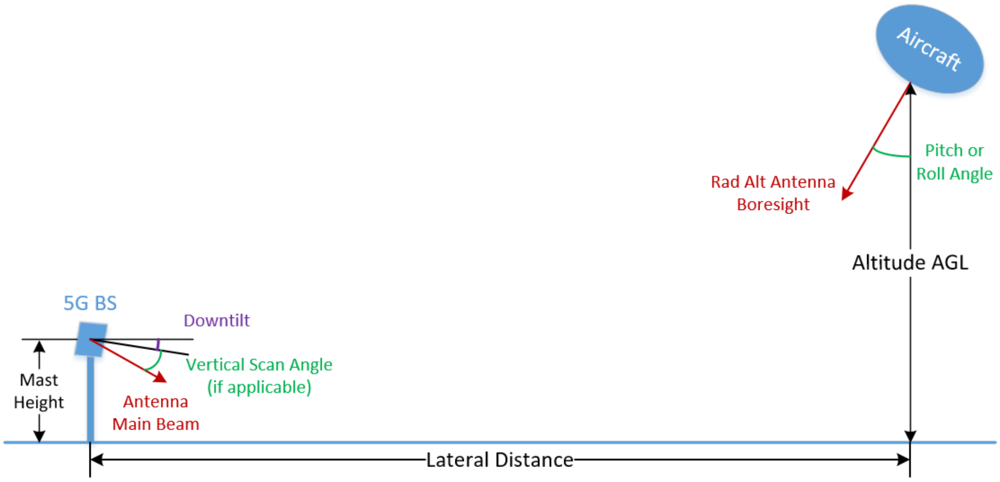

Figure 6-1: Parametric Analysis Interference Geometry

6.1.3 Specific Interference Scenario Models

The use of parametric interference models introduces some abstraction to the analysis and makes the impacts to real-world operational scenarios less obvious. Therefore, two scenarios based on actual aircraft operations and existing mobile wireless base station locations are also presented to provide this real-world context: (1) a fixed-wing aircraft conducting an instrument approach procedure, and (2) a medical evacuation helicopter landing at elevated heliports at urban hospitals. These two examples alone are of course insufficient to fully characterize the risk of harmful interference to radar altimeters across all operational scenarios, but when combined with the parametric analysis, conclusions can be drawn which are applicable to a very wide range of scenarios while still maintaining a connection to realistic operating conditions. Further, the worked examples provide a demonstration of how other interested parties can conduct their own analysis of other real-world operational scenarios using the same methodology.

Like the parametric interference models, the specific example scenarios utilized a MATLAB model to compute the received interference levels seen by the radar altimeter. Rather than compute these levels parametrically for all combinations of operating conditions, however, the interference is determined for the operating conditions dictated by the scenario geometry.

6.1.4 Analysis of 5G User Equipment on the Ground

Consideration of 5G emissions from user equipment devices (UEs) located on the ground which are overflown by a radar altimeter onboard an aircraft, as shown in Figure 6-2, can be accomplished with a similar interference model to that used to analyze 5G emissions from base stations. However, in this case the total propagation loss may also include one or both of a body loss term and a building penetration loss term for any UEs which are assumed to be indoors, as described in Section 6.3.3.2.

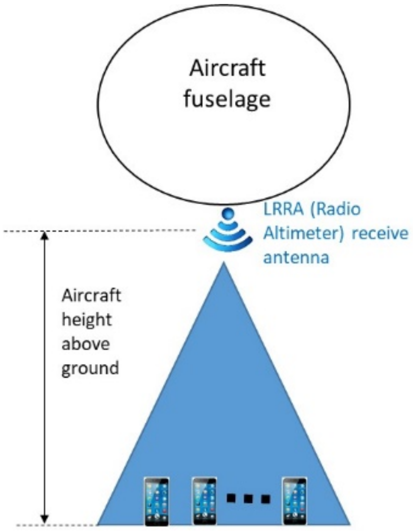

Figure 6-2: Radar Altimeter Overflying Several 5G UEs

One complication introduced in the analysis of 5G UEs on the ground is the need to consider aggregate interference from many separate emissions sources. Doing so requires some assumptions to be made regarding the number of UEs which may be transmitting simultaneously, and for the 5G fundamental emissions case, regarding the uplink channel center frequencies and bandwidths used by those UEs which transmit simultaneously. The general approach taken to analyze this scenario is to generate a large number of randomly-distributed UEs on the ground according to a specified density, compute the potential interference power or PSD received by the radar altimeter from every UE, and then aggregate these power or PSD levels using one or more sets of assumptions regarding simultaneous transmission and uplink channelization for the UEs. This is accomplished using a MATLAB model, similar to that used for both the parametric analysis and the analysis of specific real-world interference scenarios.

6.1.5 Analysis of 5G User Equipment Onboard Aircraft

The case of 5G UEs located onboard an aircraft is unique and must be analyzed differently. Although 47 CFR § 22.925 [18] specifically prohibits the use of cellular telephones onboard any aircraft while that aircraft is airborne, this regulation applies in the context of current 800 MHz cellular services governed by 47 CFR § 22 Subpart H, and it is not clear how or if it would be extended to 5G operations in the 3.7–3.98 GHz band operating according to 47 CFR § 27 Subpart O[8]. Further, studies have shown that not all users will comply with this regulation in all instances, due to either apathy or inattentiveness[9]. Therefore, despite the FCC regulation, the possibility of 5G UEs operating onboard an aircraft must be considered to ensure operation through the worst-case scenario.

Further complicating the scenario of 5G UEs onboard an aircraft is the fact that the RF propagation path from the interference sources to the radar altimeter receiver is not a simple line-of-sight path, and thus the propagation loss cannot be easily calculated. Instead, empirical data must be used to estimate the expected propagation losses for various types of aircraft, and potentially for various locations of the UEs throughout the aircraft cabin, as shown in Figure 6-3. These data and the resulting propagation loss assumptions are provided in Section 6.3.3.3.

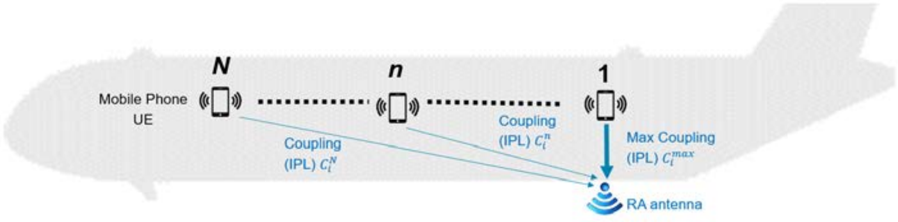

Figure 6-3: Multiple UEs Located Onboard an Aircraft

Finally, as with the case of 5G UEs located on the ground, determining the aggregate interference levels received from 5G UEs onboard an aircraft requires assumptions to be made regarding the transmission timing characteristics and uplink channelization scheme used by the UEs. Reasonable worst-case assumptions are made to allow for this aggregate interference calculation, which is a straightforward task in this scenario since only a relatively small number of UEs need to be considered.

6.2 Radar Altimeter Interference Tolerance Thresholds

6.2.1 Recommendation ITU-R M.2059 Protection Criteria

Protection criteria for radar altimeters are established in the ITU Radiocommunication Sector (ITU-R) Recommendation M.2059 [20]. Three criteria are defined, based on separate failure modes that may be induced by RF interference: (1) receiver front-end

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[8] The FCC Report and Order [5] establishes the 3.7 GHz service under 47 CFR § 27—Miscellaneous Wireless Communications Services, and not under 47 CFR § 22—Public Mobile Services.

[9] In the Portable Electronic Devices Aviation Rulemaking Committee Report, survey data from the Consumer Electronics Association and Airline Passenger Experience Association showed almost one-third of passengers report they have accidentally left a Portable Electronic Device (PED) turned on during a flight. 43% passengers incorrectly believe it is acceptable to use PEDs while taxiing to the runway, 32% while in the air before reaching the altitude where PEDs are approved for use, and 26% while the plane is in its final descent [19].

overload, (2) receiver desensitization, and (3) false altitude reports. Note that the criterion for false altitude reports is only directly applicable to FMCW radar altimeters, and excludes pulsed altimeters. This does not mean that pulsed altimeters are not susceptible to false altitude reports caused by interference—it is simply a result of the way in which the false altitude criterion is defined, namely in terms of the power contained within a certain assumed resolution bandwidth in the intermediate frequency (IF) stage of the receiver. Of the three protection criteria, receiver overload is the only one which explicitly applies to RF interference sources outside of the 4.2–4.4 GHz band. However, any spurious emissions from such interference sources which land within the 4.2–4.4 GHz band must also satisfy the receiver desensitization criterion and, for FMCW altimeters, false altitude protection criterion.

In addition to defining the protection criteria in terms of assumed radar altimeter receiver characteristics, Rec. ITU-R M.2059 also provides such characteristics for ten different radar altimeter models (in anonymized fashion), meant to be representative of currently deployed radar altimeters used in civil and commercial aviation. This allows interference tolerance thresholds to be computed according to each of the three protection criteria for all of these representative radar altimeter models individually, and the worst case can then be selected for each to determine representative tolerance thresholds. Carrying out this process yields the interference tolerance threshold values shown below in Table 6-1.

Table 6-1: Radar Altimeter Protection Criteria Determined Using ITU-R M.2059

Protection Criterion	**ITU-R M.2059, Annex 3 Equations**	**Worst-Case Tolerance Threshold**[10]	**Worst-Case Altimeter Model**
Receiver Front-End Overload[11]	(3), (4)	-53 dBm	A3
Receiver Desensitization	(5) through (8)	-102 dBm	A5
False Altitude Reports	(9)	-103 dBm/MHz	All FMCW models

In addition, the receiver desensitization threshold may be translated into a PSD envelope threshold across the 4.2–4.4 GHz band by accounting for the total receive bandwidth in addition to the desensitization threshold as computed in accordance with Rec. ITU-R M.2059. In the case of a pulsed altimeter, the total receive bandwidth is simply the IF bandwidth of the receiver; in the case of an FMCW altimeter, the total receive bandwidth is equal to the sweep bandwidth plus twice the receiver IF bandwidth. Using this method to determine receiver desensitization PSD thresholds for each altimeter model in Rec. ITU-R M.2059 and then taking the worst case yields the interference tolerance threshold value shown below in Table 6-2.

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[10] Rec. ITU-R M.2059 protection criteria are specified in terms of interference power or PSD at the altimeter receiver input.

[11] Receiver overload threshold is computed assuming a center frequency for the 5G interference signal of 3850 MHz, yielding a frequency-dependent rejection (FDR) factor of 3 dB according to Table 3 in Annex 3 of Rec. ITU-R M.2059.

Table 6-2: Radar Altimeter Receiver Desensitization PSD Tolerance Threshold

Protection Criterion	ITU-R M.2059, Annex 3 Equations	Worst-Case Tolerance Threshold	Worst-Case Altimeter Model
Receiver Desensitization	(5) through (8)	-117 dBm/MHz	A2 and A3

6.2.2 Empirical Tolerance Thresholds

While the protection criteria from Rec. ITU-R M.2059 are commonly used to determine interference tolerance thresholds which are useful for basic sharing and compatibility studies concerning radar altimeters, they do not offer a complete characterization of radar altimeter behavior and susceptibility to RF interference, for a few reasons. First, the protection criteria are not exhaustive in considering all possible failure modes and interference mechanisms that could be encountered in radar altimeters. Second, the protection criteria are defined statically, and do not vary across the functional measurement range of altitudes for a given altimeter model. This limitation may not capture the true behavior of radar altimeters operating in the presence of RF interference, since the receiver sensitivity characteristics may vary significantly throughout this altitude range, and it is expected that the interference tolerance may also vary accordingly. Finally, the example radar altimeter models listed in Rec. ITU-R M.2059 are not correlated with any specific aircraft types or use cases, and thus it is not clear whether certain models are inappropriate to consider in operational scenarios which are not common across all aircraft types. For example, some altimeter models may only be used in commercial air transport applications and not in helicopter applications. In consideration of interference scenarios which are applicable only to helicopters, such as a landing at an elevated heliport, it would therefore be best to evaluate only the altimeter models which may be used in that scenario.

Due to the limitations described above, achieving the goal of conducting the most thorough interference assessment possible requires complementing the protection criteria in Rec. ITU-R M.2059 with alternatively defined interference tolerance thresholds. The best means to determine these complementary interference tolerance thresholds is through empirical observation, using a sufficiently representative sample of altimeter models used in civil and commercial aviation. This approach does not require any specific determination of interference mechanisms in the receiver. Instead, the interference tolerance is based upon the actual behavior observed from the radar altimeters in an interference test environment at the "black-box" level[12] to give the most direct indication of the expected real-world performance. Further, interference tests can be repeated at various altitudes to observe possible impacts to interference tolerance based on the measured altitude. In addition, testing of radar altimeter models used in different applications and types of aircraft allows for separate interference tolerance thresholds to be determined according to the actual usage of each altimeter model, such that the appropriate thresholds can be applied in the interference analysis based on the operational scenario being considered.

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[12] That is, the testing is performed using only the top-level input and output interfaces of each radar altimeter—namely the RF ports (transmit and receive) to simulate altitude returns and RF interference signals, and the digital or analog altitude output interface.

Although the approach of empirically determining the interference tolerance thresholds as described above addresses the limitations noted with Rec. ITU-R M.2059, it is important to note that this method has its own drawbacks and cannot serve as a comprehensive substitute for the established protection criteria. In particular, the empirical tolerance thresholds determined in this manner for interference signals outside of the 4.2–4.4 GHz band will be directly applicable only for consideration of RF interference signals which are sufficiently well represented by the interference waveforms used in the testing.

Laboratory testing of several radar altimeter models to empirically determine the interference tolerance thresholds was performed by AVSI. For more details on the test setup and methodology used, see Section 7.

6.3 Analysis Assumptions

6.3.1 Propagation Model

All interference analysis performed considering 5G emission sources on the ground (both base stations and user equipment) utilized the propagation model described in Recommendation ITU-R P.528-4 [21]. This model was incorporated into the analysis directly using the open-source United States reference implementation made available by the National Telecommunications and Information Administration (NTIA) [22]. A simple console application was built from the NTIA source code which allowed for integration into the MATLAB interference models.

The Rec. ITU-R P.528 propagation model includes five input parameters: the transmitter and receiver heights above ground in meters, which in this case will be the assumed base station or UE height above ground and the aircraft altitude, respectively; the lateral distance between the transmitter and receiver in kilometers; the center frequency of the RF signal in megahertz; and the time availability percentage, which dictates the portion of time during which the transmission loss is less than or equal to the value computed by the model.

For interference scenarios considering 5G fundamental emissions in the 3.7–3.98 GHz band, the center frequency used in the propagation model is assumed to be 3850 MHz to determine transmission losses representative for signals located anywhere throughout this band. Likewise, for interference scenarios considering 5G spurious emissions in the 4.2–4.4 GHz band, the propagation model center frequency is assumed to be 4300 MHz. For interference scenarios considering downlink emissions from 5G base stations, the time availability is assumed to be 1%, based upon recommendations from ICAO for consideration of interference to radar altimeters using the Rec. ITU-R P.528 propagation model [23]. For interference scenarios considering uplink emissions from 5G UEs located on the ground, the time availability is assumed to be 50% (yielding median transmission losses, equivalent to free-space path losses under line-of-sight propagation conditions), since additional assumptions are made in this case regarding simultaneous transmissions from multiple UEs (as described in Section 6.1.4), and assuming a 1% time availability for each device would thus lead to an overly conservative computation of aggregate interference levels.

Interference analysis performed considering uplink emissions from 5G UEs located onboard an aircraft does not utilize the Rec. ITU-R P.528 propagation model. Instead, empirical interference path loss values are used for each applicable aircraft type, as described in Section 6.1.5.

6.3.2 Interference Safety Margin

The ICAO *Handbook on Radio Frequency Spectrum Requirements for Civil Aviation* [17] states in paragraph 9.2.23 that an additional safety margin should be considered for interference analysis concerning aeronautical safety systems. This paragraph, in its entirety, is included below:

> *Aeronautical safety applications are required to have continued operation through worst case interference, so all factors which contribute to harmful interference should be considered in analyses involving those applications. An aviation safety margin is included in order to address the risk that some such factors cannot be foreseen (for example impacts of differing modulation schemes). This margin is applied to the system protection criteria to increase the operational assurances to the required level. Traditionally for aviation systems/scenarios an aviation safety margin of 6–10 dB is applied. Until established on the basis of further study on a case-by-case basis, an aviation safety margin of not less than 6 dB should be applied.*

To summarize, according to ICAO guidelines an aviation safety margin of 6 dB must be included in the interference analysis, unless there are specific scenarios in which the assumptions made in the analysis are sufficient to meet the necessary operational assurances (i.e. system integrity, availability, and continuity). In this analysis, the combination of worst-case assumptions made regarding the propagation model (1% time availability), the radar altimeter receive antenna pattern, and the testing conditions used to determine the empirical interference tolerance thresholds may be sufficient to allow for the 6 dB margin to be excluded in the analysis of some operational scenarios. However, this will not be true in general. Instead, the possibility of excluding the 6 dB margin must be evaluated on a case-by-case basis for specific operational scenarios being considered and their associated failure condition severities and radar altimeter integrity, availability, and continuity requirements to support system safety.

It is expected that the combination of worst-case assumptions explicitly made in this analysis may be sufficient to evaluate operational impacts due to harmful interference on the order of 1 x 10^{-5} per flight hour without including additional safety margin. This occurrence rate is associated with operational scenarios having, at most, Major failure conditions. For operational scenarios that may have Hazardous/Severe Major or Catastrophic failure conditions, or any other scenarios which require greater levels of radar altimeter integrity, availability, and/or continuity, the assumptions made in the analysis are not sufficient to provide the necessary level of operational assurance. In such scenarios, a safety margin of not less than 6 dB must therefore be included in the interference analysis.

6.3.3 5G Emissions Sources

6.3.3.1 Base Stations

6.3.3.1.1 Active Antenna System Phased Array Base Stations

It is anticipated, based on inputs received from mobile wireless industry experts in TWG-3, that most 5G implementations in the 3.7–3.98 GHz band will utilize Advanced Antenna System (AAS) phased array technology for their base stations (see Appendix B). These mobile wireless industry experts also provided representative operational characteristics for such AAS base stations to be used in the interference analysis. These characteristics are provided in Table 6-3 and Table 6-4.

Table 6-3: 5G Base Station Characteristics[13] for 8 x 8 AAS Arrays

Environment	Urban	Suburban	Rural
Antenna Pattern	ITU-R M.2101-0	ITU-R M.2101-0	ITU-R M.2101-0
Array Size	8 x 8	8 x 8	8 x 8
Element Gain	6.4 dBi	7.1 dBi	7.1 dBi
Element Horizontal 3 dB Beamwidth	90 degrees	90 degrees	90 degrees
Element Vertical 3 dB Beamwidth	65 degrees	54 degrees	54 degrees
Front-to-Back Ratio	30 dB	30 dB	30 dB
Horizontal Array Spacing Coefficient	0.5	0.5	0.5
Vertical Array Spacing Coefficient	0.7	0.9	0.9
Vertical Scan Range[14]	-30 to 0 degrees	-10 to 0 degrees	-10 to 0 degrees
Peak Array Gain	24.5 dBi	25.2 dBi	25.2 dBi
Mechanical Downtilt[15]	10 degrees	6 degrees	3 degrees
Mast Height	20 meters	25 meters	35 meters
Downlink Bandwidth	100 MHz	100 MHz	100 MHz
Activity Factor	50%	50%	50%
Conducted Power per Element	25 dBm	25 dBm	25 dBm
Peak Output EIRP	67.5 dBm	68.2 dBm	68.2 dBm
Peak Output PSD (EIRP)[16]	47.5 dBm/MHz	48.2 dBm/MHz	48.2 dBm/MHz
Conducted PSD, Spurious	-20 dBm/MHz	-20 dBm/MHz	-20 dBm/MHz
Peak Output PSD, Spurious (EIRP)[17]	-13.6 dBm/MHz	-12.9 dBm/MHz	-12.9 dBm/MHz

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[13] While these operational characteristics are compliant with the technical restrictions established in the FCC Report and Order, they are not specifically defined or limited by the Order or any other FCC regulations.

[14] The vertical scan angle of the AAS array is specified in reference to the array broadside direction, and not to the local horizontal.

[15] Mechanical downtilt gives the angle of the AAS array broadside direction below the local horizontal.

[16] Calculated from Peak Output PSD (Conducted) and Peak Array Gain.

[17] Calculated from Conducted PSD, Spurious and Element Gain per Rec. ITU-R M.2101 [25].

Table 6-4: 5G Base Station Characteristics[18] for 16 x 16 AAS Arrays

Environment	Urban	Suburban	Rural
Antenna Pattern	ITU-R M.2101-0	ITU-R M.2101-0	ITU-R M.2101-0
Array Size	16 x 16	16 x 16	16 x 16
Element Gain	6.4 dBi	7.1 dBi	7.1 dBi
Element Horizontal 3 dB Beamwidth	90 degrees	90 degrees	90 degrees
Element Vertical 3 dB Beamwidth	65 degrees	54 degrees	54 degrees
Front-to-Back Ratio	30 dB	30 dB	30 dB
Horizontal Array Spacing Coefficient	0.5	0.5	0.5
Vertical Array Spacing Coefficient	0.7	0.9	0.9
Vertical Scan Range[19]	-30 to 0 degrees	-10 to 0 degrees	-10 to 0 degrees
Peak Array Gain	30.5 dBi	31.2 dBi	31.2 dBi
Mechanical Downtilt[20]	10 degrees	6 degrees	3 degrees
Mast Height	20 meters	25 meters	35 meters
Downlink Bandwidth	100 MHz	100 MHz	100 MHz
Activity Factor	50%	50%	50%
Conducted Power per Element	25 dBm	25 dBm	25 dBm
Peak Output EIRP	79.6 dBm	80.3 dBm	80.3 dBm
Peak Output PSD (EIRP)[21]	59.6 dBm/MHz	60.3 dBm/MHz	60.3 dBm/MHz
Conducted PSD, Spurious	-20 dBm/MHz	-20 dBm/MHz	-20 dBm/MHz
Peak Output PSD, Spurious (EIRP)[22]	-13.6 dBm/MHz	-12.9 dBm/MHz	-12.9 dBm/MHz

The 50% activity factor is assumed based on Report ITU-R M.2292-0, using the deployment parameters for bands between 3 and 6 GHz given in Table 4 of Section 5.3 [24]. This factor is treated as a duty cycle in order to compute average output power from the base stations based on the peak power listed in the table. With a 50% activity factor,

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[18] While these operational characteristics are compliant with the technical restrictions established in the FCC Report and Order, they are not specifically defined or limited by the Order or any other FCC regulations.

[19] The vertical scan angle of the AAS array is specified in reference to the array broadside direction, and not to the local horizontal.

[20] Mechanical downtilt gives the angle of the AAS array broadside direction below the local horizontal.

[21] Calculated from Peak Output PSD (Conducted) and Peak Array Gain.

[22] Calculated from Conducted PSD, Spurious and Element Gain per Rec. ITU-R M.2101.

this therefore corresponds to average power levels 3 dB less than the peak power levels.

For reference, the FCC Order limits radiated emissions within the licensed bandwidth to 62 dBm/MHz EIRP for non-rural environments, and 65 dBm/MHz EIRP for rural environments. Even with the 16 x 16 AAS base stations considered, the emissions assumed in the analysis remain well within these limits. Further, the FCC Order limits all emissions outside of the licensed bandwidth to -13 dBm/MHz conducted PSD at the input to the antenna. This limit includes both the out-of-band and spurious emission domains, and thus it may be overly conservative to assume that actual 5G implementations will produce spurious emissions in the 4.2–4.4 GHz band at this level. Instead, based upon input received from the mobile wireless industry experts in TWG-3, a maximum spurious conducted PSD of -20 dBm/MHz is assumed throughout the 4.2–4.4 GHz band (see Appendix B).

The AAS antenna patterns are computed using the methods outlined in Recommendation ITU-R M.2101-0 [25]. For interference analysis considering the fundamental 5G emissions in the 3.7–3.98 GHz band, the full composite antenna patterns are determined using the characteristics listed above and an assumed vertical scan angle, which is parameterized. For interference analysis considering the spurious 5G emissions in the 4.2–4.4 GHz band, the base station antenna pattern is assumed to be that of a single array element, as specified in Rec. ITU-R M.2101 for cases which consider emissions outside of the designed operating bandwidth of the AAS array.

Computed antenna pattern cuts in the elevation plane for the Urban AAS base stations are shown in Figure 6-4 for several different vertical scan angles. Note that since pattern in the 4.2–4.4 GHz band is assumed to be that of a single array element, this pattern will be the same for both the 8 x 8 and 16 x 16 array configurations, as well as for all vertical scan angles. Likewise, computed antenna pattern cuts in the elevation plane for the Suburban AAS base stations are shown in Figure 6-5, and pattern cuts in the elevation plane for the Rural AAS base stations are shown in Figure 6-6. In each of the antenna pattern plots, the x-axis shows the angle in degrees relative to the local horizontal, with negative angles being below the horizon and positive angles being above the horizon.

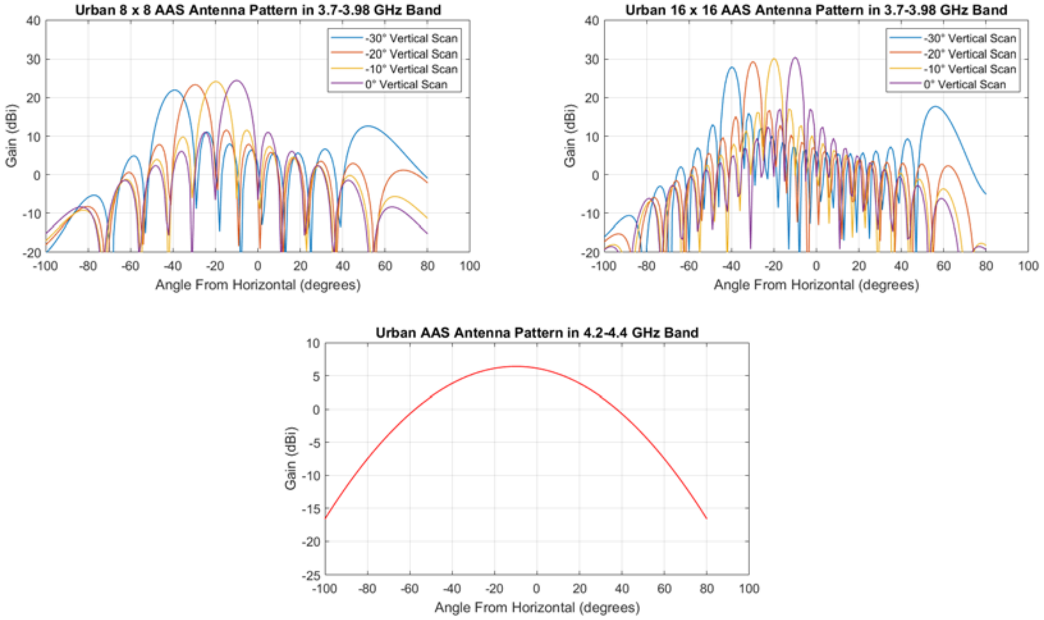

Figure 6-4: Antenna Pattern Elevation Plane Cuts for Urban AAS Base Stations

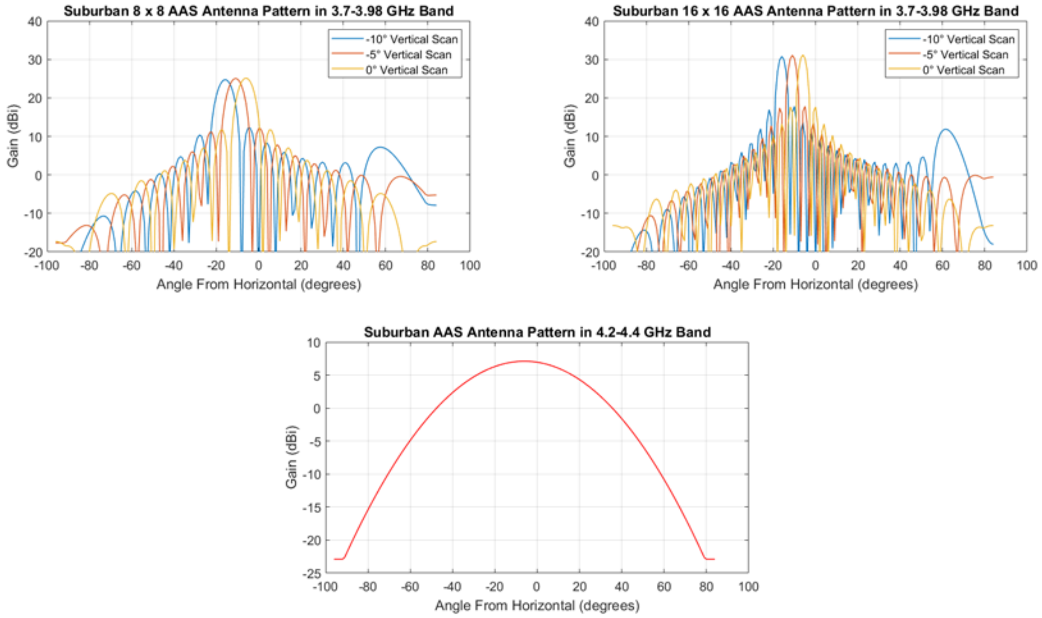

Figure 6-5: Antenna Pattern Elevation Plane Cuts for Suburban AAS Base Stations

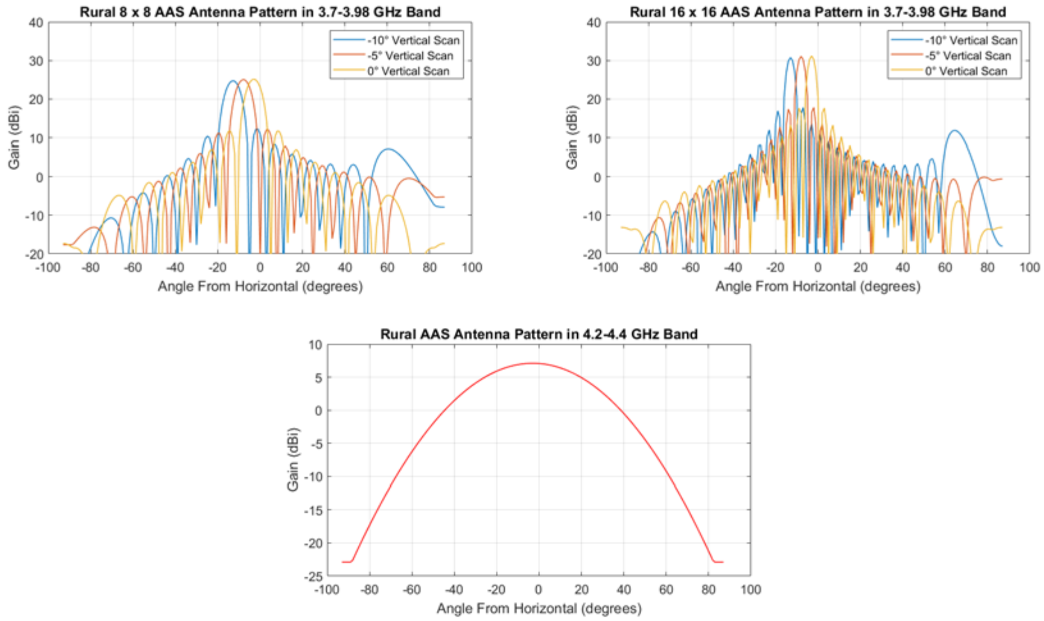

Figure 6-6: Antenna Pattern Elevation Plane Cuts for Rural AAS Base Stations

6.3.3.1.2 Fixed-Beam Sectoral Base Stations

Although the expectation is that most 5G deployments in the United States in the 3.7–3.98 GHz band will use AAS base stations, the possibility of fixed-beam sectoral antennas, such as those commonly used in fourth-generation Long-Term Evolution (4G LTE) mobile networks, is not precluded by the FCC Order and thus cannot be ruled out in accounting for all worst-case conditions. Therefore, in addition to the six AAS base station configurations defined in Section 6.3.3.1.1, the three fixed-beam sectoral base station configurations described in Table 6-5 are also considered in the analysis. The characteristics for these base station configurations are taken primarily from Rep. ITU-R M.2292, with the exception of the mast heights, downlink bandwidths, spurious output PSD, and antenna frequency-dependent rejection (FDR) factors, which were determined based upon inputs from the mobile wireless industry experts in TWG-3. The mechanical downtilt, mast height, downlink bandwidth, activity factor, and spurious output PSD are all assumed to be the same as the AAS base station configurations for each applicable environment.

Table 6-5: 5G Base Station Characteristics[23] with Fixed-Beam Sectoral Antennas

Environment	Urban	Suburban	Rural
Antenna Pattern	ITU-R F.1336-5 $k_a = 0.7$ $k_p = 0.7$ $k_h = 0.7$ $k_v = 0.3$	ITU-R F.1336-5 $k_a = 0.7$ $k_p = 0.7$ $k_h = 0.7$ $k_v = 0.3$	ITU-R F.1336-5 $k_a = 0.7$ $k_p = 0.7$ $k_h = 0.7$ $k_v = 0.3$
Peak Antenna Gain	18 dBi	18 dBi	18 dBi
Horizontal 3 dB Beamwidth (Sector)	65 degrees	65 degrees	65 degrees
Vertical 3 dB Beamwidth[24]	7.56 degrees	7.56 degrees	7.56 degrees
Mechanical Downtilt	10 degrees	6 degrees	3 degrees
Mast Height	20 meters	25 meters	35 meters
Downlink Bandwidth	100 MHz	100 MHz	100 MHz
Activity Factor	50%	50%	50%
Peak Output EIRP Per Sector	61 dBm	61 dBm	61 dBm
Peak Output PSD (EIRP)	41 dBm/MHz	41 dBm/MHz	41 dBm/MHz
Conducted PSD, Spurious	-20 dBm/MHz	-20 dBm/MHz	-20 dBm/MHz
Antenna FDR in 4.2–4.4 GHz Band	3 dB	3 dB	3 dB
Peak Output PSD, Spurious (EIRP)	-5 dBm/MHz	-5 dBm/MHz	-5 dBm/MHz

The sectoral base station antenna patterns are computed using the methods outlined in Recommendation ITU-R F.1336-5 [26]. For interference analysis considering the fundamental 5G emissions in the 3.7–3.98 GHz band, the antenna patterns computed based on Rec. ITU-R F.1336 are used directly. For interference analysis considering the spurious 5G emissions in the 4.2–4.4 GHz band, the same pattern is used, but the gain is uniformly reduced by an assumed antenna FDR value of 3 dB.

Computed antenna pattern cuts in the elevation plane for the Urban sectoral base station are shown in Figure 6-7. Likewise, antenna pattern cuts in the elevation plane for the Suburban sectoral base station are shown in Figure 6-8, and pattern cuts in the elevation plane for the Rural sectoral base station are shown in Figure 6-9.

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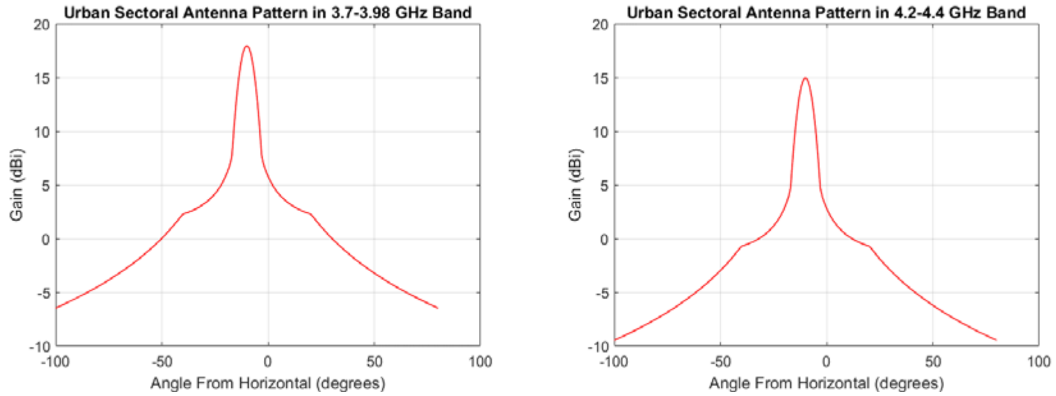
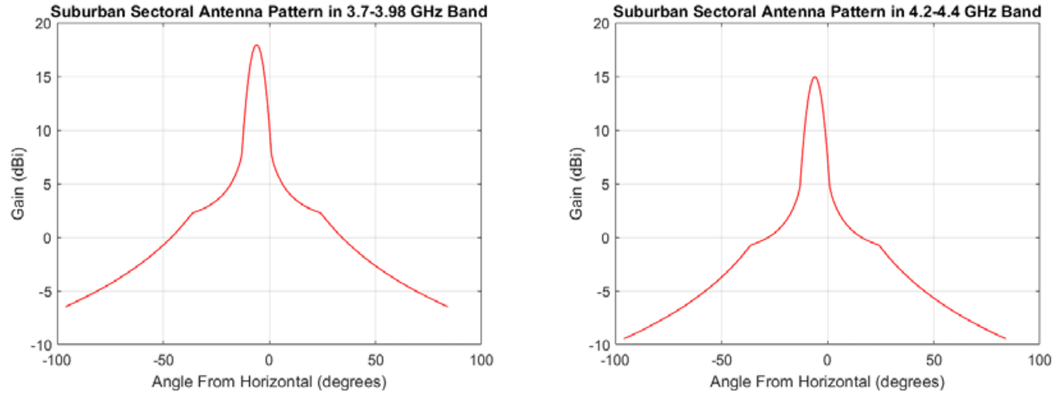
[23] While these operational characteristics are compliant with the technical restrictions established in the FCC Report and Order, they are not specifically defined or limited by the Order or any other FCC regulations.

[24] Vertical beamwidth is calculated from the horizontal beamwidth and peak gain using the equations in Rec. ITU-R F.1336-5 Annex 2, Section 4.


Urban Sectoral Antenna Pattern in 3.7-3.98 GHz Band

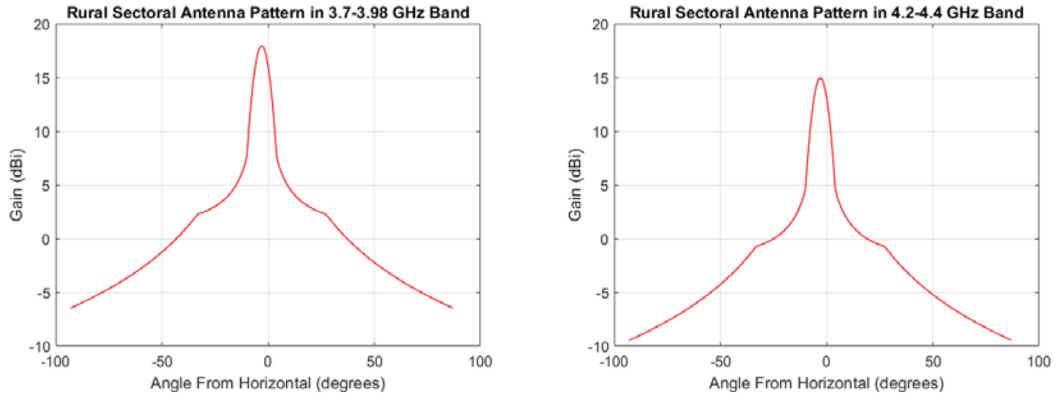
Urban Sectoral Antenna Pattern in 4.2-4.4 GHz Band

Figure 6-7: Antenna Pattern Elevation Plane Cuts for Urban Sectoral Base Station


Suburban Sectoral Antenna Pattern in 3.7-3.98 GHz Band

Suburban Sectoral Antenna Pattern in 4.2-4.4 GHz Band

Figure 6-8: Antenna Pattern Elevation Plane Cuts for Suburban Sectoral Base Station


Rural Sectoral Antenna Pattern in 3.7-3.98 GHz Band

Rural Sectoral Antenna Pattern in 4.2-4.4 GHz Band

Figure 6-9: Antenna Pattern Elevation Plane Cuts for Rural Sectoral Base Station

6.3.3.2 User Equipment on the Ground

The operational characteristics assumed for the 5G UEs located on the ground are listed in Table 6-6. All values except for the uplink channel bandwidth, uplink time factor, output power, output PSD, and spurious output PSD are taken from Rep. ITU-R M.2292[25]. The uplink channel bandwidth is taken from the 3rd Generation Partnership Project (3GPP) Technical Specification (TS) 38.101-1, which specifies channel bandwidths ranging from 10 MHz to 100 MHz for New Radio (NR) band n77 (3.3–4.2 GHz) in Table 5.3.5-1 [27]. A bandwidth of 20 MHz is considered to be reasonably representative and was selected for the analysis. The uplink time factor is assumed based on inputs received from the mobile wireless industry experts in TWG-3, indicating that a 2:1 downlink-to-uplink time ratio can be considered typical. The output power is taken from the emissions limits for user equipment in the FCC Order. The conducted spurious output PSD is taken from 3GPP TS 38.101-1, Table 6.5.3.1-2.

Table 6-6: 5G UE Characteristics[26] for On-Ground Scenario

Environment	Urban	Suburban	Rural
Antenna Pattern	Omnidirectional	Omnidirectional	Omnidirectional
Antenna Gain	-4 dBi	-4 dBi	-4 dBi
Indoor Usage	70%	70%	50%
Indoor Penetration Loss	20 dB	20 dB	15 dB
Body Loss	4 dB	4 dB	4 dB
Active UE Density	3/5 MHz/km^2	2.16/5 MHz/km^2	0.17/5 MHz/km^2
UE Height Above Ground	1.5 m	1.5 m	1.5 m
Uplink Channel Bandwidth	20 MHz	20 MHz	20 MHz
Uplink Time Factor	33%	33%	33%
Peak Output EIRP	30 dBm	30 dBm	30 dBm
Peak Output PSD (EIRP)	17 dBm/MHz	17 dBm/MHz	17 dBm/MHz
Conducted PSD, Spurious	-30 dBm/MHz	-30 dBm/MHz	-30 dBm/MHz
Peak Output PSD, Spurious (EIRP)	-34 dBm/MHz	-34 dBm/MHz	-34 dBm/MHz

As with the activity factor for the 5G base stations, the uplink time factor is treated as a duty cycle to calculate average output power based on the peak output power specified above. With an uplink time factor of 33%, this corresponds to average power levels 4.8 dB less than the peak power levels.

The analysis of UEs on the ground is conducted by first generating a series of UEs on the ground randomly distributed throughout a large area according to the Active UE Density provided in Table 6-6 and an assumed total operating bandwidth of 100 MHz (the same bandwidth assumed for the downlink emissions from a single 5G base station). For example, with a density of 3 UEs per 5 MHz per square kilometer in the Urban environment

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[25] See Table 4 of Section 5.3, under the subheading "User terminal characteristics."

[26] While these operational characteristics are compliant with the technical restrictions established in the FCC Report and Order, they are not specifically defined or limited by the Order or any other FCC regulations (with the exception of the 30 dBm EIRP limit).

case, a total of 60 UEs are generated per square kilometer. Each UE is then randomly selected to be either an indoor or outdoor UE, with the probability of being selected as an indoor UE equal to the Indoor Usage percentage for the given environment. A body loss term is applied to all UEs as indicated in Table 6-6. Note that for specific operational scenarios considering an aircraft overflying active UEs, it may not be appropriate to include a body loss term in any additional worst-case analyses—for example, in the case of spectators in a viewing area near the end of a runway who will likely be holding their devices up and away from their bodies to take pictures. However, since the scenario considered here is instead a generic analysis of an aircraft flying over an area inhabited by active UEs distributed in accordance with Rep. ITU-R M.2292, the body loss term is considered to be applicable in this limited example. However, this parameter should be removed for any specific scenario analyses, especially for UEs which are active near areas in which aircraft operate at low altitudes.

An example of the distribution of UEs on the ground is shown in Figure 6-10. The aircraft is assumed to be at some altitude above the point (0, 0) kilometers.

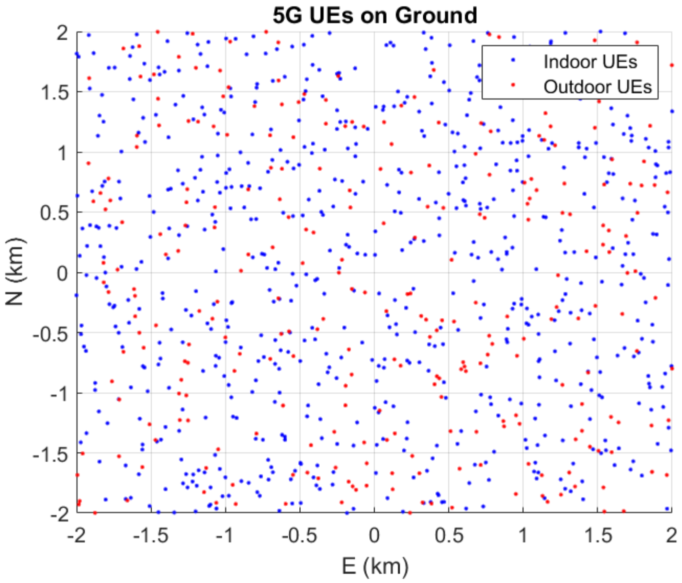

Figure 6-10: Example Distribution of 5G UEs on the Ground

After the UE locations are determined and each is assigned as either an indoor or outdoor UE, the path loss from each UE to the radar altimeter receiver is calculated using the propagation model described in Section 6.3.1 and the radar altimeter antenna and installation characteristics described in Section 6.3.4. The interference PSD received by the radar altimeter from each UE can then also be determined, based on these path losses and the EIRP characteristics given in Table 6-6. This is done for both the 5G fundamental emissions in the 3.7–3.98 GHz band and for the 5G spurious emissions in the 4.2–4.4 GHz band.

Since the UEs on the ground are operating in close vicinity and will likely be communicating with the same base station, it is not expected that multiple UEs will be able to transmit on the same uplink channel at the same time. Therefore, the aggregation of the interference received from the UEs does not consider all UEs in the scenario, but only those which may be expected to be simultaneously transmitting. As a worst case, the *N* UEs with the lowest path losses (generally the *N* closest outdoor UEs to the radar altimeter receive antenna boresight) are considered to transmit simultaneously, where *N* is the number of uplink channels available. Since the assumed total operating bandwidth in a localized area (i.e. the bandwidth available from a single base station) is 100 MHz, and the assumed Uplink Channel Bandwidth for the UEs is 20 MHz (given in Table 6-6), this leads to N = 5 available uplink channels. For the 5G fundamental emissions case, the aggregate received interference PSD is determined by summing the power received from the five UEs with the lowest path loss, and then averaging this power across the 100 MHz total bandwidth. For the 5G spurious emissions case, the aggregate received interference PSD is simply the non-coherent sum of the received spurious levels from these five UEs (since the spurious emissions all land within the same band).

6.3.3.3 User Equipment Onboard Aircraft

As previously discussed, the case of 5G UEs onboard aircraft requires special consideration to determine the path losses from the interference sources to the radar altimeter. Several studies have been conducted to evaluate the interference coupling from Portable Electronic Devices (PEDs) located inside an aircraft cabin to various aircraft navigational equipment and radios, for several different aircraft types [28] [29] [30] [31] [32] [33]. Each of these studies was considered, and the results were aggregated to define a worst-case interference coupling assumption for three main aircraft categories: commercial air transport; regional, business aviation, and general aviation; and helicopters. These worst-case coupling values, defined from an isotropically radiating interferer inside the aircraft cabin up to the RF port of the radar altimeter receive antenna, are listed in Table 6-7. The coupling values are assumed to be applicable to RF signal propagation both in the 3.7–3.98 GHz band, and in the 4.2–4.4 GHz band, to allow for consideration of both fundamental emissions and spurious emissions from the 5G UEs.

Table 6-7: Interference Coupling for 5G UEs Onboard Aircraft

Aircraft Type	Worst-Case Interference Coupling from Onboard UEs	Studies Considered
Commercial Air Transport	80 dB	Schmidt et al., Schüür & Nunes
Regional, Business Aviation, and General Aviation	70 dB	Schüür & Nunes, Futatsumori
Helicopters	57 dB	Schüür & Nunes, Ponçon

The operational characteristics assumed for the 5G UEs located onboard an aircraft are the same as those for the 5G UEs on the ground, and are listed in Table 6-8.

Table 6-8: 5G UE Characteristics[27] for Onboard Aircraft Scenario

Antenna Pattern	Omnidirectional
Antenna Gain	-4 dBi
Uplink Channel Bandwidth	20 MHz
Uplink Time Factor	33%
Peak Output EIRP	30 dBm
Peak Output PSD (EIRP)	17 dBm/MHz
Conducted PSD, Spurious	-30 dBm/MHz
Peak Output PSD, Spurious (EIRP)	-34 dBm/MHz

As with the case of UEs on the ground, the received PSD from each UE is determined individually, and the results are aggregated to evaluate the overall interference levels received by the radar altimeter. Once again, a total available operating bandwidth of 100 MHz is assumed, allowing for five uplink channels. As a worst case, it is assumed that all five UEs transmitting simultaneously in these uplink channels are located at a point in the aircraft yielding the minimum path losses provided in Table 6-7. This could correspond, for example, to the five UEs being used by passengers seated in the same row of a transport aircraft.

Since all five UEs are assumed to have the same path loss, the calculation of the aggregate received interference is simplified. For the 5G fundamental emissions case, the interference PSD at the radar altimeter receive port is given by Equation 6-3:

$$PSD_{RX} = PSD_{source} + 10\log_{10} t - C - L_{RX} \tag{6-3}$$

In this equation, PSD_{source} is assumed to be defined in terms of EIRP as in Table 6-8, t is the Uplink Time Factor, C is the worst-case interference coupling for the given aircraft type as specified in Table 6-7, and L_{RX} is the radar altimeter receive path cable loss. For the 5G spurious emissions case, the interference PSD at the radar altimeter receive port is given by Equation 6-4:

$$PSD_{RX} = PSD_{source} + 10\log_{10} t - C - L_{RX} + 10\log_{10} N \tag{6-4}$$

In this case, since the spurious emissions all land within the 4.2–4.4 GHz band regardless of the uplink channel used by each UE, an aggregation factor is included to non-coherently sum the interference received from each UE. As discussed above, N = 5 UEs is assumed in this analysis.

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[27] While these operational characteristics are compliant with the technical restrictions established in the FCC Report and Order, they are not specifically defined or limited by the Order or any other FCC regulations (with the exception of the 30 dBm EIRP limit).

6.3.4 Radar Altimeter Characteristics

6.3.4.1 Antenna Patterns

Reference radar altimeter antenna patterns exist in literature, for example as described in Annex 3 of Report ITU-R M.2319-0 [34]. However, such patterns are defined based on the assumed or observed characteristics of altimeter antennas with respect to signals within the 4.2–4.4 GHz band only. Further, it is not sufficient to define the radiation or reception pattern of an altimeter antenna outside of this band simply by adding a constant FDR factor, since the shape of the pattern may change substantially at other frequencies in addition to the peak gain being reduced.

In order to provide an accurate representative radar altimeter antenna pattern applicable to the 3.7–3.98 GHz band, measured patterns were taken at 3850 MHz, near the middle of the band. Two separate altimeter antenna models from two different manufacturers were tested. These particular antenna models and their variants are in widespread use across a wide range of aircraft types (including commercial air transport and regional aircraft, business and general aviation aircraft, and helicopters), and with a variety of different altimeter models. The antenna models are therefore considered reasonably representative of the antennas that are used with all FAA-approved radar altimeter models on civil and commercial aircraft.

Co-polarized pattern cuts were collected in an antenna test range for both the E-plane and H-plane of each antenna, across angles ranging from ±90° from boresight. A single reference pattern was formed by taking an envelope of the patterns measured from both antenna models for both polarizations and then smoothing the result using a central average with a 5° window. Finally, the reference pattern was extended to the range of ±180° from boresight by extrapolation using the same roll-off rate observed at ±90°. This final step is largely inconsequential to the interference analysis results, since interference signal angles of arrival well outside of ±90° from the altimeter receive antenna boresight will only be encountered when the aircraft is simultaneously at an altitude less than the 5G base station height, and at a very small lateral distance from the base station. Further, in such cases fuselage attenuation may affect the apparent radar altimeter antenna gain, depending on the signal angle of arrival. However, this approach makes the interference model development simpler by ensuring the altimeter antenna gain can be calculated for all possible angles about the aircraft.

The process above was repeated using measurements taken at 4300 MHz in order to develop reference radar altimeter patterns applicable to the 4.2–4.4 GHz band in addition to the 3.7–3.98 GHz band, with both determined from the same source and using the same methods. The resulting reference pattern for the 3.7–3.98 GHz band is shown in Figure 6-11, and the reference pattern for the 4.2–4.4 GHz band is shown in Figure 6-12. In both cases, the radar altimeter antenna pattern is assumed to be rotationally symmetric about the boresight axis.

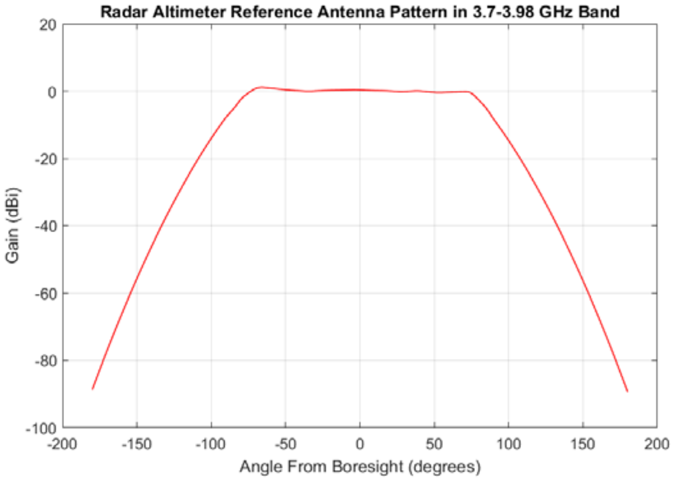

Figure 6-11: Radar Altimeter Reference Antenna Pattern for the 3.7–3.98 GHz Band

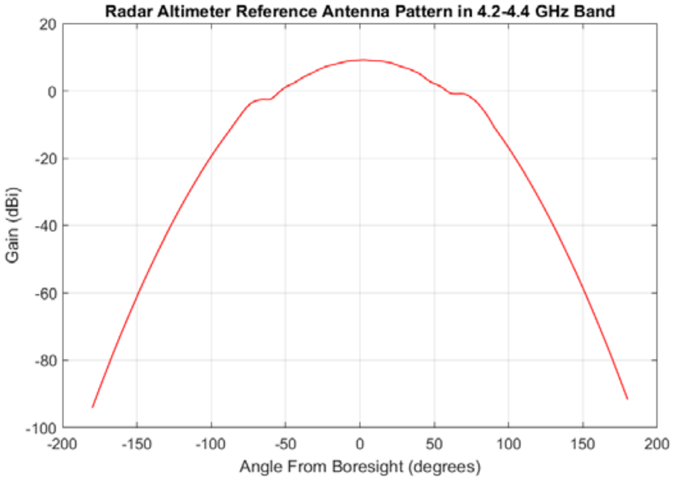

Figure 6-12: Radar Altimeter Reference Antenna Pattern for the 4.2–4.4 GHz Band

6.3.4.2 Aircraft Installation Parameters

To ensure consistency between the interference analysis and the empirical interference tolerance thresholds determined by laboratory testing at AVSI, the same altimeter installation assumptions used in the AVSI tests are also applied to the interference models. In particular, a cable loss of 3 dB is assumed between the radar altimeter receive antenna and the receiver input port. The AVSI testing setup further assumes a 3 dB cable loss between the radar altimeter transmitter output port and the transmit antenna (as described in Section 7.3.1), but this does not directly impact the computation of received interference power or PSD in the analysis.

6.3.5 Aircraft Operational Envelope

For the parametric interference analysis, it is desirable to consider the full range of operating conditions in which the radar altimeter is expected to behave properly and meet its performance requirements. Three parameters of these operating conditions, in particular, will have an effect on the computed interference levels in the analysis model: the aircraft altitude, the aircraft pitch angle, and the aircraft roll angle. Therefore, the full range of each of these parameters in which radar altimeters are expected to operate must be considered.

The current radar altimeter MOPS specify that altitude must be measured up to at least 2,500 feet. However, some of the altimeter models included in the test group used at AVSI to empirically determine interference tolerance thresholds (see Section 7.2) are capable of measuring altitude up to as high as 7,500 feet. Therefore, the maximum altitude utilized in the parametric interference analysis is chosen to cover the full measurement range of all altimeter models included in the applicable usage category under consideration. For all usage categories, this maximum altitude will be at least 2,500 feet.

For the aircraft pitch and roll angles, the radar altimeter MOPS provide two performance categories: Category L, which includes pitch angles of ±20° and roll angles of ±20°, and Category P, which includes pitch angles of ±30° and roll angles of ±40°. Of the altimeter models included in the test group used at AVSI to empirically determine interference tolerance thresholds, some have TSO authorization approvals for Category L performance only, while others have TSO authorization approvals for Category P performance (or both Category P and Category L). Therefore, the maximum pitch and roll angles utilized in the parametric interference analysis are chosen to cover the full pitch and roll capability of all altimeter models which are applicable to each given interference scenario under consideration.

It is understood that certain combinations of aircraft operating conditions considered in the parametric interference analysis may not be realistic for the aircraft types of one or more radar altimeter usage categories. For example, a commercial air transport aircraft will not be capable of operating with a 30° pitch angle and 40° roll angle while at an altitude of 100 feet. However, the goal of the parametric analysis is to consider all possible combinations of operating conditions. Then, for any combinations of conditions at which the computed interference level exceeds the tolerance thresholds (or is within an applicable safety margin of the tolerance thresholds), further context and clarification regarding the operational scenarios in which those combinations of conditions may or may not be encountered can be provided.

7 INTERFERENCE TOLERANCE THRESHOLD TESTING METHODOLOGY

7.1 General Approach

The empirical determination of interference tolerance thresholds is accomplished by simulating, in a laboratory environment, the existing operating conditions of each radar altimeter under test, and then systematically injecting increasing levels of representative 5G interference into the altimeter receiver until the altitude output is affected to an unacceptable extent. The existing operation conditions consist of, at a minimum, an altitude return signal with an amplitude corresponding to the loop loss standards given in the MOPS for the test altitude being considered. This is done using one or more optical fiber delay lines along with fixed and variable RF attenuators. Further, for any altimeter models which may be used in dual or triple installations on a single aircraft, the own-ship interference from these co-located radar altimeters is represented using one or two voltage-controlled oscillators (VCOs) to generate FMCW interference waveforms with sweep characteristics and power levels determined based on the transmission and installation parameters of the altimeter under test. Finally, for tests considering low altitude (200 feet in this case) operations at an airport, fourteen additional VCOs are used to model the FMCW interference from the radar altimeters installed in other aircraft on the ground, with power levels determined based on an assumed scenario geometry derived from ICAO aerodrome design guidelines.

For more details on the exact test setup and methods used by AVSI for the interference tolerance threshold testing, see Appendix A.

7.2 Radar Altimeter Models and Usage Categories

A total of nine radar altimeter models, from five different manufacturers, were obtained by AVSI for testing of interference tolerance thresholds. These models are representative of a significant majority of radar altimeter models currently deployed on commercial air transport, regional, business aviation, and general aviation aircraft, as well as helicopters. Therefore, while the group of models tested does not include every active FAA-approved radar altimeter, the interference tolerance threshold test results are considered to be generally applicable across all present civil aviation applications. Eight of the radar altimeter models utilize FMCW radar technology, while one model utilizes unmodulated pulsed radar technology.

Since the test group of radar altimeters spans the full range of market segments and use cases in civil aviation, it is anticipated that significant variations in performance will be observed throughout the group. Therefore, considering the worst-case interference tolerance thresholds across all nine altimeter models will not yield a result that is reasonably applicable to every civil aviation use case or aircraft type. To account for this and instead provide reasonably applicable interference tolerance thresholds for any particular aviation use cases or aircraft types that may be considered in subsequent analysis, the test group of altimeter models is divided into three usage categories based on both their intended and actual use on different types of aircraft:

- 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.

In addition, Usage Category 2 and 3 radar altimeters generally have lower size, weight, power, and cost than Usage Category 1 models, in order to serve their respective markets appropriately. Note that it is possible for a given radar altimeter model in the test group to be included in multiple usage categories, depending on the intended and actual use of that model in commercial and civil aviation. Each usage category consists of at least four separate radar altimeter models.

Within each usage category, an overall Interference Tolerance Mask (ITM) is determined by combining the measured interference tolerance thresholds among all altimeter models included in that usage category. This is done by taking the worst-case interference tolerance threshold across all altimeter models applicable to a given usage category for each interference test case. Such an aggregation is possible since for a given usage category, *all* other parameters used in the interference analysis, including the radar altimeter antenna patterns and receive path cable losses, aircraft operational envelope, and interference scenario geometries, will remain the same regardless of which specific altimeter model within the usage category is being considered. Further, the analysis of a particular interference scenario generally will not be able to consider only one specific model of radar altimeter, but instead must consider all possible models which may be installed on a given type of aircraft. Therefore, the aggregation of the interference tolerance thresholds by usage category greatly simplifies such analysis—without compromising the analysis results—by providing a single ITM that is sufficient to ensure that *any* radar altimeter model which could be used in a given scenario will be protected.

In addition to limiting the specific radar altimeter models considered in determining the interference tolerance thresholds, the usage categories are also used to define certain parameters and assumptions in the test setup to ensure the results are applicable to the appropriate usage category. For example, a particular altimeter model may be used in both fixed-wing and helicopter applications, but with a dual installation on certain fixed-wing aircraft and only single installations on helicopters. In this case, the test setup would be adjusted to exclude any representation of own-ship radar altimeter interference for tests applicable to the helicopter usage category, while tests applicable to the appropriate fixed-wing usage category would consider own-ship interference from the adjacent altimeter in the dual installation. Further, the different usage categories may imply operational scenarios that are not applicable to other usage categories. For example, when considering fixed-wing usage categories for the low altitude test case (200 feet AGL), the aircraft can be assumed to always be at an airport, and thus it is necessary to consider existing interference from the radar altimeters located in other aircraft on the ground at the airport. However, for the helicopter usage category, operations at 200 feet AGL may be encountered either at an airport or far away from an airport. In the latter case, no interference from radar altimeters installed in other aircraft on the ground is included in the test scenario.

Table 7-1 lists the altimeter models used in the testing campaign in anonymized fashion, along with characteristics relevant to the testing and the applicable usage categories. Note that all of these altimeter models have been approved by the FAA for use on certified commercial and civil aircraft through the TSO authorization process.

Table 7-1: Radar Altimeter Models Used in Interference Tolerance Testing

Altimeter Model	Modulation	Maximum Altitude[28]	Maximum Installation[29]	Usage Category		
				1	**2**	**3**
Type 1	FMCW	7500 ft	Triple	Yes	No	No
Type 2	FMCW	5500 ft	Triple	Yes	No	No
Type 3	FMCW	5500 ft	Triple	Yes	No	No
Type 4	FMCW	5500 ft	Triple	Yes	No	No
Type 5	FMCW	5500 ft	Triple	Yes	No	No
Type 6	FMCW	2500 ft	Triple	No	Yes	Yes
Type 7	FMCW	2500 ft	Single	No	Yes	Yes
Type 8	Pulsed	2500 ft	Dual	No	Yes	Yes
Type 9	FMCW	2500 ft	Triple	No	Yes	Yes

In previous test reports published by AVSI[30], data was only available for altimeter Types 1 through 7, and Type 7 in some cases exhibited substantially different behavior from Types 1 through 6. Based on this behavior, it was considered that Type 7 may be an outlier among radar altimeters used in commercial and civil aviation with regard to out-of-band interference tolerance. However, this consideration did not appropriately account for the usage categories, as the altimeter models tested were mostly applicable to Usage Category 1 only, while Type 7 is only applicable to Usage Categories 2 and 3. To further investigate this matter, AVSI obtained two additional radar altimeter models from separate manufacturers (Type 8 and Type 9) which are applicable to Usage Categories 2 and 3, both to have a more representative sample of these usage categories, and to determine if Type 7 is in fact an outlier when judged against its peers. Testing of these additional models revealed that Type 7 is *not* an outlier among Usage Category 2 and 3 altimeter models, and instead provides comparable performance to other models used in those applications. For more details and discussion on the interference tolerance threshold testing results, see Section 9.

7.3 Test Cases

7.3.1 Test Altitudes and Loop Losses

Interference tolerance threshold tests are performed at three separate altitudes for each radar altimeter model: a “low” altitude of 200 feet, a “medium” altitude of 1,000 feet, and a “high” altitude which is set to within 500 feet of the maximum measurement altitude of each altimeter model, which varies between 2,500 feet and 7,500 feet across all of the altimeter models in the test group, as shown in Table 7-1 (and thus the high altitude test point varies between 2,000 feet and 7,000 feet). The low and medium altitude test points were chosen to allow for measurement of the interference tolerance thresholds at consistent

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[28] The altitudes given here correspond to the maximum altitudes at which each radar altimeter model is designed to provide a reliable altitude measurement and meet all performance requirements. However, radar altimeters generally remain operational at all altitudes throughout all phases of flight.

[29] This refers to multiplex installations onboard a single aircraft. The configurations listed for each altimeter are the maximum allowed, and many aircraft installations may use fewer than this (e.g. a dual installation of Type 1).

[30] See, for example, the AFE 76s2 Preliminary Report on the Behavior of Radio Altimeters Subject to Out-Of-Band Interference, filed with the FCC under GN Docket No. 18-122 on October 22, 2019 [6].

altitudes across all altimeter models in the range of altitudes in which accurate radar altimeter operation is most critical to aviation safety. The high altitude test points were chosen to allow for direct measurement of the interference tolerance thresholds of each altimeter model under conditions which lead to the greatest interference susceptibility. Radar altimeter receivers are generally more sensitive while tracking higher altitudes in order to compensate for the increased path losses experienced by the altitude return signal, and thus they are expected to have the lowest overall interference tolerance in this condition.

The external loop losses[31] for each test altitude were set based on the curves provided in RTCA DO-155 for the case of an antenna with 10.8 dBi of gain (linear power gain of 12) and 60° beamwidth, in accordance with FAA TSO-C87a which specifies that the loop loss determination methods in DO-155 should be utilized [1] [4]. The DO-155 loop loss curves were adjusted to account for an assumed terrain reflection coefficient of $\sigma_0 = 0.01$, which is the minimum specified for testing purposes in ED-30 [2]. This therefore corresponds to the highest loop loss dictated by the MOPS at which the radar altimeters must successfully measure altitude and meet the required accuracy performance. Thus, this testing condition corresponds to a worst-case assumption of the minimum altitude return signal amplitude, and in turn the minimum SINR for a given level of interference. However, since radar altimeters are required to meet the MOPS performance in all specified operating conditions and environments, this worst-case assumption must be utilized in determining the interference tolerance thresholds.

In addition to the worst-case external loop loss in accordance with the MOPS requirements, the total altitude loop loss simulated in the AVSI test setup includes an additional 6 dB to represent the RF cable losses present in an actual radar altimeter installation on an aircraft. This corresponds to 3 dB of cable losses between the antenna and the altimeter transceiver in both the transmit and receive paths, which is a reasonably representative assumption that can be considered applicable across all aircraft types (and thus for all usage categories). These same cable loss assumptions are maintained throughout the test setup, for example when determining the appropriate power levels for the VCOs used to represent existing radar altimeter interference, as well as in the subsequent interference analysis which utilizes the empirically determined interference tolerance thresholds.

7.3.2 Existing Radar Altimeter Interference

The existing RF interference environment in which radar altimeters operate is dominated by in-band interference received from other radar altimeters. This includes both one or two co-located (own-ship) altimeters on the same aircraft in the case of a dual or triple installation, as well as the off-board altimeters installed in other aircraft. In most operational scenarios, the interference from off-board radar altimeters is negligible due to the large separation distances between aircraft, and thus very high path losses from these interference sources to the victim altimeter. However, this is not the case when the victim aircraft is operating at a low altitude near an airport, such as during a final approach just prior to landing. The safe operation of radar altimeters is of course highly critical during landing scenarios, and thus it is important to consider any impacts of the interference

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[31] External loop loss is defined in RTCA DO-155, Appendix B as “the ratio of the available power entering the receiving antenna aperture to the power leaving the transmitter antenna aperture” [4]. Note that although the current radar altimeter MOPS are specified by EUROCAE ED-30, TSO-C87a specifically states that the methods outlined for determining external loop loss in DO-155 shall still be used.

provided by other altimeters in these scenarios when assessing the 5G interference tolerance thresholds.

For the medium and high altitude tests, it is assumed that any radar altimeter interference from other aircraft is insignificant and can be ignored. Therefore, in these cases only the own-ship radar altimeter interference is modeled in the test setup, as applicable for each altimeter model based on its installation characteristics on the assumed platform type for the usage category being considered. The own-ship radar altimeter interference is modeled using one or two VCOs—representing dual or triple installations, respectively—to generate FMCW interference signals consistent with the operational characteristics of the altimeter model under test. For the pulsed altimeter (Type 8) no own-ship interference is modeled, since the presence of RF interference from a second pulsed altimeter in a dual installation is not expected to have a significant impact on the interference tolerance of either 5G fundamental emissions in the 3.7–3.98 GHz band, or 5G spurious emissions in the 4.2–4.4 GHz band.

For low altitude tests, off-board radar altimeter interference is also modeled using additional VCOs to generate FMCW interference signals. The power levels are determined for each VCO based upon a specific interference scenario geometry referred to by AVSI as the Worst-Case Landing Scenario (WCLS). The WCLS considers the victim aircraft to be at an altitude of 200 feet just prior to landing, while several other aircraft are located nearby on the taxiway and apron. The exact scenario geometry is defined using ICAO aerodrome design guidelines, and is explained in more detail in Appendix A.1.

In addition, the low altitude test case is repeated for Usage Category 3 with no off-board radar altimeter interference. This is to account for low altitude aircraft operations away from airports, which is a scenario unique to helicopters.

7.3.3 5G Fundamental and Spurious Emissions

The AVSI testing considers the interference tolerance thresholds based upon both the 5G fundamental emissions in the 3.7–3.98 GHz band and the 5G spurious emissions which land in the 4.2–4.4 GHz band. To isolate the effects caused by the 5G fundamental emissions and 5G spurious emissions, the two are tested separately and two different interference tolerance thresholds are determined for each test case.

The interference tolerance thresholds for the 5G fundamental emissions are expected to be much higher than those for the 5G spurious emissions which land directly within the radar altimeter receive bandwidth. Therefore, caution must be exercised in the test setup design to ensure that when testing with the relatively high-power fundamental emissions waveform, there will be no undesired signals output from the interference signal generator in the 4.2–4.4 GHz band. If not kept below a reasonable level, such signals could breach the much lower spurious interference tolerance threshold and synthesize a lower interference tolerance threshold falsely attributed to the fundamental emissions. To avoid this possibility, and ensure the highest possible confidence in the fundamental emissions interference tolerance threshold results, a 4.2–4.4 GHz band-stop filter was included in the test setup at the output of the interference signal generator for the 5G fundamental emissions test. The utilized filter provides additional attenuation ranging from 25 to 40 dB throughout the 4.2–4.4 GHz band.

Based on the characterization testing of the spurious output levels from the VSG (see Appendix A.3.1), a 5G fundamental emissions waveform generated in the 3.7–3.98 GHz band will produce spurious levels in the 4.2–4.4 GHz band of no more than -114 dBm/MHz at the radar altimeter receiver input (after accounting for the band-stop filter attenuation) when the VSG output power is set to +5 dBm. As the VSG output power is reduced below this level, it is expected that both the 5G fundamental emissions power in the 3.7–3.98 GHz band and the VSG spurious output in the 4.2–4.4 GHz band will decrease accordingly, even though the spurious levels in these cases cannot be measured directly with the instruments available. Instead, to confirm that the 5G fundamental emissions interference tolerance testing was not affected by the spurious output of the VSG, the predicted VSG spurious levels for each 5G fundamental emissions interference tolerance threshold case (determined based on the maximum -114 dBm/MHz value measured with +5 dBm VSG output power) can be compared to the measured 5G spurious interference tolerance thresholds for the same test case. Using the test results provided in Section 9.1 and Section 9.2, this comparison is summarized in Table 7-2. The spurious levels are specified at the radar altimeter receiver input.

Table 7-2: Comparison of VSG Spurious Output to Spurious Tolerance Thresholds

Usage Category	Altitude	Maximum VSG Output for 5G Fundamental Tolerance Threshold[32]	Predicted Worst-Case VSG Spurious in 4.2–4.4 GHz Band	Measured 5G Spurious Tolerance Threshold
1	200 ft	+7 dBm	-112 dBm/MHz	-80 dBm/MHz
	1,000 ft	-1 dBm	-120 dBm/MHz	-85 dBm/MHz
	5,000 ft	-7 dBm	-126 dBm/MHz	-107 dBm/MHz
2	200 ft	-19 dBm	-138 dBm/MHz	-112 dBm/MHz
	1,000 ft	-26 dBm	-145 dBm/MHz	-103 dBm/MHz
	2,000 ft	-35 dBm	-154 dBm/MHz	-119 dBm/MHz
3	200 ft	-14 dBm	-133 dBm/MHz	-96 dBm/MHz
	1,000 ft	-26 dBm	-145 dBm/MHz	-103 dBm/MHz
	2,000 ft	-35 dBm	-154 dBm/MHz	-119 dBm/MHz

As shown in Table 7-2, the expected spurious output from the VSG which reaches the radar altimeter receiver input during the 5G fundamental emissions tolerance threshold tests is far lower (by at least 19 dB) than the measured tolerance thresholds for spurious interference in the 4.2–4.4 GHz band for all altimeters and test conditions.

7.3.4 Test Case Summary

The test cases described in Sections 7.3.1 and 7.3.2 are summarized in Table 7-3. The own-ship VCO configurations correspond to both the number of own-ship VCOs used in the test scenario (ranging from zero to two, depending on the altimeter model and installation platform), as well as the power levels of any own-ship VCOs that are used (based upon the transmitter output power and waveform characteristics of the altimeter model under test, the minimum antenna isolation characteristics for the altimeter model under test on the given installation platform, and the RF cable loss assumptions).

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[32] This is the VSG output power setting corresponding to the power at the radar altimeter receiver input port being equal to the measured 5G fundamental emissions tolerance threshold.

Each test case is performed to determine the interference tolerance thresholds for both the 5G fundamental emissions in the 3.7–3.98 GHz band, and the 5G spurious emissions in the 4.2–4.4 GHz band.

Table 7-3: Interference Tolerance Threshold Test Cases

Usage Category	Own-Ship VCO Configuration	Low Altitude (200 feet)	Medium Altitude (1,000 feet)	High Altitude (Variable)
1	Large fixed-wing	WCLS	No off-board VCOs	No off-board VCOs
2	Small/medium fixed-wing	WCLS	No off-board VCOs	No off-board VCOs
3	Helicopter	WCLS	No off-board VCOs	No off-board VCOs
		No off-board VCOs		

Each altimeter model is evaluated in all test cases for each usage category to which it applies. In some instances the test cases may overlap for multiple usage categories. For example, if a particular altimeter model which applies to Usage Category 2 and Usage Category 3 has identical installation characteristics on both small/medium fixed-wing and helicopter platforms, then the test cases performed for Usage Category 3 would include all test cases for Usage Category 2.

7.4 Interference Tolerance Threshold Determination

For each test case, the interference tolerance threshold is determined by first allowing the radar altimeter under test to initialize and produce a stable and accurate baseline altitude output. Increasing levels of 5G interference are then injected until the altitude output is affected. This process is done in a sequence known as an interference power sweep, in which a particular level of interference is injected for a set duration, the interference is then disabled for another set duration, and then the next higher level of interference is injected. This process is repeated with increasing interference power levels in 1 dB steps. If at any point while the interference signal is applied the radar altimeter output transitions to an NCD state (indicating a loss of track), or a sufficient portion of the altitude readings deviate from the baseline by more than the specified accuracy requirement, then the interference power level is noted. The lowest such interference power level forms the basis of the tolerance threshold for the given test case and altimeter model. For more details on the exact criteria used to determine when the altitude output is unacceptably affected by the 5G interference, see Appendix A.4.

The lowest interference power level at which the altitude output from the altimeter under test is affected for a given test case cannot be taken directly as the interference tolerance threshold. First, this power level must be reduced by 1 dB to yield the maximum interference power level at which the altimeter under test is *not* unacceptably affected, thus corresponding to the maximum tolerable interference power level. Next, the power level is reduced by an additional 1 dB to account for the measurement uncertainty of the AVSI test setup. Finally, a further adjustment is required to consider both the manufacturing tolerances of the radar altimeters, and the performance variation that is anticipated across environmental conditions such as temperature. The AVSI testing is all performed on the basis of one single unit of each altimeter model, in a laboratory environment at room temperature. Thus, to ensure that the results of the AVSI tests are universally applicable to all produced units of each altimeter model, and across all environmental operating conditions, an additional reduction in power level of 4 dB is applied to form the final interference tolerance threshold value. This 4 dB value was selected based on consultation with technical experts from several different radar altimeter manufacturers. With all of these factors accounted for, the interference tolerance threshold for a given test case and altimeter model will be a total of 6 dB less than the lowest measured interference power at which the altitude output is impacted. The interference tolerance threshold results reported in Section 9 include this 6 dB total reduction from the observed failure points.

After the interference tolerance thresholds are determined for each individual altimeter model, they are combined to form the overall ITM for each usage category. The ITM will generally vary based on altitude, and for the 5G fundamental emissions case, on the interference center frequency. Separate interference tolerance thresholds are measured for each fundamental emissions center frequency of interest, as well as for the spurious emissions within the 4.2–4.4 GHz band, and thus a separate ITM can be determined for each case. However, the interference tolerance thresholds are only measured at three discrete altitudes for each altimeter model, while the interference analysis must consider all possible altitudes within the functional measurement range of each altimeter. Therefore, determining the final ITM for each usage category and 5G interference case (fundamental emissions at various center frequencies, and spurious emissions within the 4.2–4.4 GHz band) throughout the full altitude range requires interpolation of the measured tolerance thresholds. Since radar altimeters are generally designed to have receiver sensitivity characteristics which vary linearly with the logarithm of the measured altitude[33], a log-linear interpolation scheme is employed between the measured data points. That is, the measured data points are plotted with a logarithmically scaled altitude axis, and then joined using straight-line segments. At altitudes below the low altitude test point (200 feet), the same tolerance threshold measured at 200 feet is assumed, and at altitudes above the high altitude test point (ranging from 2,000 feet to 7,000 feet depending on the altimeter model), the same tolerance threshold measured at the high altitude test point is assumed.

7.5 Interference Waveform Representation and Assumptions

7.5.1 5G Fundamental Emissions

As described in Appendix A.1, the AVSI test setup utilizes a Rohde & Schwarz SMW200A vector signal generator (VSG) to produce the representative 5G interference waveform used in the interference tolerance threshold testing. The VSG is further configured with the SMW-K144 5G NR software option to allow for straightforward generation of 5G NR waveforms which comply with 3GPP testing standards.

In particular, the VSG is configured to produce a 5G interference test waveform in accordance with the 5G NR Frequency Range 1 (FR1) test model 1.1 (NR-FR1-TM1.1) described in 3GPP TS 38.141-1, Section 4.9.2.2.1 [35], which is an Orthogonal Frequency-Division Multiplexing (OFDM) waveform using Quadrature Phase-Shift Keying (QPSK) subcarrier modulation. This model is designed for conducted tests of base station output power, unwanted emissions, and transmitter intermodulation, making it an appropriate choice to represent the 5G fundamental emissions in the 3.7–3.98 GHz band for the

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[33] This is true of both FMCW and pulsed altimeters and is done to offset the decreasing signal levels received at higher altitudes. The linear trend versus the logarithm of measured altitude can also be seen in the MOPS sensitivity requirements, which are based on the loop loss calculation methods described in DO-155, Appendix B [4].

interference tolerance threshold testing. A bandwidth of 100 MHz was selected for the testing, to be consistent with the downlink bandwidth assumptions used for all base station configurations in the analysis, as described in Section 6.3.3.1. This is also anticipated to be the worst-case bandwidth from a single 5G base station in the 3.7–3.98 GHz band, based on input received from the mobile wireless industry experts in TWG-3. Further, a subcarrier spacing of 30 kHz was selected, which is considered to be representative of common 5G base station downlink emissions in the 3.7–3.98 GHz band based on applicable 3GPP standards. Three different center frequencies were considered, to ensure that testing was performed throughout the full 3.7–3.98 GHz band: 3750 MHz, resulting in the 5G interference waveform being at the lower edge of the 3.7–3.98 GHz band; 3930 MHz, resulting in the 5G interference waveform being at the upper edge of the 3.7–3.98 GHz band; and 3850 MHz, resulting in the 5G interference waveform being approximately centered in the 3.7–3.98 GHz band, while observing the 20 MHz sub-blocks defined in the FCC Order.

Although the NR-FR1-TM1.1 waveform with 100 MHz bandwidth is based on testing standards for base station downlink emissions, it was also considered to be reasonably representative of aggregate UE uplink emissions spanning this same total bandwidth (for example, five UEs simultaneously transmitting on adjacent 20 MHz-wide uplink channels). This assumption is made primarily to allow for utilization of the same interference tolerance thresholds in analysis considering 5G UE uplink emissions, to enable the fastest possible completion of the interference assessment. However, this assumption is reasonable since it is anticipated that there will be little difference in the interference tolerance thresholds when considering interference waveforms with the same total bandwidth and similar modulation characteristics, regardless of the actual source of the emissions.

7.5.2 5G Spurious Emissions

The exact nature of spurious emissions from 5G sources, both base station downlink emissions and UE uplink emissions, which land within the 4.2–4.4 GHz band will depend upon actual hardware characteristics of the emissions sources in addition to the fundamental waveform characteristics. Therefore, defining specific spurious waveforms to use in interference tolerance threshold testing based upon 3GPP standards or other reasonable assumptions is not a straightforward task. To avoid this issue altogether, the 5G spurious emissions are simply represented using additive white Gaussian noise (AWGN) in the 4.2–4.4 GHz band. This will result in a constant PSD across the receive bandwidth of the radar altimeters, allowing for the determination of spurious interference tolerance thresholds in terms of a PSD envelope limit across the 4.2–4.4 GHz band.

The Rohde & Schwarz SMW200A VSG, as well as the SMW-K62 software option used to generate the AWGN waveform for testing of the interference tolerance thresholds in the 4.2–4.4 GHz band, are limited to a maximum bandwidth of 160 MHz. However, this is more than sufficient to cover the full receive bandwidth of all nine altimeter models included in the test group. Therefore, the 160 MHz AWGN waveform can still be used to determine the spurious interference tolerance thresholds in terms of a PSD envelope, provided that the PSD is computed on the basis of this 160 MHz bandwidth rather than the full 200 MHz of the 4.2–4.4 GHz band.

8 AIRCRAFT OPERATIONAL SCENARIO DESCRIPTIONS

8.1 Instrument Approach Procedure

8.1.1 Overview

For the majority of civil and commercial aircraft, the single scenario in which the radar altimeter is most critical to ensure safe operation is during a precision approach and landing. In particular, Category II and III (CAT II/III) ILS approaches[34] require continuous and accurate operation of the radar altimeter(s) onboard the aircraft, with erroneous operation or loss of availability or continuity potentially leading to Catastrophic failures which will result in multiple fatalities of the passengers and/or flight crew. In addition, many CAT II/III operations are approved by the FAA on the basis of using the autoland function in the AFGCS, in which case the autoland function must be engaged during a CAT II or III approach [36]. As described in Section 5.3, the radar altimeter is a critical input to this system, and undetected erroneous altitude output from the radar altimeter during such operations is considered a Catastrophic hazard. Further, since approach procedures require aircraft operations at low altitudes, they may be particularly susceptible to RF interference from terrestrial sources such as 5G telecommunications networks. For these reasons, studying an example of a CAT II/III instrument approach procedure is of the utmost importance.

CAT II/III approaches are a common occurrence for Usage Category 1 aircraft, and the radar altimeters in Usage Category 1 are all designed to support such operations with high integrity, availability, and continuity. Further, some Usage Category 2 aircraft may be certified for CAT II/III approaches, and some (but not all) of the altimeter models included in Usage Category 2 support these operations. Therefore, the analysis presented here will consider both Usage Category 1 and Usage Category 2 radar altimeters, although there is generally a higher potential for significant operational impacts and high safety risks with Usage Category 1.

A particular ILS approach into O’Hare International Airport in Chicago, capable of supporting CAT II/III operations, was selected for the analysis. A precision approach path was defined based on the procedures approved by the FAA. Further, five currently deployed (for 4G LTE service) mobile wireless base stations were identified in various locations along the approach path. Along the approach path, the interference levels seen by the radar altimeter(s)[35] on the landing aircraft were calculated assuming that each base station were hypothetically upgraded to a 5G system operating in accordance with the FCC Order in the 3.7–3.98 GHz band. Both the fundamental emissions in the 3.7–3.98 GHz band and the spurious emissions in the 4.2–4.4 GHz band were considered. These levels

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[34] CAT II ILS approaches are associated with a Decision Height (DH) of less than 200 feet (but not less than 100 feet) and a Runway Visual Range (RVR) of less than 1800 feet (but not less than 1000 feet). CAT III approaches are associated with a RVR of less than 1000 feet [36]. Limitations to RVR are generally due to meteorological conditions or nighttime operations. The DH is the altitude at which the pilot must either establish a visual reference along the runway, or abort the landing. CAT III approaches may include an Alert Height (AH) in lieu of a DH, above which a missed approach should be flown if a fault in automation is detected. For CAT II/III approaches, the DH or AH is determined using the radar altimeter output.

[35] CAT II ILS approaches may be performed with a single radar altimeter, provided the altimeter meets the applicable system safety requirements. In most cases, CAT II approaches are flown using at least a dual radar altimeter installation. CAT III ILS approaches require at least a dual radar altimeter installation.

are then compared to the empirical ITMs determined by AVSI for Usage Category 1 and Usage Category 2.

Figure 8-1 illustrates the basic geometry of the scenario, with the runway threshold location indicated by a red balloon, the precision approach flight path indicated by a red line with a green surface projected to the ground, and the mobile wireless base station locations indicated by cyan balloons.

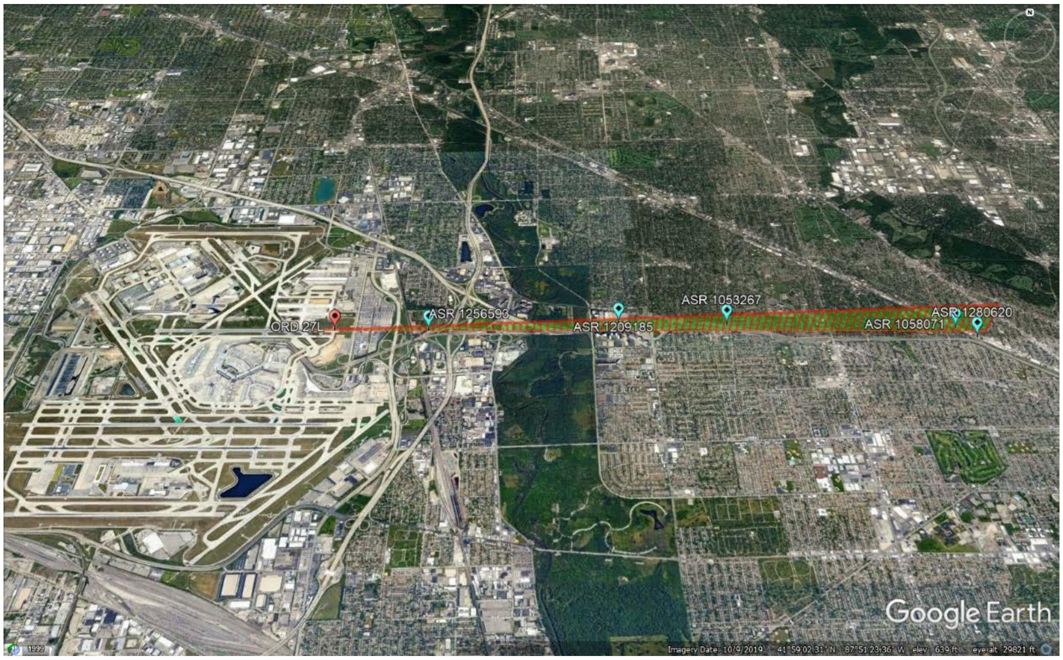

Figure 8-1: Instrument Approach Procedure Scenario Geometry

8.1.2 Airport Location and Runway

The approach selected for this analysis is into Runway 27L at O'Hare International Airport (ORD) in Chicago, Illinois. As of April 2020, this is the single most utilized runway for arrivals at O'Hare, and is designated as a primary arrival runway for nighttime operations [37]. The exact location of the threshold for this runway is listed in Table 8-1. Data is sourced from AirNav.com.

Table 8-1: Instrument Approach Procedure Scenario Runway Information

Runway	Latitude	Longitude	Elevation (MSL)
27L	41° 59' 02" N	87° 53' 21" W	654 ft

8.1.3 Flight Path

The flight path is defined based on the approach plate shown in Figure 8-2, which indicates a 3.00° glide slope angle (GS), an approach magnetic heading of 273° (corresponding to a true heading of 270°), and a final approach fix occurring at 2,200 ft barometric altitude (corresponding to about 1,550 ft AGL) at a distance of 4.7 nautical miles (NM) from the runway threshold.

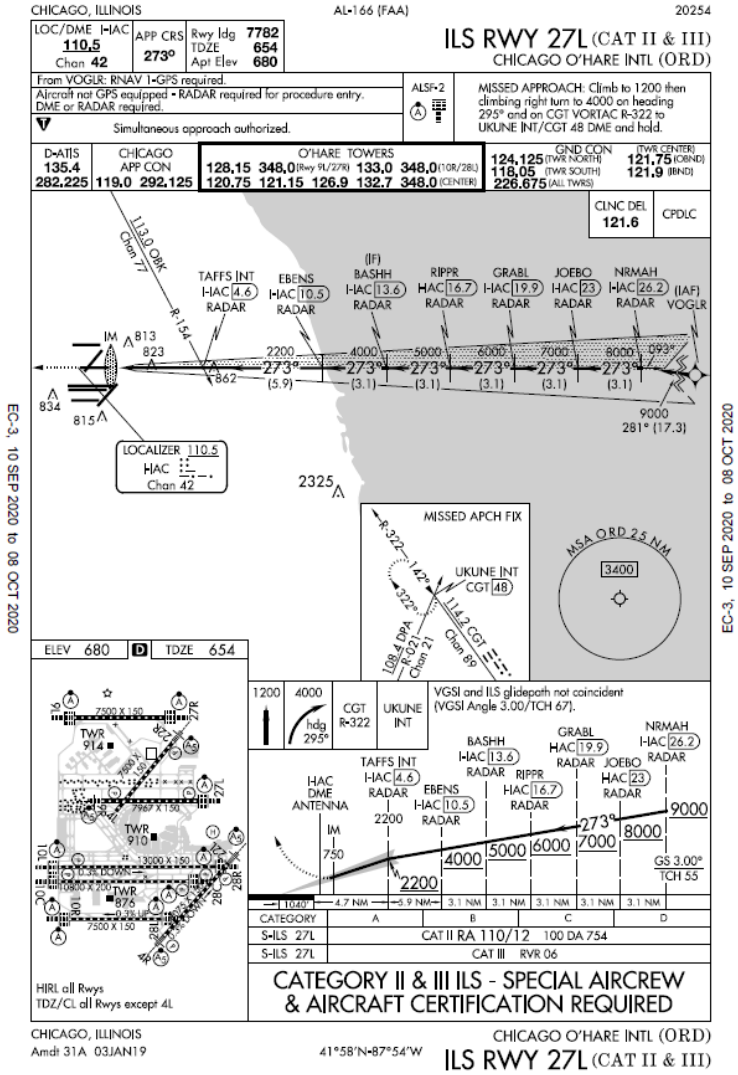

Figure 8-2: O'Hare Runway 27L CAT II/III Approach Plate

8.1.4 5G Base Station Locations

As mentioned previously, the assumed locations of 5G base stations in the interference scenario were set based on the locations of existing 4G LTE base stations in the vicinity of the approach path. This was done using CellMapper.net to initially determine approximate locations of candidate base stations, and then verifying the exact locations and antenna heights using the FCC Antenna Structure Registration (ASR) database [38]. Finally, the base stations were further identified visually using Google Earth imagery.

Five 4G LTE base stations were identified for consideration in the scenario, three of which (ASRs 1053267, 1256593, and 1280620) are operated by AT&T, and two of which (ASRs 1058071 and 1209185) are operated by T-Mobile. The locations of these base stations are given in Table 8-2.

Table 8-2: Instrument Approach Procedure Scenario Base Station Information

FCC Structure Registration	Latitude	Longitude	Elevation (MSL)	Height (AGL)
1053267	41° 59’ 06” N	87° 49’ 26” W	759 ft	103 ft
1058071	41° 59’ 04” N	87° 47’ 09” W	740 ft	115 ft
1209185	41° 59’ 07” N	87° 50’ 31” W	774 ft	134 ft
1256593	41° 59’ 02” N	87° 48’ 50” W	718 ft	78 ft
1280620	41° 58’ 58” N	87° 46’ 59” W	713 ft	90 ft

All five base stations are assumed to be the Urban 16 x 16 AAS configuration described in Section 6.3.3.1.1, with the mast height parameter adjusted to match the actual antenna heights given in Table 8-2. The AAS array for each base station is assumed to have its vertical scan angle set to -30° as the aircraft flies overhead, in order to illustrate the expected worst-case operating conditions.

8.2 Helicopter Air Ambulance Landings

8.2.1 Overview

Most commercial operations of helicopters fall under Part 135 of the Federal Aviation Regulations, which explicitly requires the use of an FAA-approved radar altimeter[36]. Included under the umbrella of Part 135 are helicopter air ambulance (HAA) operations. For this particular application, FAA rules further require the use of a Helicopter Terrain Awareness Warning System (HTAWS)[37] to alert the pilot when flying dangerously close to the terrain or other obstacles, often utilizing the output from the radar altimeter to do so (although this is not explicitly required). Given the radar altimeter equipage requirement, as well as the likely use of the radar altimeter to support HTAWS, safe operation of HAA services requires proper functionality of radar altimeters. This example examines a few particular landing scenarios for HAA aircraft and illustrates the potential for harmful interference from 5G systems operating in accordance with the FCC Order.

The Texas Medical Center in Houston is the world’s largest medical complex, containing a total of fifty-four medical institutions, including twenty-one hospitals, within a two-square-mile area. Many of these hospitals include rooftop heliports, from which HAA aircraft are dispatched, and to which HAA aircraft ferry trauma patients and others who need immediate medical attention. Further, mobile wireless base stations are located throughout the complex to provide connectivity to the masses of employees, patients, and visitors of the medical institutions in the dense urban setting.

Four heliports were selected, and approach flight paths were defined relative to each. Further, two currently deployed (for 4G LTE service) mobile wireless base station locations were identified. Along each of the four flight paths, the interference levels seen by the radar altimeter on the HAA aircraft were calculated assuming that each base station were hypothetically upgraded to a 5G system operating in accordance with the FCC Order in the 3.7–3.98 GHz band. Both the fundamental emissions in the 3.7–3.98 GHz band and the spurious emissions in the 4.2–4.4 GHz band were considered. These levels are then compared to the empirical ITMs determined by AVSI for Usage Category 3, which is

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[36] See 14 CFR §135.160 [39].
[37] See 14 CFR §135.605 [40].

applicable to helicopters.

Figure 8-3 illustrates the basic geometry of the scenario, with the heliport locations indicated by red balloons, the flight paths indicated by red lines with green surfaces projected to the ground, and the mobile wireless base station locations indicated by cyan balloons.

Figure 8-3: Helicopter Air Ambulance Landing Scenario Geometry

8.2.2 Heliport Locations

The four heliports selected for analysis were the John S Dunn Heliport (FAA identifier 38TE) at Memorial Hermann Hospital, the Alkek Heliport (FAA identifier TX86) at Houston Methodist Hospital, the Baylor St. Luke's Medical Center Heliport (FAA identifier 64TS), and the Texas Children's Hospital Downtown Heliport (FAA identifier 7XS2). The locations of each of these heliports are listed in Table 8-3. All data are sourced from AirNav.com and Google Earth.

Table 8-3: Helicopter Air Ambulance Landing Scenario Heliport Information

Hospital Name	FAA ID	Latitude	Longitude	Elevation (MSL)	Height (AGL)
Memorial Hermann	38TE	29° 42' 48" N	95° 23' 41" W	303 ft	255 ft
Houston Methodist	TX86	29° 42' 38" N	95° 23' 55" W	445 ft	400 ft
Baylor St. Luke's	64TS	29° 42' 28" N	95° 23' 57" W	165 ft	120 ft
Texas Children's	7XS2	29° 42' 29" N	95° 24' 10" W	427 ft	385 ft

8.2.3 Flight Paths

The approach paths flown into hospital heliports may vary depending on the situation and the presence of any surrounding obstacles, such as other buildings or structures. However, to define flight paths for this interference analysis scenario, a standard 8:1 approach surface was assumed in accordance with FAA AC 150/5390-2C on Heliport Design [41]. That is, each flight path is defined as a straight line between the heliport location itself and a point in space which is at a horizontal distance of 4,000 feet from the heliport and at an elevation 500 feet higher than the heliport. The azimuthal direction in which this line was drawn from each heliport was based upon a preferred approach direction determined based upon input received from the FAA regarding actual approach procedures and other operations in the airspace surrounding the Texas Medical Center. These preferred approach directions correspond to true headings along each approach of 327° for the John S Dunn Heliport, 052° for the Alkek Heliport, 202° for the Baylor St. Luke's Medical Center Heliport, and 217° for the Texas Children's Hospital Downtown Heliport.

8.2.4 5G Base Station Locations

As mentioned previously, the assumed locations of 5G base stations in the interference scenario were set based on the locations of existing 4G LTE base stations in the vicinity of the heliports. This was done using CellMapper.net to initially determine approximate locations of candidate base stations, and then verifying the exact locations and antenna mast heights using the FCC ASR database [38]. Finally, the base stations were further identified visually using Google Earth imagery.

Two 4G LTE base stations were identified for consideration in the scenario, both of which are owned by T-Mobile. The locations of these base stations are given in Table 8-4. The first base station listed in the table is located on a parking structure, and the second base station is located on top of the Fondren/Brown/Alkek building at Houston Methodist Hospital, just one building over from the Alkek Heliport.

Table 8-4: Helicopter Air Ambulance Landing Scenario Base Station Information

FCC Structure Registration	Latitude	Longitude	Elevation (MSL)	Height (AGL)
1273628	29° 42' 26" N	95° 23' 42" W	155 ft	110 ft
1273626	29° 42' 37" N	95° 23' 58" W	271 ft	225 ft

Both base stations are assumed to be the Urban 16 x 16 AAS configuration described in Section 6.3.3.1.1, with the mast height parameter adjusted to match the actual antenna heights given in Table 8-4. For the approaches into the Memorial Hermann and Baylor St. Luke's heliports, both base stations are assumed to have their AAS vertical scan angles set to 0°. For the approaches into the Houston Methodist and Texas Children's heliports, both base stations are assumed to have their AAS vertical scan angles set to -30°. These vertical scan angle assumptions are set in order to illustrate the expected worst-case operating conditions.

8.3 Consideration of Other Operational Scenarios

As previously discussed, the specific operational scenarios included in the analysis are not exhaustive, and general conclusions regarding the potential impact of 5G interference to radar altimeter operations should be drawn primarily from the parametric analysis. However, the inclusion of these specific real-world scenarios serves to provide context to the parametric analysis using realistic operating conditions and interference scenario geometries, and also illustrates an appropriate methodology for any analysis of additional scenarios that may be carried out in the future.

9 INTERFERENCE TOLERANCE THRESHOLD TEST RESULTS

9.1 5G Fundamental Emissions in the 3.7–3.98 GHz Band

9.1.1 Usage Category 1: Commercial Air Transport Aircraft

The worst-case measured 5G fundamental emissions interference tolerance thresholds for Usage Category 1, along with the interpolated ITMs, are shown in Figure 9-1 for a center frequency of 3750 MHz, Figure 9-2 for a center frequency of 3850 MHz, and Figure 9-3 for a center frequency of 3930 MHz. The ITMs are shown in terms of PSD at the radar altimeter receive port.

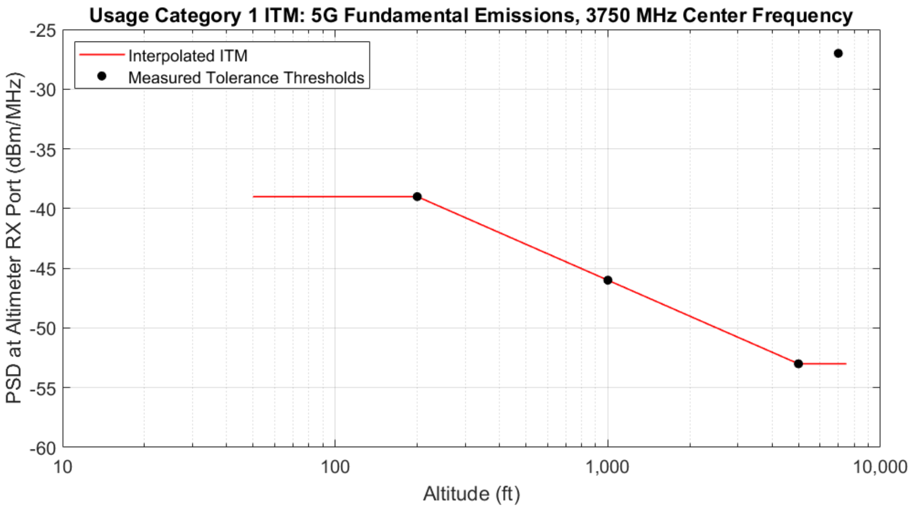

Figure 9-1: Usage Category 1 ITM for 5G Fundamental Emissions at 3750 MHz

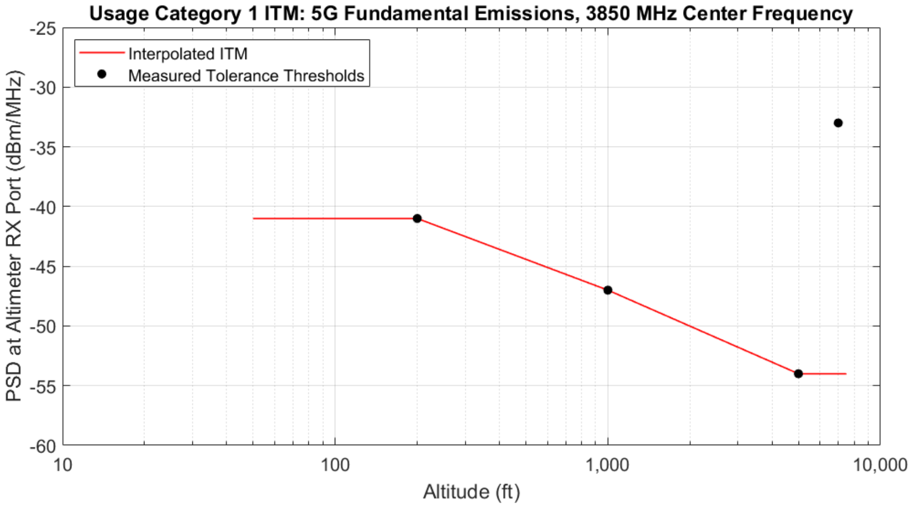

Figure 9-2: Usage Category 1 ITM for 5G Fundamental Emissions at 3850 MHz

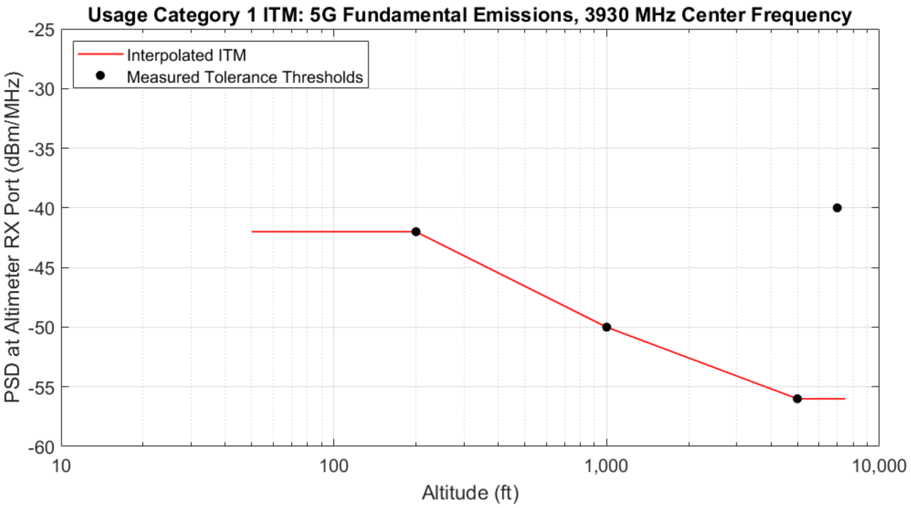

Figure 9-3: Usage Category 1 ITM for 5G Fundamental Emissions at 3930 MHz

As expected, the ITM decreases with increasing altitude as the altimeters become more sensitive. Note that the measured tolerance threshold at 7,000 feet includes altimeter Type 1 only, while the measured tolerance threshold at 5,000 feet includes altimeter Types 2 through 5. Since the measured tolerance threshold at 5,000 feet for altimeter Types 2 through 5 is lower than that for altimeter Type 1 at 7,000 feet, the ITM is extended out to 7,500 feet (the maximum altitude considered in the interference analysis) using the measured tolerance threshold at 5,000 feet. This is a reasonable assumption, since although altimeter Types 2 through 5 will not be expected to track altitudes above 5,500 feet, they will still be operational and may still be susceptible to harmful interference in this range which could result in erroneous altitudes being calculated and output from the altimeter.

The ITM also generally decreases as the 5G fundamental emissions center frequency increases, resulting in interference closer to the radar altimeter band edge.

9.1.2 Usage Category 2: Regional, Business Aviation, and General Aviation Aircraft

The worst-case measured 5G fundamental emissions interference tolerance thresholds for Usage Category 2, along with the interpolated ITMs, are shown in Figure 9-4 for a center frequency of 3750 MHz, Figure 9-5 for a center frequency of 3850 MHz, and Figure 9-6 for a center frequency of 3930 MHz. The ITMs are shown in terms of PSD at the radar altimeter receiver input port.

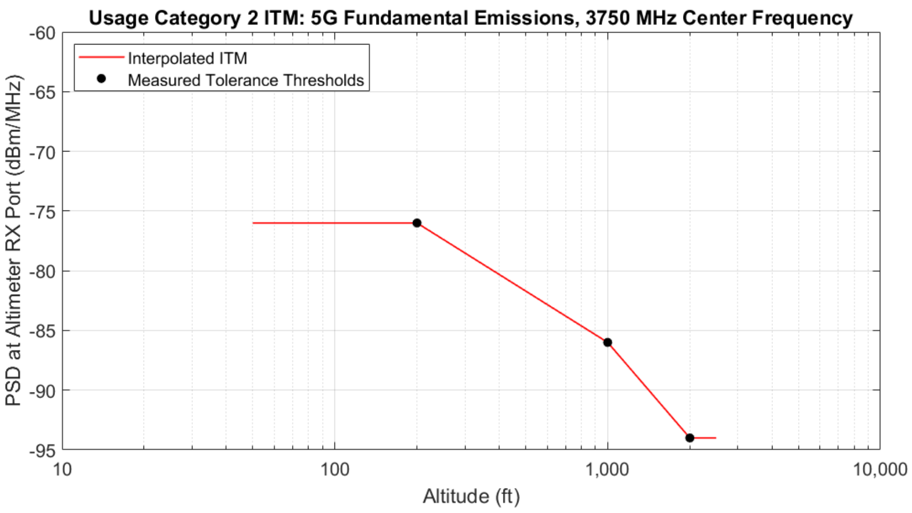

Figure 9-4: Usage Category 2 ITM for 5G Fundamental Emissions at 3750 MHz

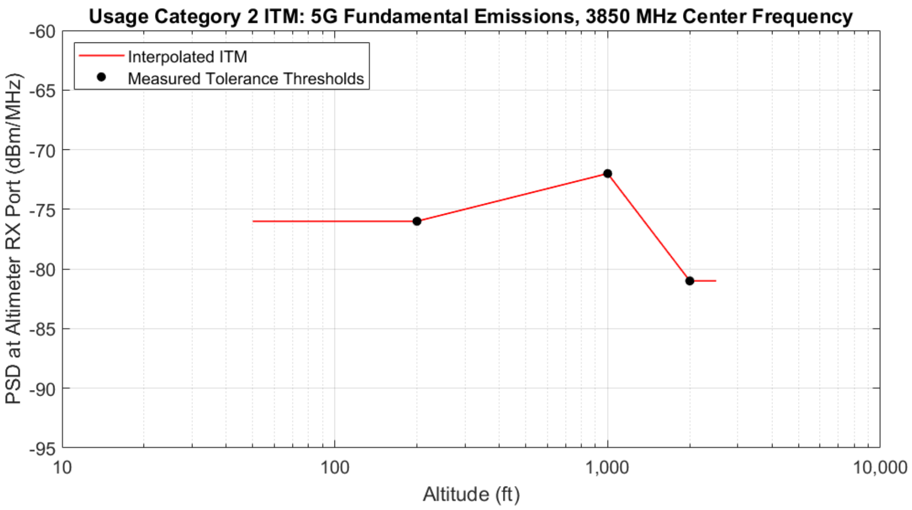

Figure 9-5: Usage Category 2 ITM for 5G Fundamental Emissions at 3850 MHz

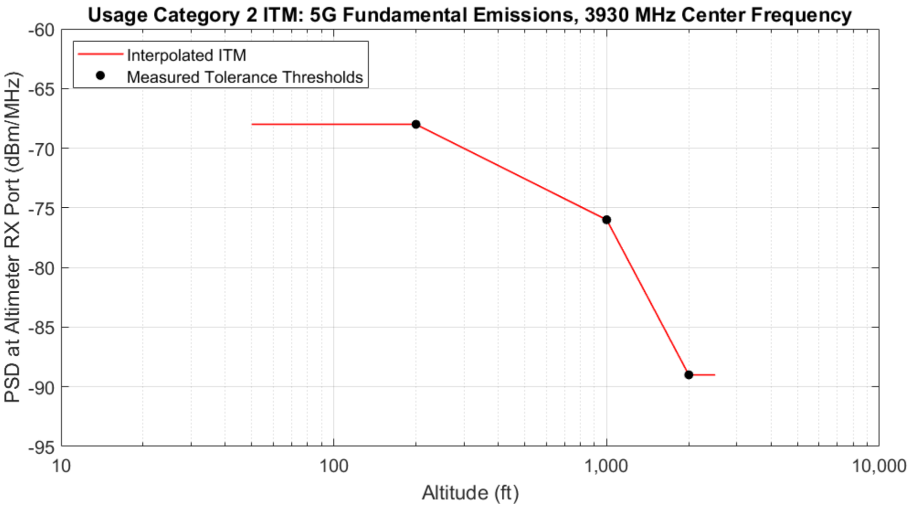

Figure 9-6: Usage Category 2 ITM for 5G Fundamental Emissions at 3930 MHz

Unlike Usage Category 1, the radar altimeters tested for Usage Category 2 exhibit reduced interference tolerance at lower 5G center frequencies in the 3.7–3.98 GHz band. This is likely a result of differing interference mechanisms in the radar altimeter receivers between the usage categories, although as discussed earlier, the testing does not seek to identify specific interference mechanisms. Further, with a center frequency of 3850 MHz, the observed interference tolerance is lower at 200 feet than at 1,000 feet, which is due to the interference from radar altimeters on other aircraft modeled in the test setup for the WCLS at 200 feet.

9.1.3 Usage Category 3: Helicopters

As shown in Table 7-1, Usage Category 2 and Usage Category 3 include all of the same radar altimeter models. Further, the installation characteristics of these altimeter models do not vary substantially, and thus the same test conditions were used for both Usage Category 2 and Usage Category 3. Therefore, for Usage Category 3 aircraft operating at low altitudes near an airport (i.e. where the WCLS applies), the ITMs for Usage Category 2 may be applied directly. For Usage Category 3 aircraft operating away from airports, such as in the vicinity of dedicated heliports, the ITMs presented in this section should be applied.

The worst-case measured 5G fundamental emissions interference tolerance thresholds for Usage Category 3 (excluding operations at traditional airports), along with the interpolated ITMs, are shown in Figure 9-7 for a center frequency of 3750 MHz, Figure 9-8 for a center frequency of 3850 MHz, and Figure 9-9 for a center frequency of 3930 MHz. The ITMs are shown in terms of PSD at the radar altimeter receive port.

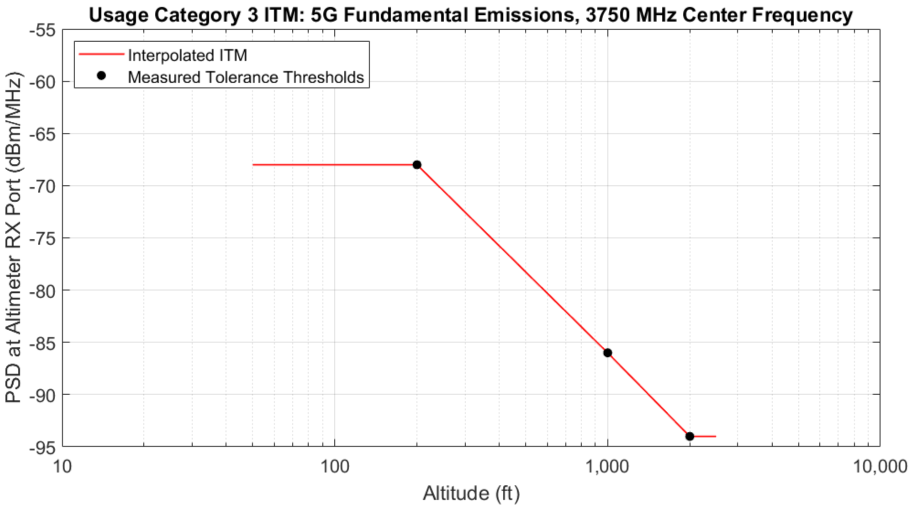

Figure 9-7: Usage Category 3 ITM for 5G Fundamental Emissions at 3750 MHz

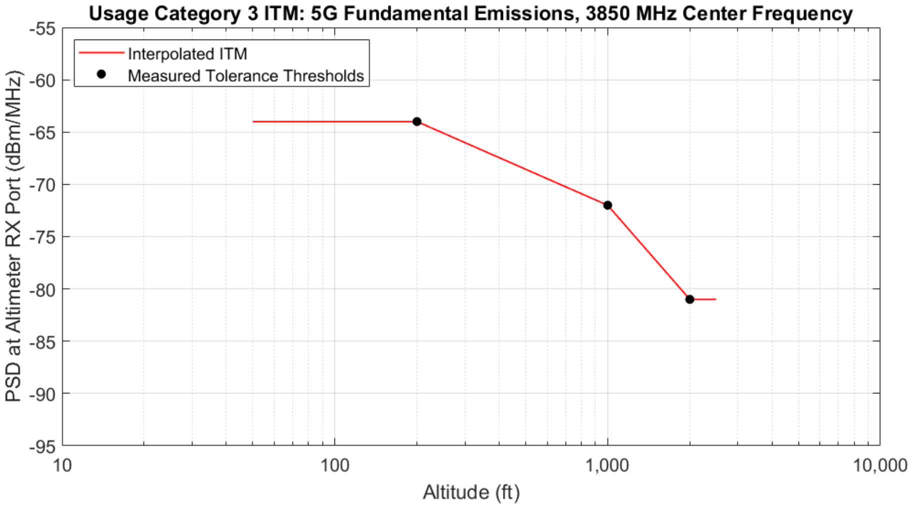

Figure 9-8: Usage Category 3 ITM for 5G Fundamental Emissions at 3850 MHz

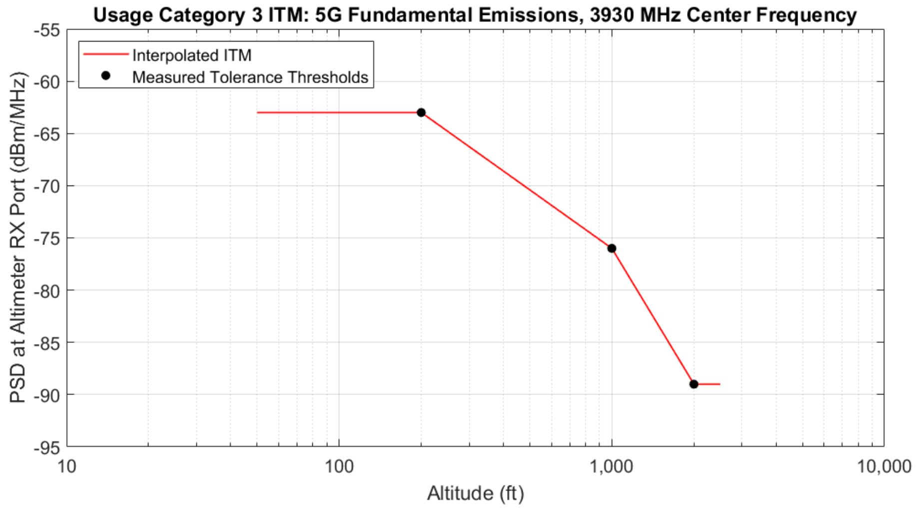

Figure 9-9: Usage Category 3 ITM for 5G Fundamental Emissions at 3930 MHz

As with Usage Category 2, Usage Category 3 shows reduced interference tolerance at lower 5G center frequencies in the 3.7–3.98 GHz band—likely due to differing internal interference mechanisms as discussed in Section 9.1.2. However, since the ITMs shown above for Usage Category 3 do not include the presences of radar altimeter interference from other aircraft for the low altitude test case at 200 feet, the ITMs decrease monotonically with increasing altitude, as expected under typical conditions.

9.2 5G Spurious Emissions in the 4.2–4.4 GHz Band

9.2.1 Usage Category 1: Commercial Air Transport Aircraft

The worst-case measured 5G spurious emissions interference tolerance thresholds for Usage Category 1, along with the interpolated ITM, are shown in Figure 9-10.

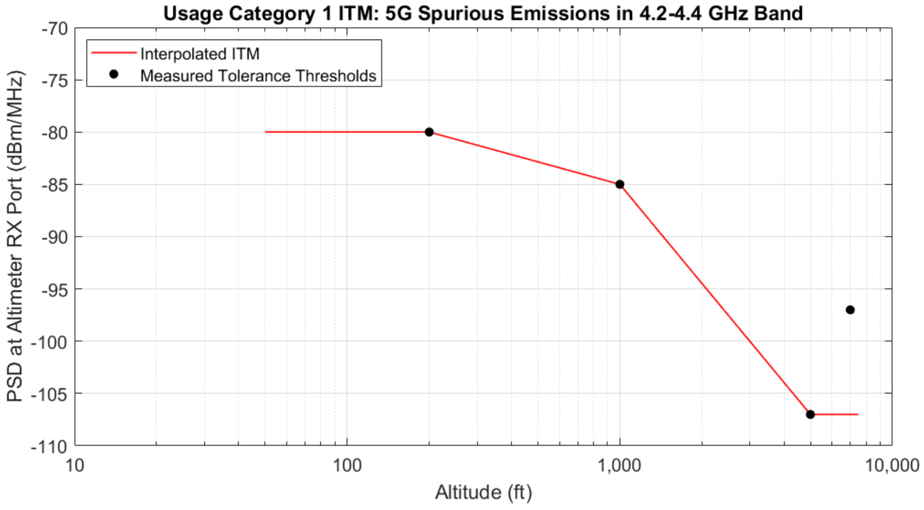

Figure 9-10: Usage Category 1 ITM for 5G Spurious Emissions in 4.2–4.4 GHz

As with the 5G fundamental emissions case, the ITM is extended out to 7,500 feet using the measured tolerance threshold at 5,000 feet, since the measured tolerance threshold at

5,000 feet for altimeter Types 2 through 5 is lower than that for altimeter Type 1 at 7,000 feet. Rationale for this assumption is given in Section 9.1.1.

9.2.2 Usage Category 2: Regional, Business Aviation, and General Aviation Aircraft

The worst-case measured 5G spurious emissions interference tolerance thresholds for Usage Category 2, along with the interpolated ITM, are shown in Figure 9-11.

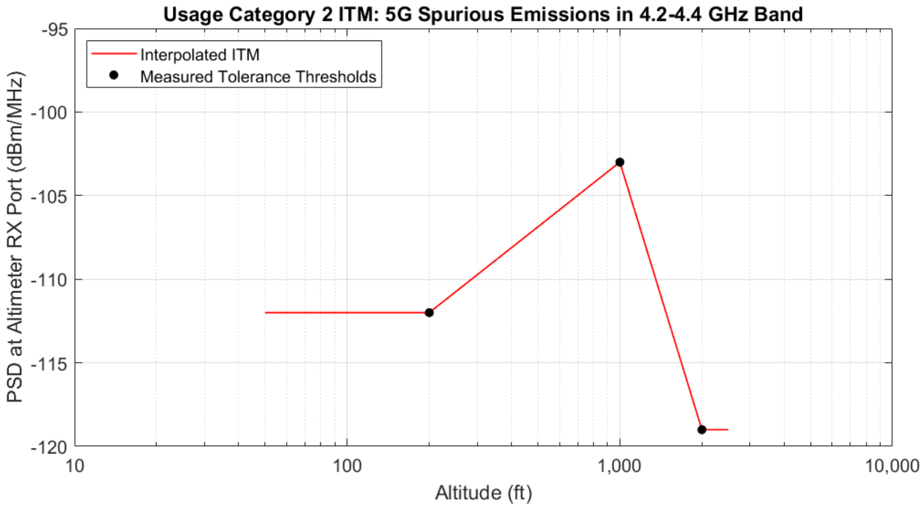

Figure 9-11: Usage Category 2 ITM for 5G Spurious Emissions in 4.2–4.4 GHz

As seen with the 5G fundamental emissions ITM at 3850 MHz for Usage Category 2, the 5G spurious emissions ITM shows a decreased interference tolerance at 200 feet due to the presence of in-band interference from the radar altimeters on other aircraft in the WCLS.

9.2.3 Usage Category 3: Helicopters

As with the 5G fundamental emissions ITMs, for Usage Category 3 aircraft operating at low altitudes near an airport (i.e. where the WCLS applies), the 5G spurious ITM for Usage Category 2 may be applied directly. For Usage Category 3 aircraft operating away from airports, such as in the vicinity of dedicated heliports, the 5G spurious ITM presented in this section should be applied.

The worst-case measured 5G spurious emissions interference tolerance thresholds for Usage Category 3, along with the interpolated ITM, are shown in Figure 9-12.

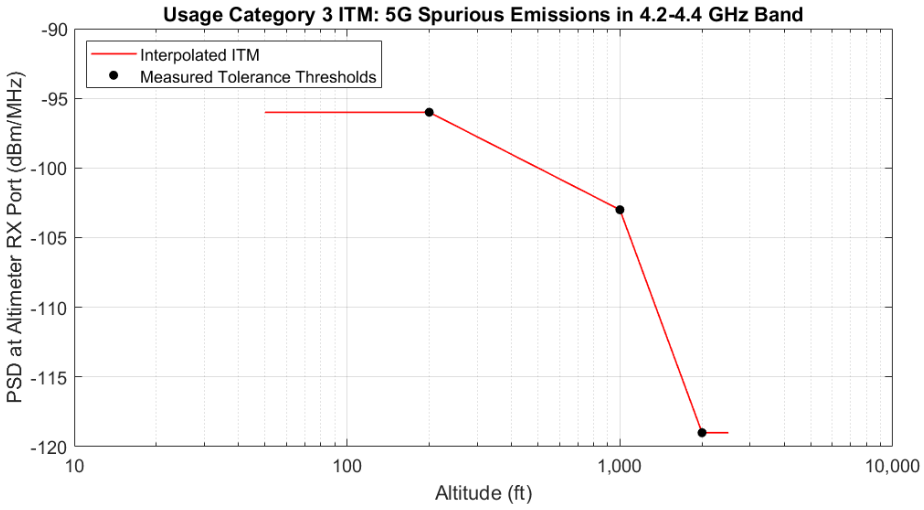

Figure 9-12: Usage Category 3 ITM for 5G Spurious Emissions in 4.2–4.4 GHz

Without the radar altimeter interference from other aircraft in the WCLS at 200 feet, the Usage Category 3 ITM for 5G spurious emissions shows monotonically decreasing interference tolerance with increasing altitude, as expected under typical conditions.

9.2.4 Comparison to Recommendation ITU-R M.2059 Protection Criteria

As expected, the minimum interference tolerance specified by the ITMs occurs at the maximum altitude for each usage category. Considering these maximum altitudes, and taking the minimum interference tolerance observed across all three center frequencies for the 5G fundamental emissions, the overall worst-case interference tolerance specified by the ITMs for each usage category can be compared to the Receiver Overload protection criterion from Rec. ITU-R M.2059 (provided in Section 6.2.1). This is shown in Table 9-1, with the minimum value from each ITM converted from PSD into total power based on the 100 MHz bandwidth assumption for the 5G fundamental emissions (thus yielding total power values 20 dB higher than the PSD values).

Table 9-1: Minimum ITM Values and ITU-R M.2059 Receiver Overload Criterion

Usage Category	Overall Minimum Tolerance from 5G Fundamental ITM[38]	Rec. ITU-R M.2059 Receiver Overload Protection Criterion
1	-36 dBm	-53 dBm
2	-74 dBm	
3	-74 dBm	

It is not unexpected for the empirically observed interference tolerance for 5G fundamental emissions to be lower than the Rec. ITU-R M.2059 Receiver Overload protection criterion for Usage Category 2 and Usage Category 3. As explained in Section 6.2.2, Rec. ITU-R M.2059 does not include performance characteristics for all FAA-approved altimeter models currently in service, and the models which are included are generally skewed towards commercial air transport applications (i.e. Usage Category 1).

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[38] Minimum interference tolerance across all altitudes and 5G center frequencies.

Further, the minimum interference tolerance specified by the ITMs for each usage category with regard to 5G spurious emissions in the 4.2–4.4 GHz band can be compared to the False Altitude and Receiver Desensitization protection criteria from Rec. ITU-R M.2059 (also provided in Section 6.2.1). This is shown in Table 9-2.

Table 9-2: Minimum ITM Values and ITU-R M.2059 In-Band Protection Criteria

Usage Category	Minimum Tolerance from 5G Spurious ITM[39]	Rec. ITU-R M.2059 Protection Criteria	
		False Altitudes	Receiver Desensitization
1	-107 dBm/MHz	-103 dBm/MHz	-117 dBm/MHz
2	-119 dBm/MHz		
3	-119 dBm/MHz		

For the case of interference within the 4.2–4.4 GHz band, there is much better agreement between the observed tolerance thresholds and the Rec. ITU-R M.2059 protection criteria. This is expected, since the interference mechanisms for in-band unwanted signals are more straightforward and less dependent on specific receiver design characteristics than for out-of-band unwanted signals.

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[39] Minimum interference tolerance across all altitudes.

10 INTERFERENCE ANALYSIS RESULTS

10.1 Parametric Analysis

10.1.1 5G Fundamental Emissions in the 3.7–3.98 GHz Band

10.1.1.1 Usage Category 1: Commercial Air Transport Aircraft

The parametric analysis for Usage Category 1 considers aircraft altitudes ranging from 50 feet to 7,500 feet, lateral distances between the single 5G base station (BS) and the aircraft ranging from 0 to 1.6 nautical miles (about 3 kilometers), and aircraft pitch or roll angles up to 40°. Note that because the radar altimeter receive antenna pattern is assumed to be rotationally symmetric about the boresight axis (as described in Section 6.3.4.1), this angle can be considered as either a pitch angle or a roll angle, or any combination of pitch and roll which yields this total angle between the radar altimeter antenna boresight and the local vertical. For the 5G fundamental emissions in the 3.7–3.98 GHz band, the analysis considers all nine BS configurations described in Section 6.3.3.1: Urban 8 x 8 and 16 x 16 AAS arrays, Suburban 8 x 8 and 16 x 16 AAS arrays, Rural 8 x 8 and 16 x 16 AAS arrays, Urban Sectoral antennas, Suburban Sectoral antennas, and Rural Sectoral antennas. For the Urban AAS arrays, vertical scan angles from -30° to 0° are considered, while for the Suburban and Rural AAS arrays, vertical scan angles from -10° to 0° are considered, in accordance with the assumptions listed in Section 6.3.3.1.1.

On Usage Category 1 aircraft, the output from the radar altimeters is generally used for a wider range of safety functions than on most Usage Category 2 or 3 aircraft. Further, the radar altimeters included in Usage Category 1 are all designed to the highest standards of integrity (Development Assurance Level[40] A) to support the most safety-critical applications. Therefore, the worst-case assumptions made in the analysis are not sufficient on their own to meet these safety criteria with high confidence, and the ICAO 6 dB safety margin (described in Section 6.3.2) must be included for all scenarios considering Usage Category 1.

For each BS configuration, a computed interference plot is generated for every combination of AAS vertical scan angle (as applicable for AAS BS configurations) and aircraft pitch or roll angle. These plots show the interference PSD at the radar altimeter receiver input port versus both the aircraft altitude above ground and the lateral distance between the BS and the aircraft. These computed interference levels are then compared to the Usage Category 1 ITM, minus the 6 dB safety margin, based on each altitude. No assumptions are made regarding the exact center frequencies used by the BS in the analysis—instead, the ITM used is the minimum across the three center frequencies considered in the AVSI interference tolerance testing. For any points in the plot at which the received interference PSD exceeds the ITM minus the safety margin, a red dot is overlaid. This procedure allows for quick identification of operating conditions and scenarios which may be impacted by interference.

Although the analysis was carried out for all combinations of parameters as described above, for Usage Category 1 the operational impacts are limited to just a few cases—in

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[40] The Development Assurance Level, or DAL, is described in SAE ARP4754A [42] and provides a top-level characterization of the integrity, availability, and continuity of a system for use in aviation safety applications. The highest is DAL A, meaning that the system can support operating conditions with Catastrophic failure severity.

particular, the lowest vertical scan angle for each of the three 16 x 16 AAS BS configurations. Figure 10-1 shows the case with the Urban 16 x 16 AAS BS at -30° vertical scan, and Figure 10-2 shows the case with the Suburban 16 x 16 AAS BS at -10° vertical scan. The Rural 16 x 16 AAS BS at -10° vertical scan produces similar results to the Suburban 16 x 16 AAS BS. In each case, only the plots for 0° aircraft pitch or roll are shown, as the operational impact exhibits little dependency on the aircraft attitude in these cases. Note that although the interference impacts for Usage Category 1 are only seen in certain scenarios, within these scenarios the consequences to aircraft operations and aviation safety may be exceptionally severe, as described in Section 10.2.1.

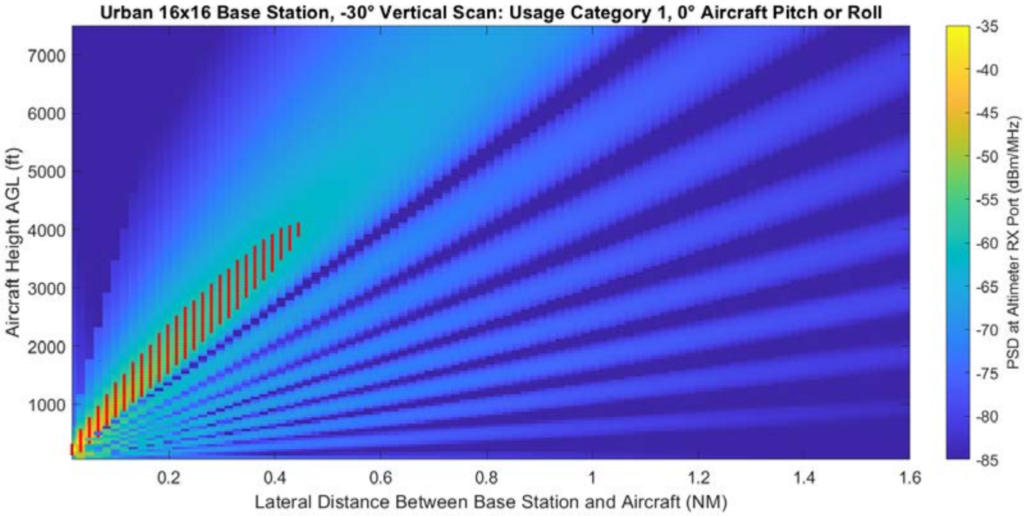

Figure 10-1: Urban 16 x 16 AAS BS at -30° Vertical Scan, Usage Category 1

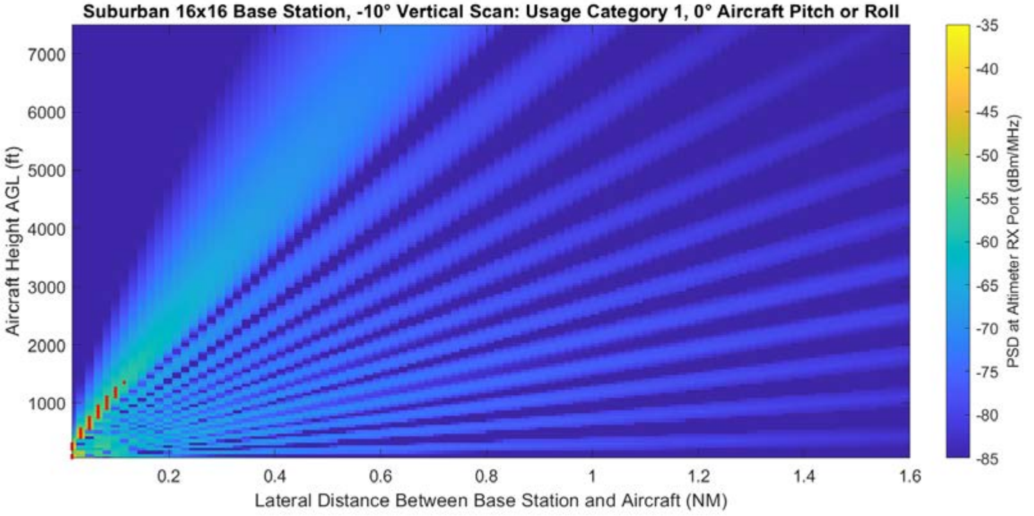

Figure 10-2: Suburban 16 x 16 AAS BS at -10° Vertical Scan, Usage Category 1

As shown in the plots, Usage Category 1 aircraft may be impacted by 5G interference to the radar altimeters at altitudes of up to approximately 4,000 feet, and at distances of just over 0.4 nautical miles from the BS. Since the scope of this impact is concentrated to a relatively narrow operational envelope, it may be possible to adequately mitigate the impacts through appropriate planning of BS deployments relative to the flight paths used by Usage Category 1 aircraft (in particular, takeoff and climb-out areas, low-altitude traffic patterns, and approach paths).

The reason for the interference impact occurring specifically at the minimum AAS vertical scan angles is due to a grating lobe[41] which is formed at these scan angles, directing a significant amount of RF energy well above the horizon. Grating lobes such as this may arise in any phased array antenna system based on the design characteristics. In particular, the presence of grating lobes in the elevation plane at steep vertical scan angles is a consequence of the Vertical Array Spacing Coefficient being greater than 0.5 (that is, the radiating elements are located more than half of an RF wavelength apart from each other in the vertical dimension), as shown in Table 6-4. Grating lobes can be avoided either by decreasing the array spacing coefficient or limiting the scan angle range.

Figure 10-3 provides a top-level summary of the 5G fundamental emissions parametric analysis for Usage Category 1. This plot is generated by taking the overall worst-case interference level across all parametrized variables at each altitude (lateral distance from BS, aircraft pitch or roll angle, and AAS vertical scan angle, if applicable), for each BS configuration. Only aircraft pitch or roll angles ranging from 0° to 20° are considered. Figure 10-4 then shows the maximum exceedance of the safe interference limit (defined as the ITM minus the 6 dB safety margin) across all altitudes by each BS configuration.

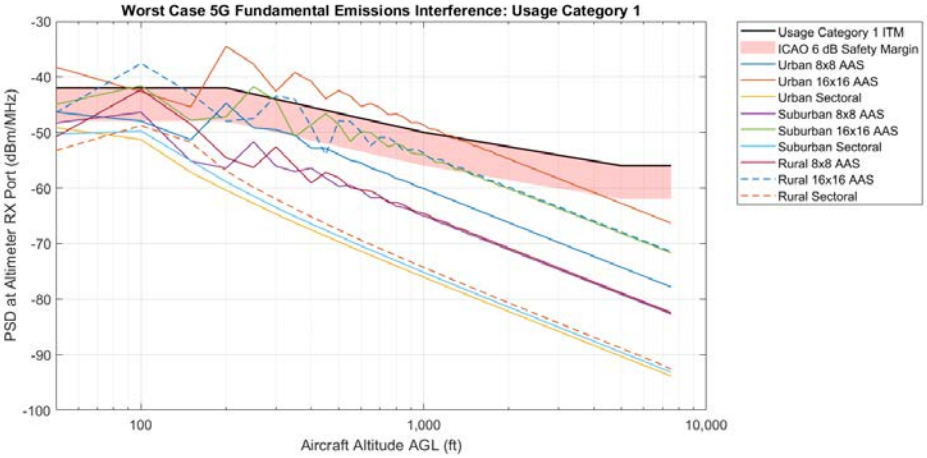

Figure 10-3: Maximum 5G Fundamental Emissions Levels, Usage Category 1

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[41] A grating lobe is a secondary main lobe in an antenna radiation pattern, caused by the radiating elements being uniformly spaced at intervals which are too large in relation to the RF wavelength.

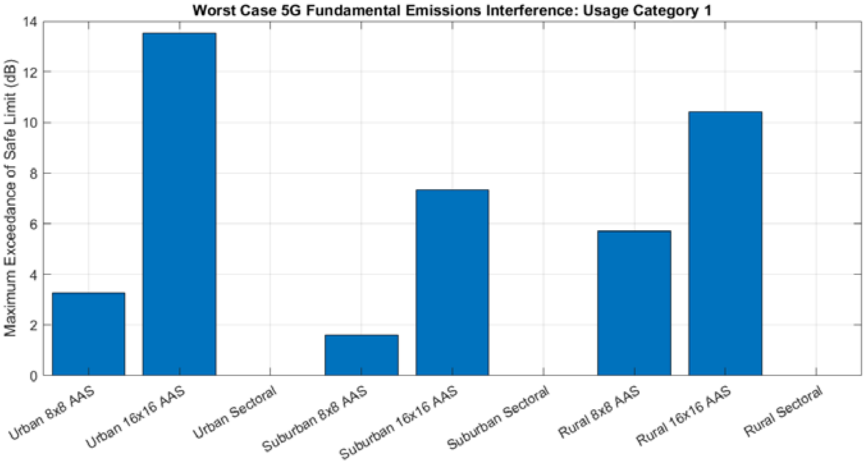

Figure 10-4: 5G Fundamental Emissions Exceedance of Safe Interference Limit, Usage Category 1

10.1.1.2 Usage Category 2: Regional, Business Aviation, and General Aviation Aircraft

The parametric analysis for Usage Category 2 is carried out in much the same way as for Usage Category 1, with two exceptions. First, the altitude range is limited to 2,500 feet, which is the maximum altitude that can be tracked by the radar altimeter models included in Usage Category 2. Second, the radar altimeter models included in Usage Category 2 range from DAL C[42] to DAL A. Further, on many types of Usage Category 2 aircraft, the radar altimeter(s) may not serve as critical of a role in all operational scenarios as they do on Usage Category 1 aircraft. Therefore, for illustrative purposes, the parametric analysis results for Usage Category 2 are presented without the ICAO 6 dB safety margin included. However, it is important to note that this does *not* mean that this margin can be excluded from the analysis of all operational scenarios for Usage Category 2. When considering specific operational scenarios, the potential failure condition severity and the associated integrity, availability, and continuity requirements imposed on the radar altimeter must be evaluated carefully to determine whether the safety margin can be excluded.

The analysis results for Usage Category 2, even with the safety margin excluded, show a much broader operational impact due to 5G interference than that seen for Usage Category 1. All nine BS configurations produce interference levels exceeding the Usage Category 2 ITM throughout the majority of the altitude range, at all lateral distances between the BS and the aircraft. A subset of these cases is shown and discussed below to provide a general characterization of the operational impact to Usage Category 2. Further, the results show that the operational impacts would continue out at greater lateral distances from the BS than the maximum of 1.6 nautical miles considered in this study. It is anticipated that the cell radius for BS deployments in the 3.7–3.98 GHz band would likely be less than this 1.6 nautical mile limit, and therefore this result indicates that Usage Category 2 aircraft may be impacted nearly everywhere when flying over populated areas at altitudes within the measurement range of the radar altimeter.

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[42] DAL C systems can support operations with, at most, Major failure severity. DAL B systems can support up to Hazardous/Severe Major failure conditions.

Figure 10-5 shows the case with the Rural 8 x 8 AAS BS at -10° vertical scan, and Figure 10-6 shows the case with the same BS at 0° vertical scan. Note that the presence of the grating lobe at low scan angles produces high levels of interference as seen with Usage Category 1, but for Usage Category 2 the AAS array sidelobes also have an impact. As the AAS scan angle increases to 0°, the grating lobe disappears, but the edge of the main lobe near the horizon causes a greater impact at low altitudes across the full range of lateral distances. Similar results were observed with the Urban and Suburban 8 x 8 AAS BS configurations.

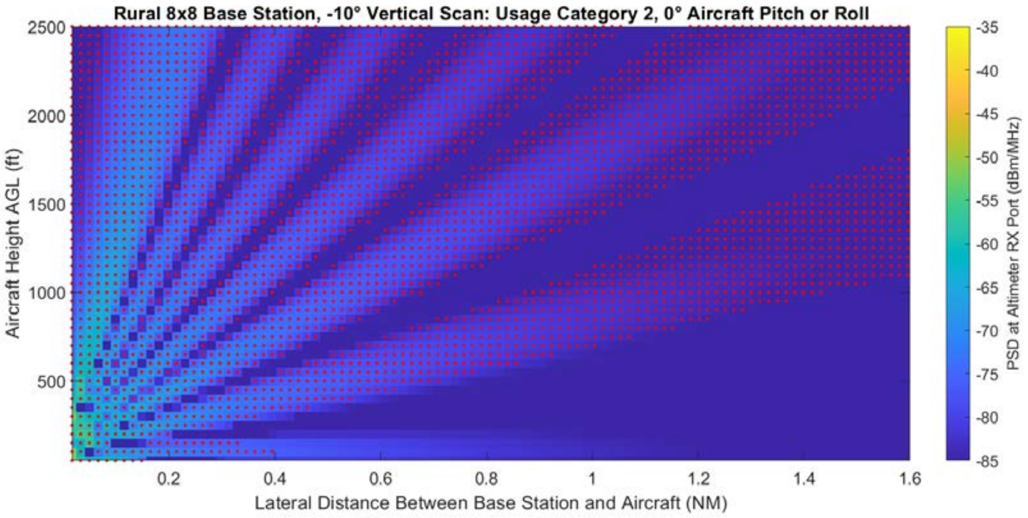

Figure 10-5: Rural 8 x 8 AAS BS at -10° Vertical Scan, Usage Category 2

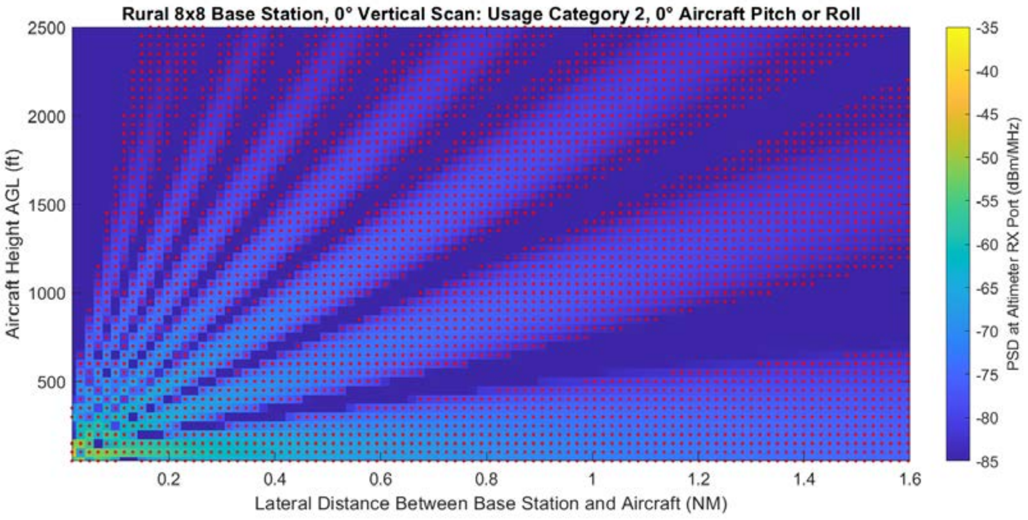

Figure 10-6: Rural 8 x 8 AAS BS at 0° Vertical Scan, Usage Category 2

Figure 10-7 and Figure 10-8 show similar results with the Urban 16 x 16 AAS BS, at -30° and 0° vertical scan angles respectively. The Suburban and Rural 16 x 16 AAS BS configurations produce similar results across the -10° to 0° vertical scan angle range.

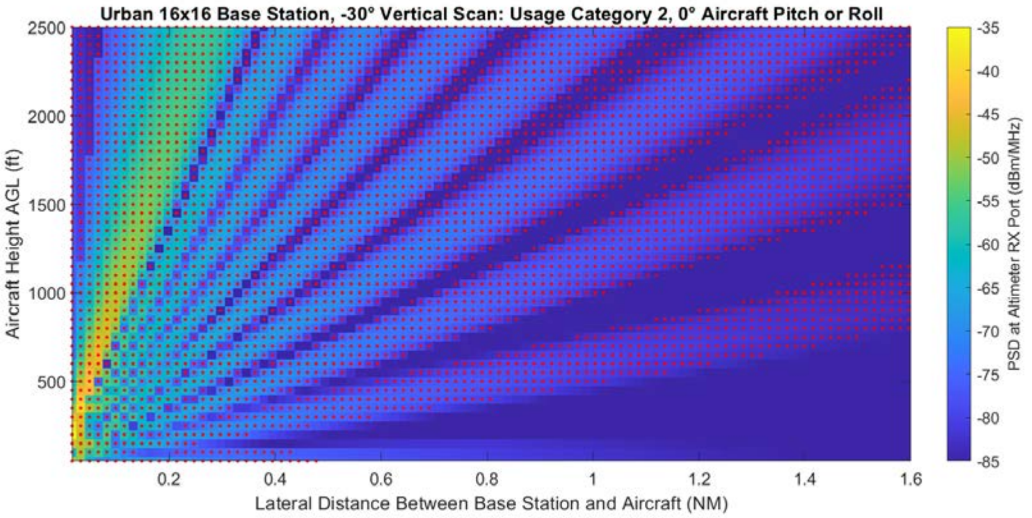

Figure 10-7: Urban 16 x 16 AAS BS at -30° Vertical Scan, Usage Category 2

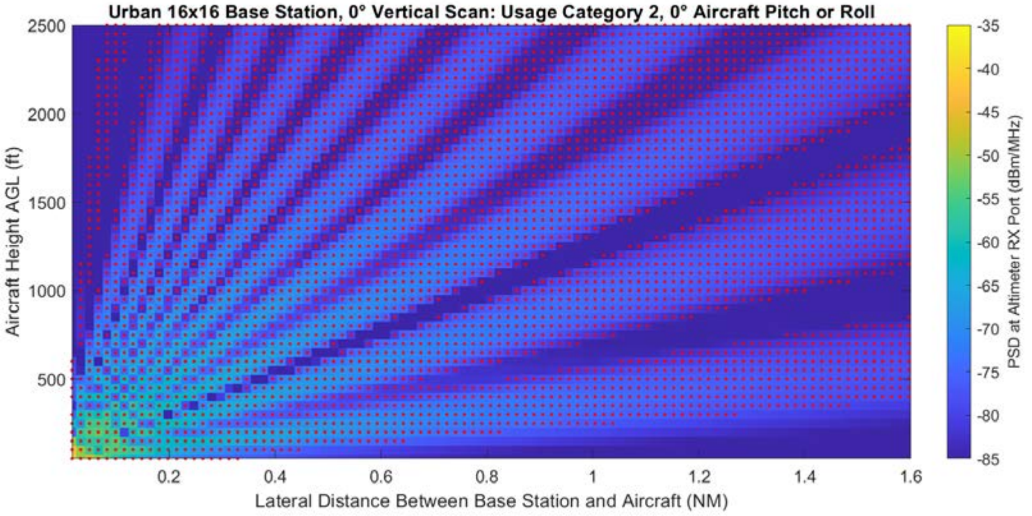

Figure 10-8: Urban 16 x 16 AAS BS at 0° Vertical Scan, Usage Category 2

As with Usage Category 1, with all of the AAS BS configurations there is little dependence on the aircraft pitch or roll angle (and thus all examples shown above consider only the 0° pitch or roll case). However, unlike Usage Category 1, Usage Category 2 is also impacted by interference from the Sectoral BS configurations. In these cases, there is some dependence on the aircraft pitch or roll angle. Figure 10-9 and Figure 10-10 show the results with the Rural Sectoral BS at aircraft pitch or roll angles of 0° and 10°, respectively. While the range of the operational impact at 0° pitch or roll is significant, at just 10° pitch or roll nearly every single point shows interference levels above the ITM.

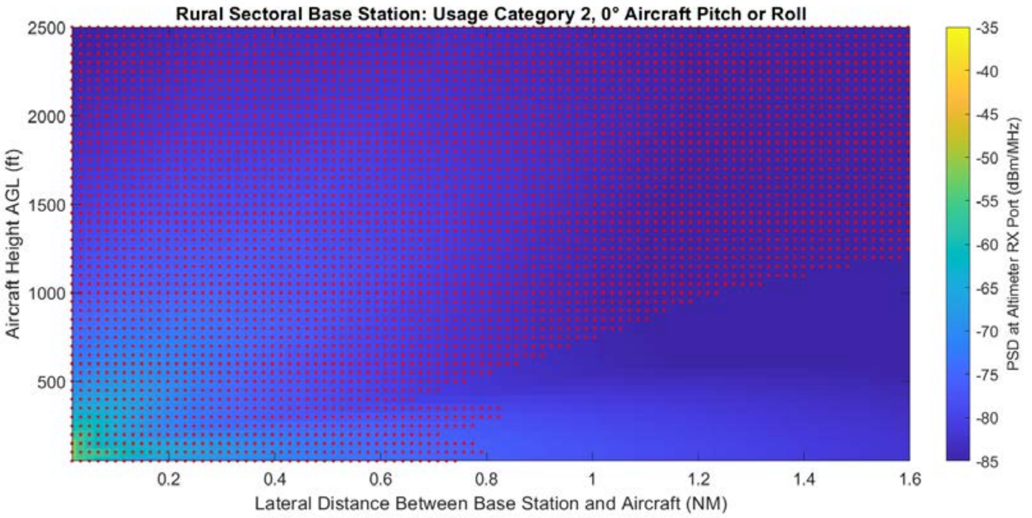

Figure 10-9: Rural Sectoral BS, Usage Category 2 at 0° Pitch/Roll

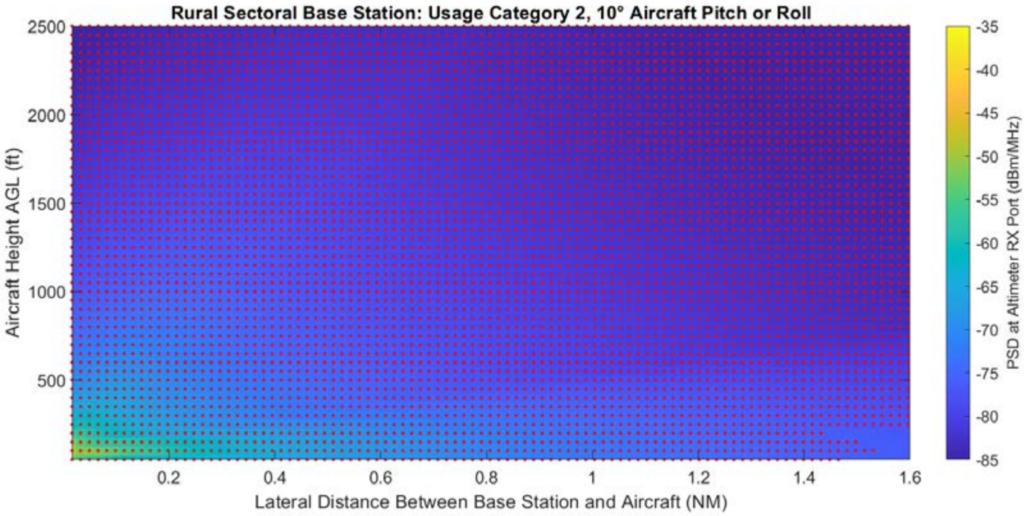

Figure 10-10: Rural Sectoral BS, Usage Category 2 at 10° Pitch/Roll

Figure 10-11 provides a top-level summary of the 5G fundamental emissions parametric analysis for Usage Category 2. This plot is generated by taking the overall worst-case interference level across all parametrized variables at each altitude (lateral distance from BS, aircraft pitch or roll angle, and AAS vertical scan angle, if applicable), for each BS configuration. Only aircraft pitch or roll angles ranging from 0° to 20° are considered. Figure 10-12 then shows the maximum exceedance of the safe interference limit (defined as the ITM minus the 6 dB safety margin) across all altitudes by each BS configuration.

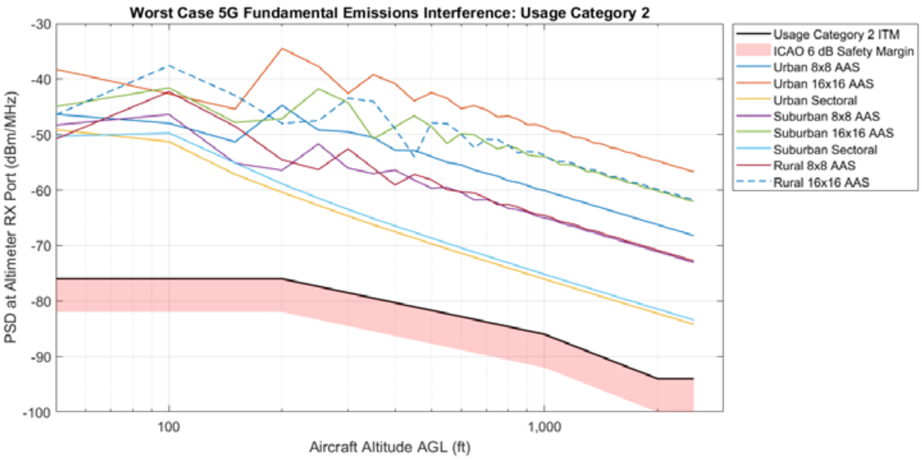

Figure 10-11: Maximum 5G Fundamental Emissions Levels, Usage Category 2

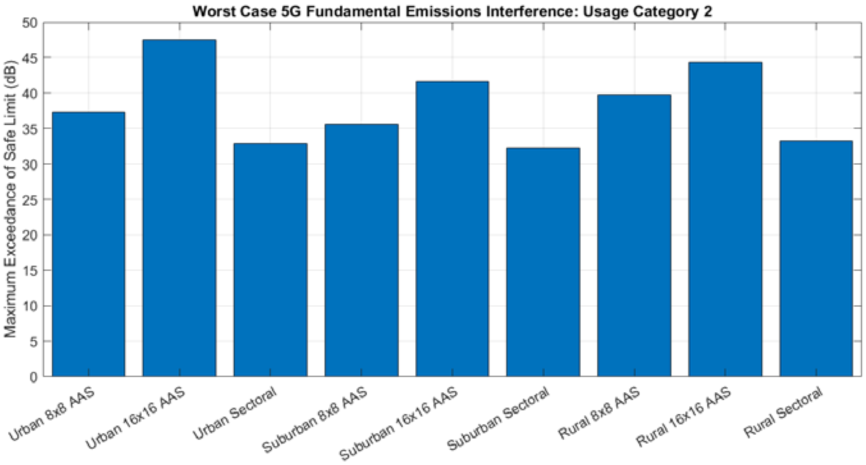

Figure 10-12: 5G Fundamental Emissions Exceedance of Safe Interference Limit, Usage Category 2

10.1.1.3 Usage Category 3: Helicopters

The parametric analysis for Usage Category 3 is carried out in much the same way as for Usage Category 2, but using the Usage Category 3 ITM (taking the minimum ITM across the three center frequencies). As with Usage Category 2, the 6 dB ICAO safety margin is excluded for illustrative purposes. However, as with Usage Category 2, this does *not* mean that this margin can be excluded from the analysis of all operational scenarios for Usage Category 3. When considering specific operational scenarios for Usage Category 3, the potential failure condition severity and the associated integrity, availability, and continuity requirements imposed on the radar altimeter must be evaluated carefully to determine whether the safety margin can be excluded.

Since the Usage Category 3 ITM is the same as the Usage Category 2 ITM except at low altitudes, the results for Usage Category 3 follow closely with those for Usage Category 2. The operational impact of 5G interference is very widespread, and occurs from all nine BS configurations. As noted in Section 9.2.3, operations of Usage Category 3 aircraft at or near airports should consider the ITM for Usage Category 2. The results shown in this section for Usage Category 3 only consider operations away from airports.

To demonstrate the minor differences between the Usage Category 2 and Usage Category 3 results, Figure 10-13 and Figure 10-14 show the case with the Urban 16 x 16 AAS BS at -30° and 0° vertical scan angles, equivalent to Figure 10-7 and Figure 10-8 for Usage Category 2. As expected, the impact is mostly the same, with Usage Category 3 exhibiting slightly greater interference tolerance (and thus decreased operational impact) at low altitudes.

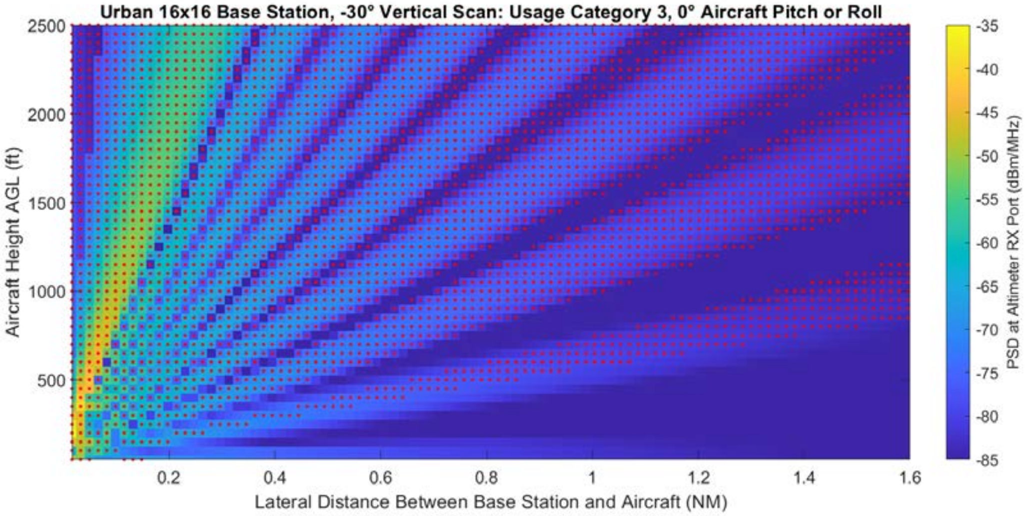

Figure 10-13: Urban 16 x 16 AAS BS at -30° Vertical Scan, Usage Category 3

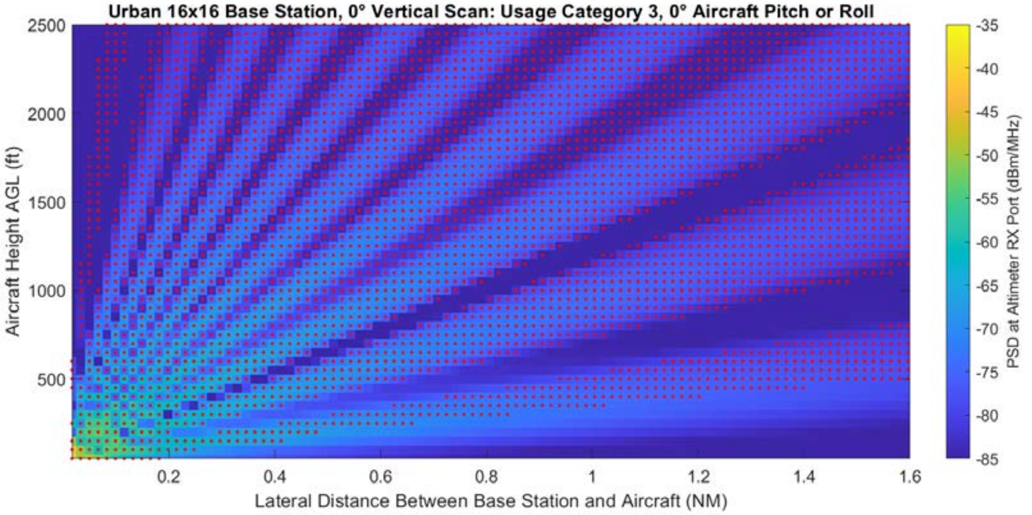

Figure 10-14: Urban 16 x 16 AAS BS at 0° Vertical Scan, Usage Category 3

Figure 10-15 provides a top-level summary of the 5G fundamental emissions parametric analysis for Usage Category 3. This plot is generated by taking the overall worst-case interference level across all parametrized variables at each altitude (lateral distance from

BS, aircraft pitch or roll angle, and AAS vertical scan angle, if applicable), for each BS configuration. Only aircraft pitch or roll angles ranging from 0° to 20° are considered. Figure 10-16 then shows the maximum exceedance of the safe interference limit (defined as the ITM minus the 6 dB safety margin) across all altitudes by each BS configuration.

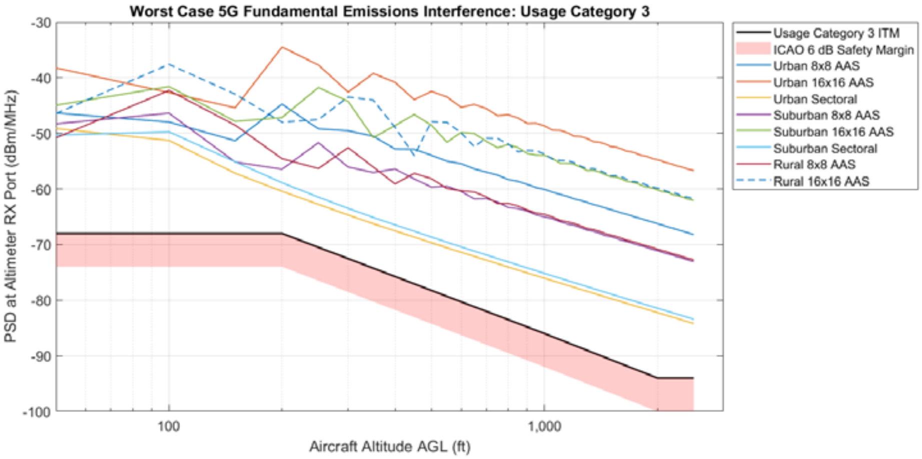

Figure 10-15: Maximum 5G Fundamental Emissions Levels, Usage Category 3

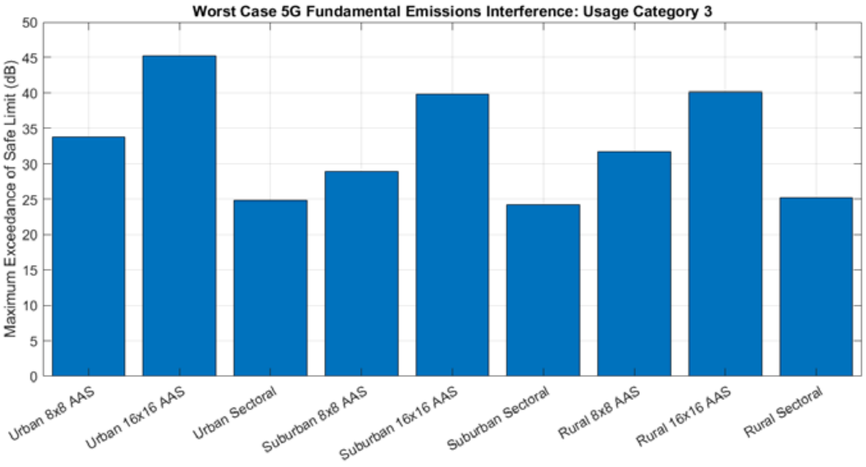

Figure 10-16: 5G Fundamental Emissions Exceedance of Safe Interference Limit, Usage Category 3

10.1.2 5G Spurious Emissions in the 4.2–4.4 GHz Band

10.1.2.1 Usage Category 1: Commercial Air Transport Aircraft

The parametric analysis of 5G spurious emissions in the 4.2–4. 4 GHz band is carried out in the same manner as for the 5G fundamental emissions, with the exception that there are only six unique BS configurations rather than nine, and there is no need to consider different vertical scan angles for the AAS BS configurations.

For Usage Category 1, no operational impacts were observed due to 5G spurious interference from any of the six BS configurations. Figure 10-17 shows an example of the Rural AAS BS case, with no points exceeding the ITM minus the 6 dB safety margin.

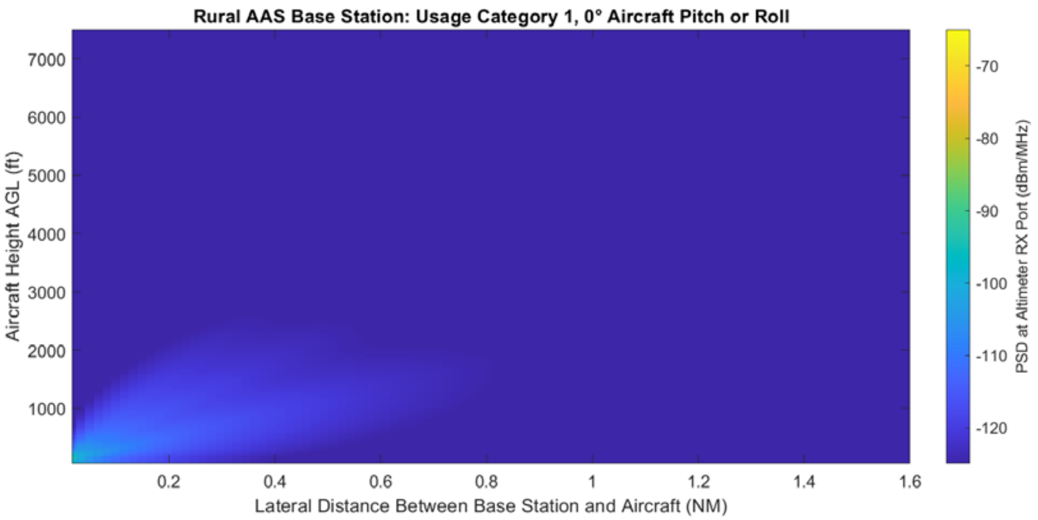

Figure 10-17: Rural AAS BS Spurious, Usage Category 1 at 0° Pitch/Roll

Figure 10-18 provides a top-level summary of the 5G spurious emissions parametric analysis for Usage Category 1. This plot is generated by taking the overall worst-case interference level across all parametrized variables at each altitude (lateral distance from BS and aircraft pitch or roll angle), for each BS configuration. Only aircraft pitch or roll angles ranging from 0° to 20° are considered.

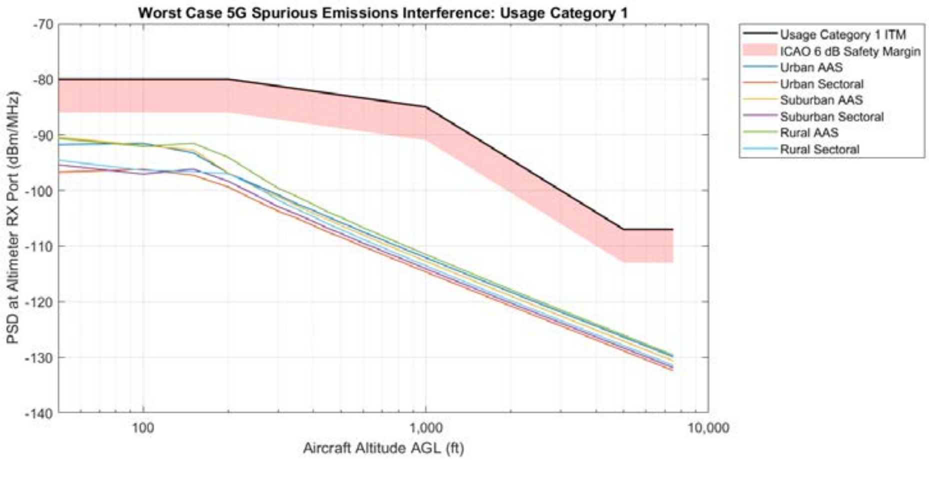

Figure 10-18: Maximum 5G Spurious Emissions Levels, Usage Category 1

10.1.2.2 Usage Category 2: Regional, Business Aviation, and General Aviation Aircraft

For Usage Category 2, operational impacts were observed due to 5G spurious emissions from all six BS configurations. The impacts were primarily concentrated at low altitudes and near the BS, except when the aircraft is at high pitch or roll angles. In these cases, the Usage Category 2 operations may be impacted at altitudes above 1,500 feet at distances of up to 1 nautical mile from the BS. Figure 10-19, Figure 10-20, and Figure 10-21 show the case with the Urban AAS BS at aircraft pitch or roll angles of 0°, 20°, and 40°, respectively. Similar results were observed with the Suburban and Rural AAS BS configurations. Figure 10-22 and Figure 10-23 show the case with the Rural Sectoral BS at aircraft pitch or roll angles of 0° and 20°, respectively.

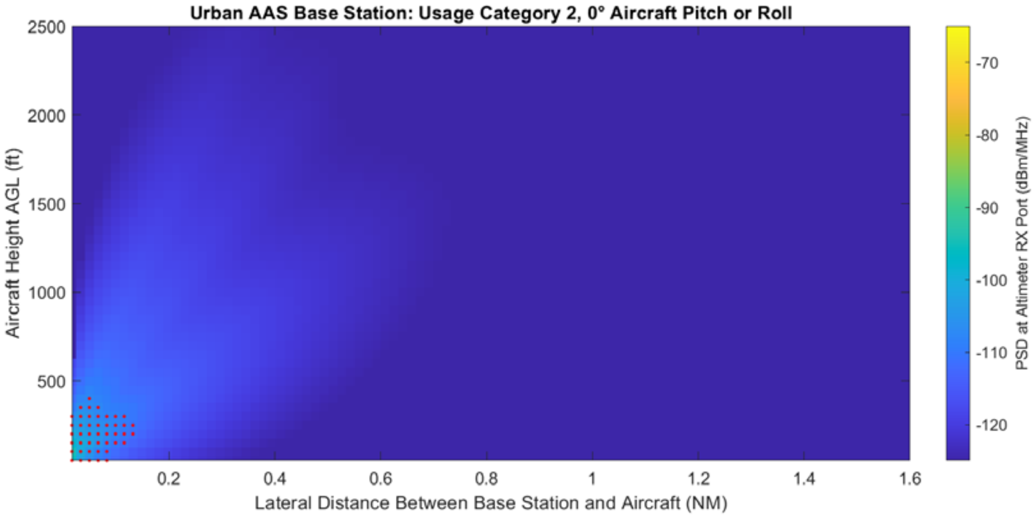

Figure 10-19: Urban AAS BS Spurious, Usage Category 2 at 0° Pitch/Roll

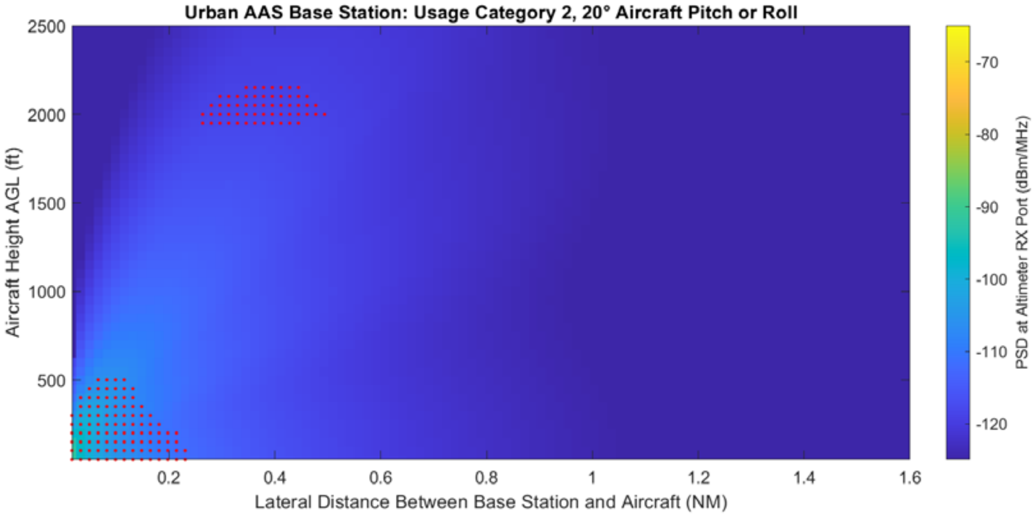

Figure 10-20: Urban AAS BS Spurious, Usage Category 2 at 20° Pitch/Roll

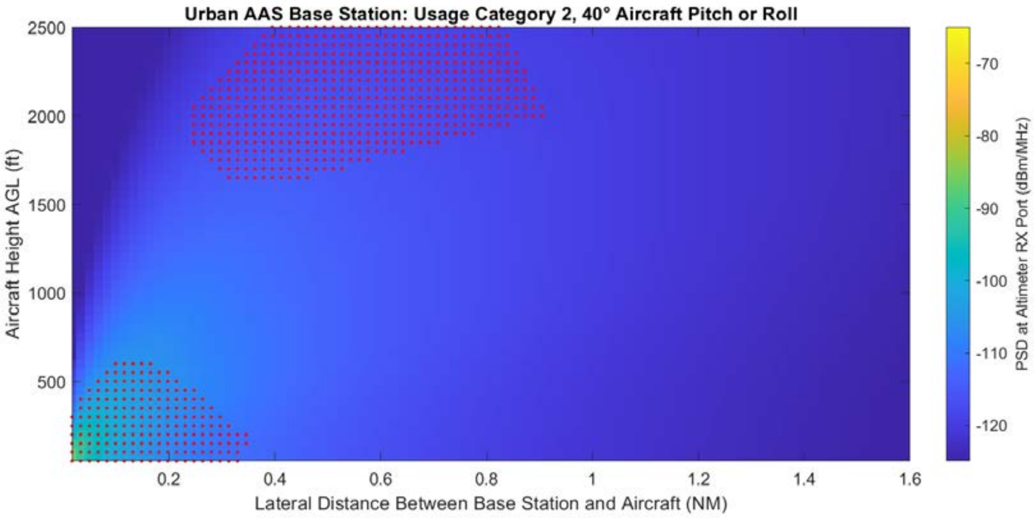

Figure 10-21: Urban AAS BS Spurious, Usage Category 2 at 40° Pitch/Roll

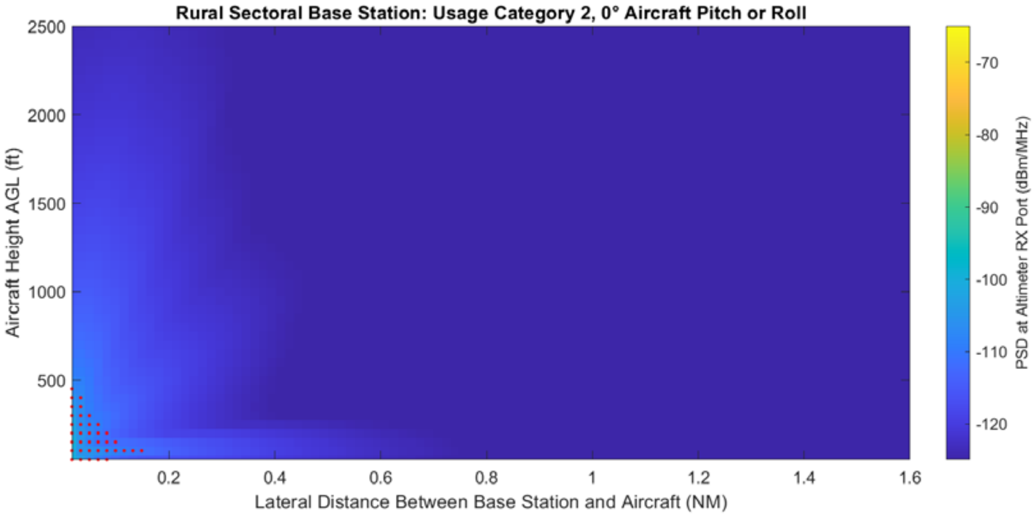

Figure 10-22: Rural Sectoral BS Spurious, Usage Category 2 at 0° Pitch/Roll

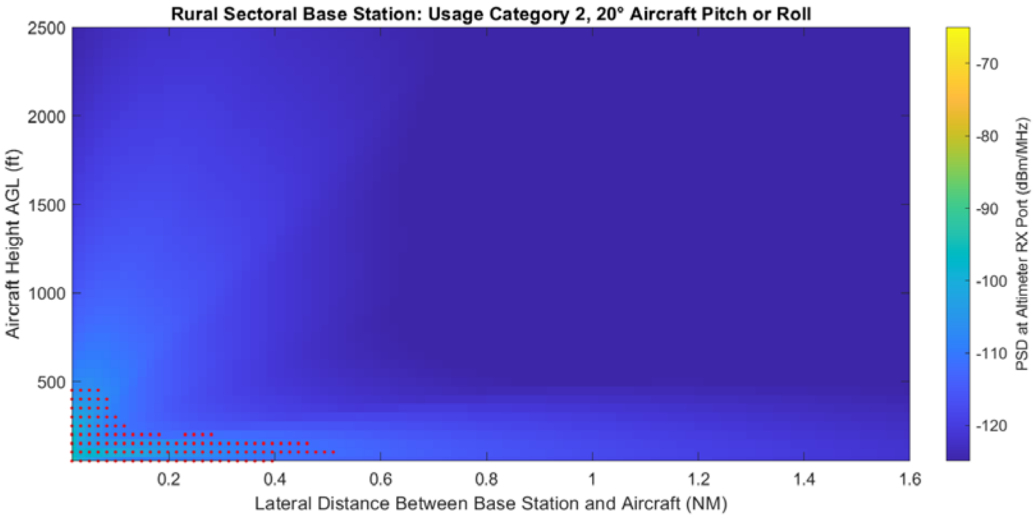

Figure 10-23: Rural Sectoral BS Spurious, Usage Category 2 at 20° Pitch/Roll

Figure 10-24 provides a top-level summary of the 5G spurious emissions parametric analysis for Usage Category 2. This plot is generated by taking the overall worst-case interference level across all parametrized variables at each altitude (lateral distance from BS and aircraft pitch or roll angle), for each BS configuration. Only aircraft pitch or roll angles ranging from 0° to 20° are considered. Figure 10-25 then shows the maximum exceedance of the safe interference limit (defined as the ITM minus the 6 dB safety margin) across all altitudes by each BS configuration.

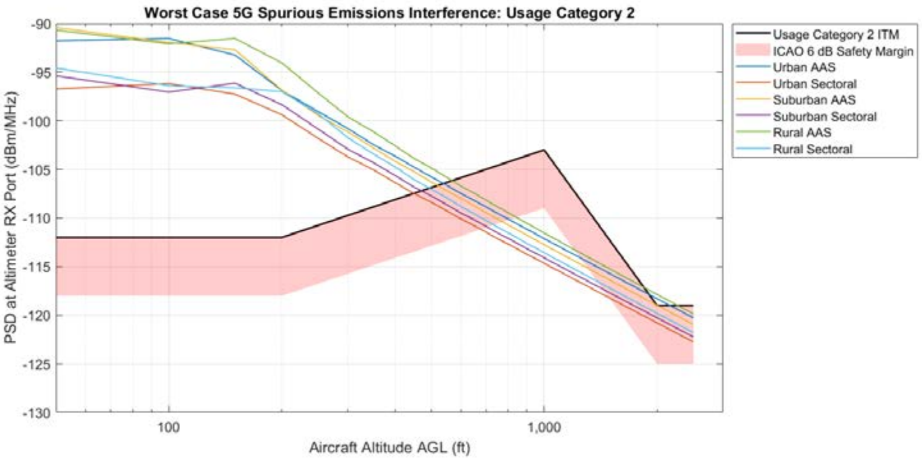

Figure 10-24: Maximum 5G Spurious Emissions Levels, Usage Category 2

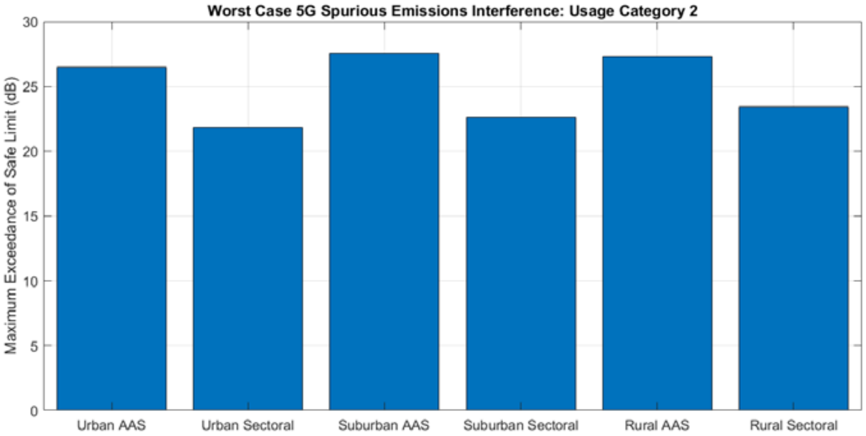

Figure 10-25: 5G Spurious Emissions Exceedance of Safe Interference Limit, Usage Category 2

10.1.2.3 Usage Category 3: Helicopters

As with the 5G fundamental emissions, when considering the 5G spurious emissions in the 4.2–4.4 GHz band Usage Category 3 produces largely the same results as Usage Category 2, except at low altitudes. Due to the slight differences in the ITM, Usage Category 3 has no operational impact due to spurious emissions from the Sectoral BS configurations. Further, the impact from the AAS BS configurations is mostly limited to high aircraft pitch or roll angles. Figure 10-26 and Figure 10-27 show the Rural AAS BS case with 20° and 40° aircraft pitch or roll, respectively.

As noted in Section 9.2.3, operations of Usage Category 3 aircraft at or near airports should consider the ITM for Usage Category 2. The results shown in this section for Usage Category 3 only consider operations away from airports.

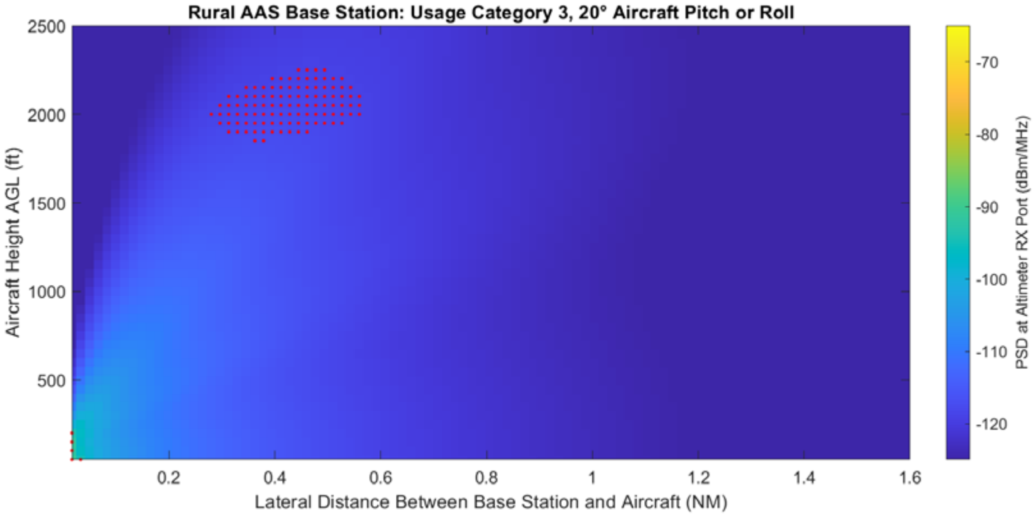

Figure 10-26: Rural AAS BS Spurious, Usage Category 3 at 20° Pitch/Roll

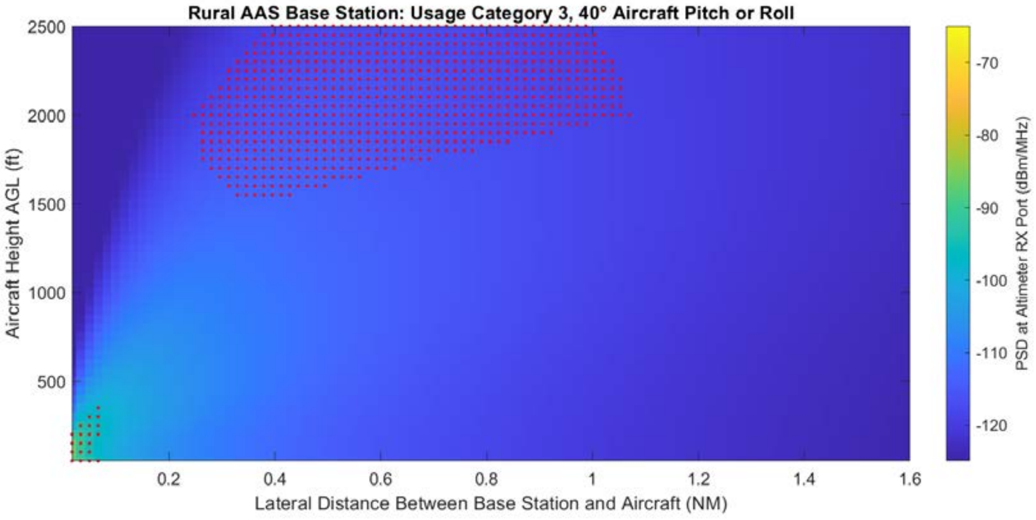

Figure 10-27: Rural AAS BS Spurious, Usage Category 3 at 40° Pitch/Roll

Figure 10-28 provides a top-level summary of the 5G spurious emissions parametric analysis for Usage Category 3. This plot is generated by taking the overall worst-case interference level across all parametrized variables at each altitude (lateral distance from BS and aircraft pitch or roll angle), for each BS configuration. Only aircraft pitch or roll angles ranging from 0° to 20° are considered. Figure 10-29 then shows the maximum exceedance of the safe interference limit (defined as the ITM minus the 6 dB safety margin) across all altitudes by each BS configuration.

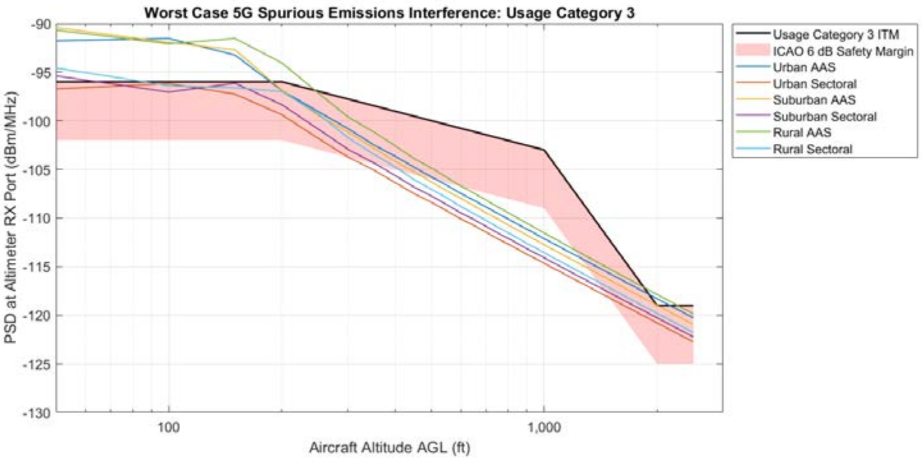

Figure 10-28: Maximum 5G Spurious Emissions Levels, Usage Category 3

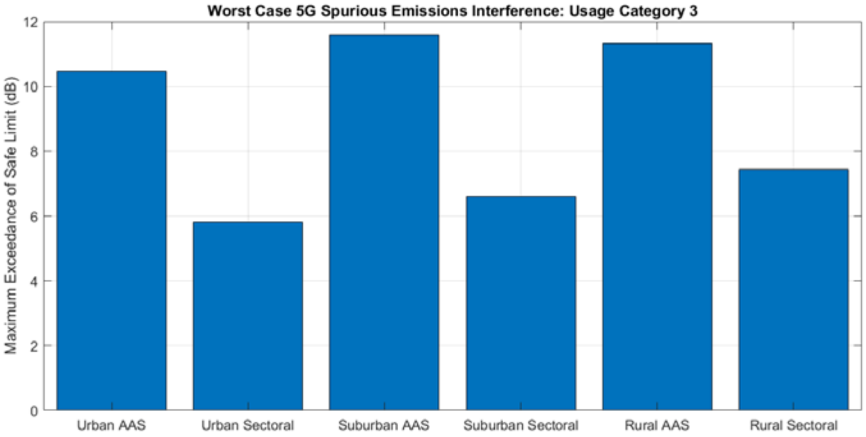

Figure 10-29: 5G Spurious Emissions Exceedance of Safe Interference Limit, Usage Category 3

10.1.3 Commentary on AAS Base Station Vertical Scan Angles

Although the analysis assumptions are generally limited to AAS scan angles of 0° or less based on the current understanding of potential 5G deployments in the 3.7–3.98 GHz band (see Section 6.3.3.1.1), it could not be confirmed that no future applications in this band will utilize scan angles greater than 0° (see Appendix B). To demonstrate the impact of such applications, a few additional analysis cases were evaluated. This included the Urban 16 x 16 AAS BS with a vertical scan angle of +15° (corresponding to the main beam being steered to 5° above the horizon, since this BS configuration uses a 10° mechanical downtilt), the Suburban 16 x 16 AAS BS with a vertical scan angle of +10° (4° above the horizon given the 6° mechanical downtilt), and the Rural 16 x 16 AAS BS with a vertical scan of +5° (2° above the horizon given the 3° mechanical downtilt). The interference levels determined in these cases were compared to the ITM for Usage Category 1 (with the 6 dB safety margin included), which yields the highest interference tolerance. Figure 10-30, Figure 10-31, and Figure 10-32 show the results for the Urban, Suburban, and Rural 16 x 16 AAS cases, respectively.

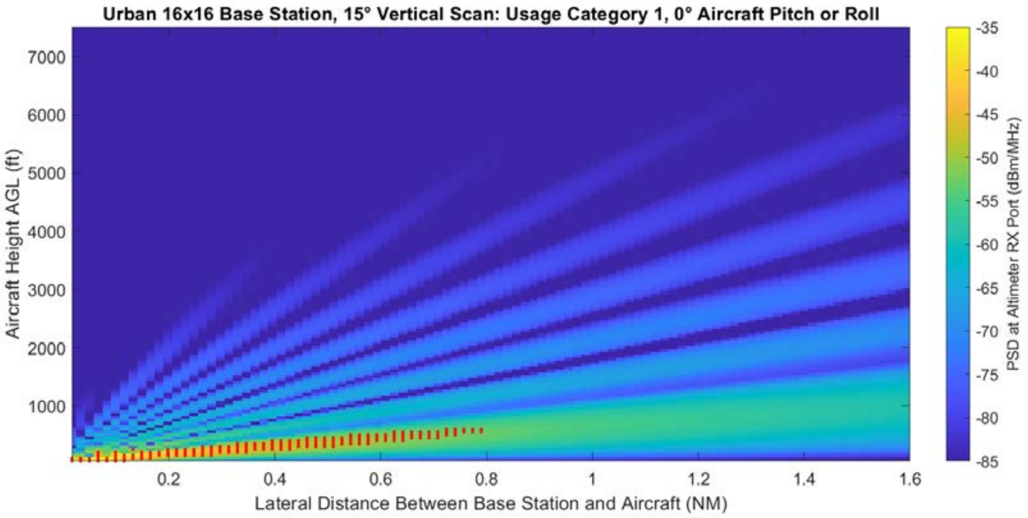

Figure 10-30: Urban 16 x 16 AAS BS at +15° Vertical Scan, Usage Category 1

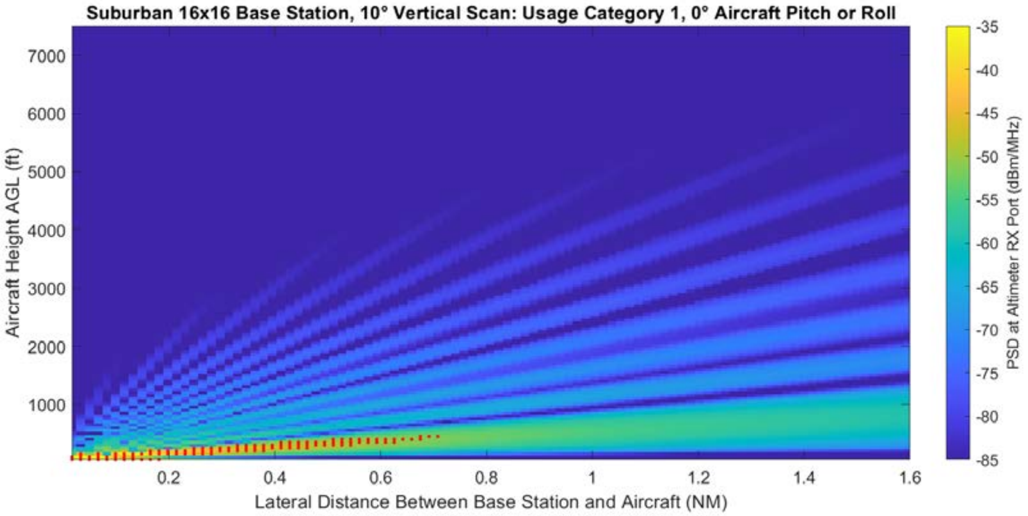

Figure 10-31: Suburban 16 x 16 AAS BS at +10° Vertical Scan, Usage Category 1

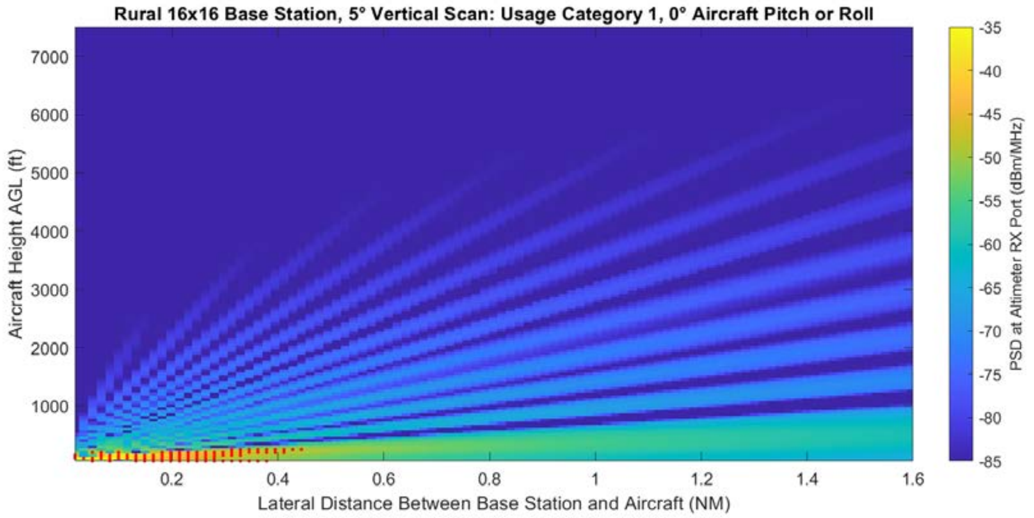

Figure 10-32: Rural 16 x 16 AAS BS at +5° Vertical Scan, Usage Category 1

These results show that even when considering the radar altimeters which are the most robust with regard to RF interference in the 3.7–3.98 GHz band, allowing for AAS scan angles just a few degrees above the horizon would result in significant impacts in the altitude range where radar altimeters are most critical to ensure safe flight operations, even while the aircraft is up to 0.8 nautical miles (nearly 1.5 kilometers) away from the BS.

10.2 Instrument Approach Procedure Scenario

10.2.1 5G Fundamental Emissions in the 3.7–3.98 GHz Band

Results for the 5G fundamental emissions interference case along the CAT II/III ILS approach into O'Hare runway 27L are shown in Figure 10-33. The computed interference levels from each of the five base stations are shown throughout the approach as a function of the landing aircraft altitude. The ITMs[43] for both Usage Category 1 and Usage Category 2 are also shown, along with shaded regions indicating the 6 dB ICAO safety margin. A low-visibility landing scenario such as the CAT II/III approach considered here necessitates the highest possible level of integrity, availability, and continuity from the radar altimeter(s) on the landing aircraft, and failures of the radar altimeter(s) may be Catastrophic in this scenario. Therefore, the safety margin cannot be excluded in this scenario for either Usage Category 1 or Usage Category 2.

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[43] As in the parametric analysis, no specific assumptions regarding the base station center frequencies are made, and the ITMs are therefore taken to be the minimum ITM across the three center frequencies used in the interference tolerance testing at AVSI.

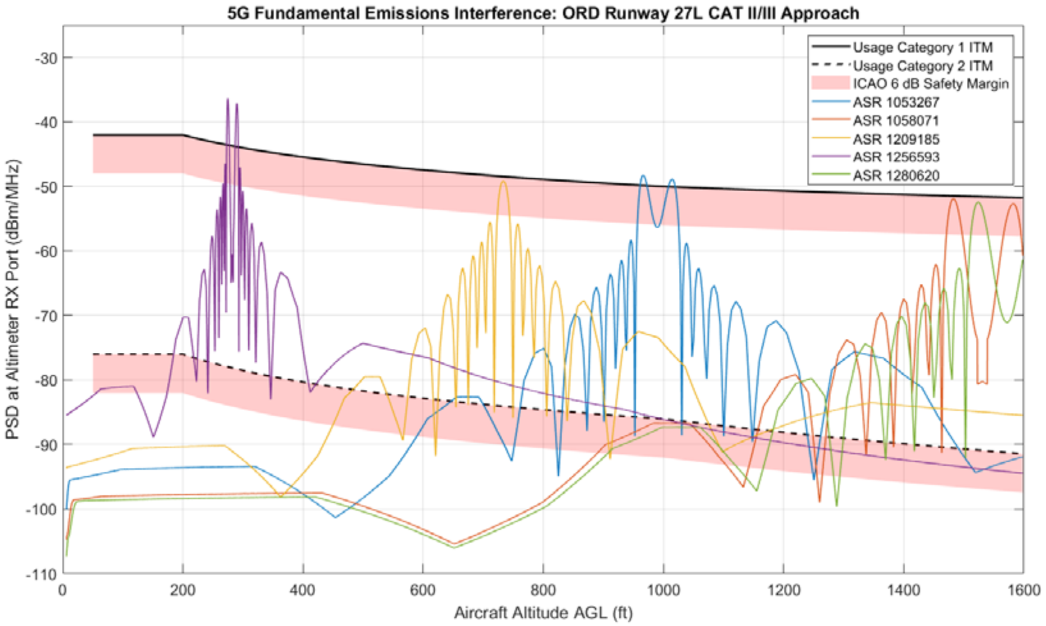

Figure 10-33: CAT II/III Approach Scenario Results for 5G Fundamental Emissions

Consistent with the parametric analysis results, the Usage Category 2 ITM is exceeded throughout nearly the entire approach until the aircraft gets below 200 feet altitude. Even for Usage Category 1, however, the results show significant impacts throughout the approach with the potential for Catastrophic effects. All five base stations produce interference above the safety margin relative to the Usage Category 1 ITM, and two of the five base stations even breach the ITM itself. It should also be noted that the computed interference levels from all five base stations significantly exceed the Rec. ITU-R M.2059 Receiver Overload protection criterion of -73 dBm/MHz (based on the -53 dBm limit given in Table 6-1 and an assumed signal bandwidth of 100 MHz).

The interference seen throughout the CAT II/III approach scenario is likely to cause many of the operational impacts noted in Table 5-1 which are applicable to approach and landing (or to all phases of flight). However, the most concerning result shown in Figure 10-33 is the large interference spike (more than 7 dB above the Usage Category 1 ITM) seen at an altitude of about 275 feet. Since the radar altimeter antennas in a multiplex installation are typically adjacent to each other, it is anticipated that such an interference spike would result in a common-mode failure of all radar altimeters on the aircraft. Considering a dual radar altimeter installation, which is the most common on Usage Category 1 aircraft, the following outcomes are possible:

1. Both radar altimeters become inoperative (either reporting NCD or indicating a hardware failure);
2. One radar altimeter becomes inoperative, while the other radar altimeter provides erroneous altitude readings;
3. Both radar altimeters provide erroneous altitude readings which do not agree; or

4. Both radar altimeters provide erroneous altitude readings which are in agreement.

In the first case, it is expected that the autoland function will disengage, and the flight crew will need to intervene to determine whether the aircraft can be landed safely or if they must execute a missed approach or go-around. Such a determination must be made very quickly, and using limited information. For a typical Usage Category 1 aircraft, the interference event at 275 feet AGL leaves as little as 20 seconds[44] before touchdown if the approach is continued. Further, in a CAT II/III approach the pilots will have little or no visibility along the runway to identify visual cues to assist in their determination of the actual height above ground. Even if the pilots are able to react in time and execute a missed approach, this maneuver poses a significant safety risk to both the landing aircraft and other air traffic in the immediate area, particularly in low-visibility conditions. This places additional burden on air traffic controllers to safely manage the airspace. In addition, if multiple landing aircraft are impacted by RF interference and must execute missed approaches in low-visibility conditions with high volume air traffic, controllers may need to stop issuing approach clearances to the specific runway or airport that is affected.

In the second case, the availability of only one radar altimeter means that the erroneous readings from the second altimeter cannot be identified as such by either the autopilot system or the flight crew. On some Usage Category 1 aircraft, this situation may not result in the pilots being alerted to abort the landing, and they must make their own determination on whether the approach can be safely continued. As in the first case, this determination must be made very quickly, and with limited information. If the approach is continued in this scenario, the erroneous altitude readings will likely cause the flight crew to conduct the landing flare and throttle retard either too early or too late. At best, this would lead to a hard landing, and at worst, a Catastrophic impact with the ground would occur.

In the third case, it is expected that the autopilot system will be able to identify the miscomparison of the radar altimeter readings and conclude that the data is erroneous. This scenario will then typically lead to the same result as the first case. However, on some aircraft types the erroneous readings from one altimeter may be continued to be used by the autopilot system unless there is flight crew intervention in response to the miscomparison. In this instance, if the pilots do not respond in time, the result may be a Catastrophic impact with the ground due to improper timing of the automated flare maneuver and autothrottle retard. Such was the case for the Turkish Airlines flight 1951 crash near Schiphol Airport in Amsterdam on February 25, 2009 [43].

The fourth case presents the greatest danger. If both radar altimeters are erroneous but in agreement, then neither the autopilot system nor the flight crew will be able to identify this situation, and the approach will proceed with incorrect altitude readings. This will lead to the autoland system executing the flare maneuver and autothrottle retard at the incorrect time, causing either direct Catastrophic impact with the ground, or causing the aircraft to stall and subsequently have a Catastrophic impact with the ground. In this instance, the pilots will be unaware of the erroneous data and unable to intervene.

In all cases, possibility of harmful interference in this instrument approach scenario is particularly dangerous given that up to the present time, radar altimeter failures during this phase of flight have been extremely uncommon, especially on Usage Category 1 aircraft.

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[44] Based on a typical descent rate of 600 to 800 feet per minute.

Thus, the occurrence of such failures is certain to cause confusion among the flight crew which could further complicate and delay their response.

10.2.2 5G Spurious Emissions in the 4.2–4.4 GHz Band

Results for the 5G spurious emissions interference case along the CAT II/III ILS approach into O'Hare runway 27L are shown in Figure 10-34. As with the fundamental emissions case, the computed interference levels from each of the five base stations are shown throughout the approach as a function of the landing aircraft altitude, as well as the ITMs for both Usage Category 1 and Usage Category 2 and shaded regions indicating the 6 dB ICAO safety margin.

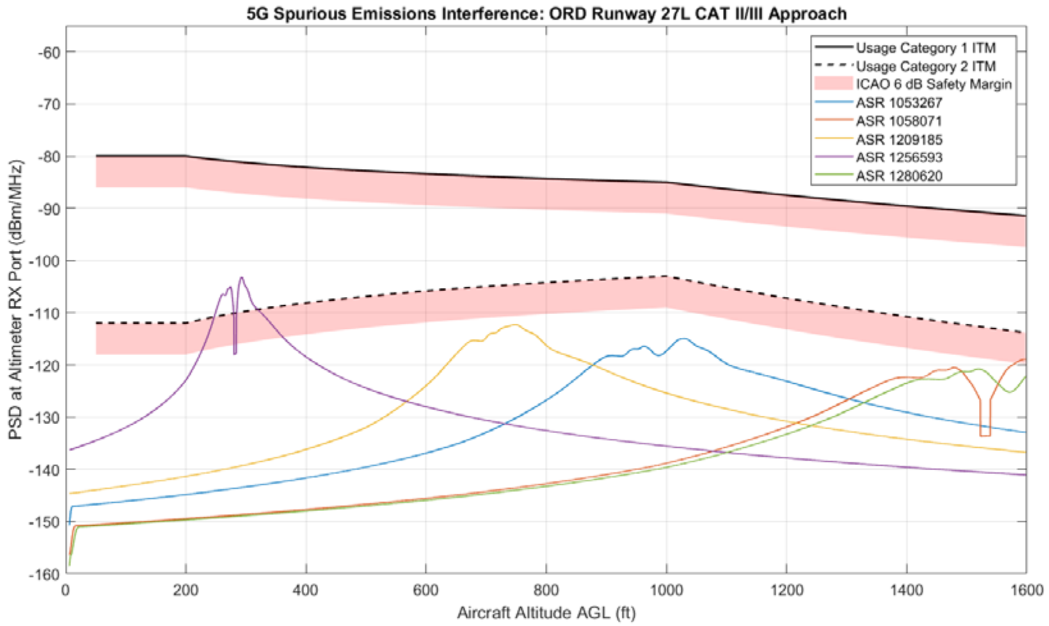

Figure 10-34: CAT II/III Approach Scenario Results for 5G Spurious Emissions

For the case of 5G spurious emissions, only Usage Category 2 is impacted, with one base station violating the 6 dB safety margin at the beginning of the approach, and another base station completely breaching the ITM at about 275 feet. Further, the spurious emissions from three of the five base stations exceed the Rec. ITU-R M.2059 Receiver Desensitization criterion of -117 dBm/MHz (given in Table 6-2).

10.3 Helicopter Air Ambulance Landing Scenario

10.3.1 5G Fundamental Emissions in the 3.7–3.98 GHz Band

Results for the 5G fundamental emissions interference case along each of the HAA approaches into the Texas Medical Center are shown in Figure 10-35 for the Memorial Hermann heliport, Figure 10-36 for the Houston Methodist Hospital heliport, Figure 10-37 for the Baylor St. Luke's Medical Center heliport, and Figure 10-38 for the Texas Children's Hospital heliport. The computed interference levels from both base stations are shown throughout each approach as a function of the landing helicopter altitude, along with the ITM[45] for Usage Category 3 and a shaded region indicating the 6 dB ICAO safety margin. A helicopter landing scenario in an obstacle-dense urban environment such as the approaches considered here necessitates the highest possible level of integrity, availability, and continuity from the radar altimeter(s) on the landing aircraft, and failures of the radar altimeter(s) may be Catastrophic. Therefore, the safety margin cannot be excluded in this scenario.

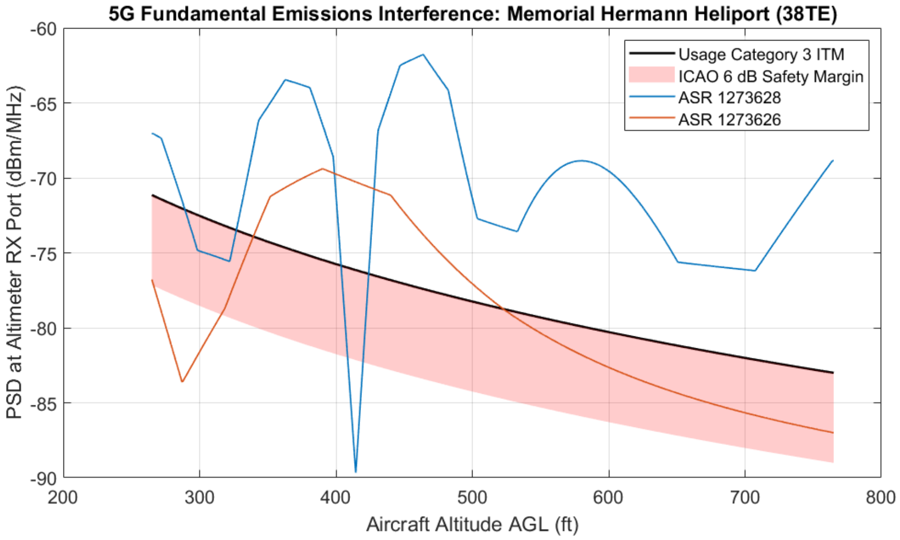

Figure 10-35: HAA Scenario Results for 5G Fundamental Emissions: Heliport 38TE

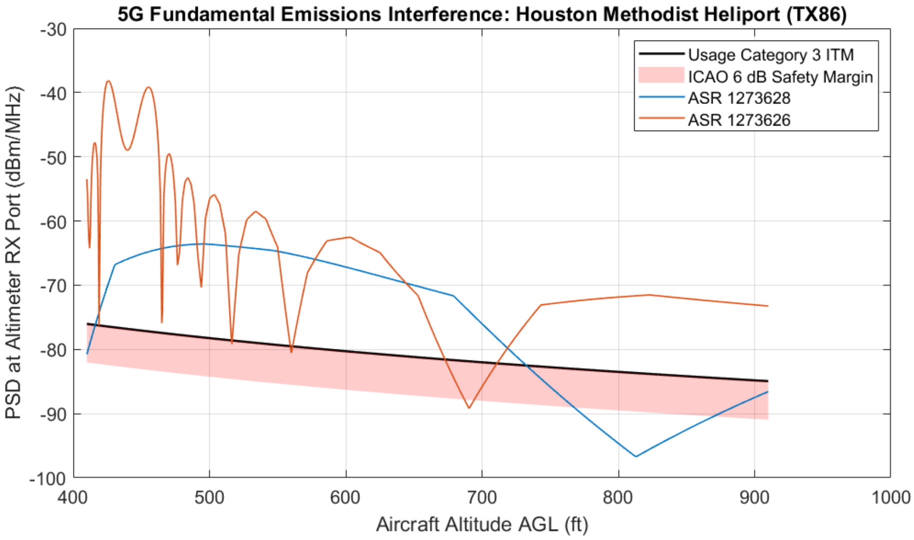

Figure 10-36: HAA Scenario Results for 5G Fundamental Emissions: Heliport TX86

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[45] As in the parametric analysis, no specific assumptions regarding the base station center frequencies are made, and the ITM is therefore taken to be the minimum ITM across the three center frequencies used in the interference tolerance testing at AVSI.

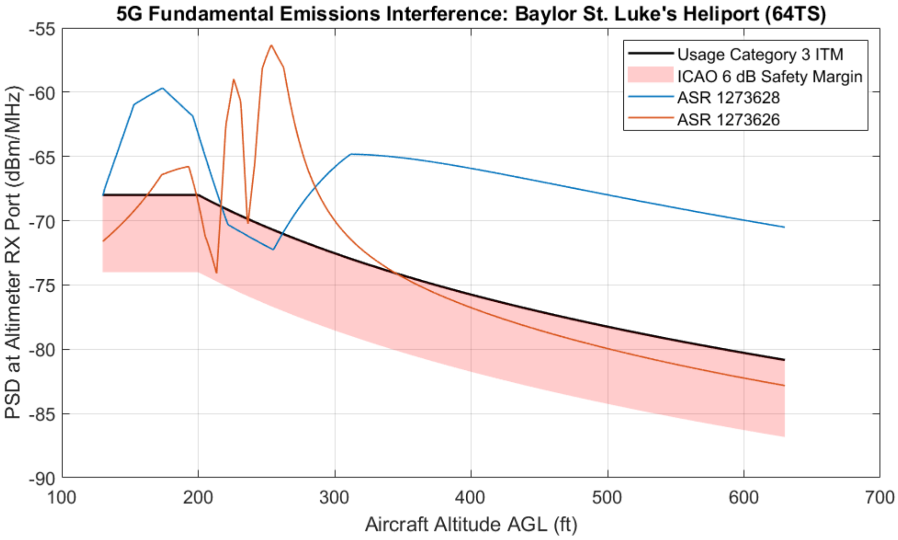

Figure 10-37: HAA Scenario Results for 5G Fundamental Emissions: Heliport 64TS

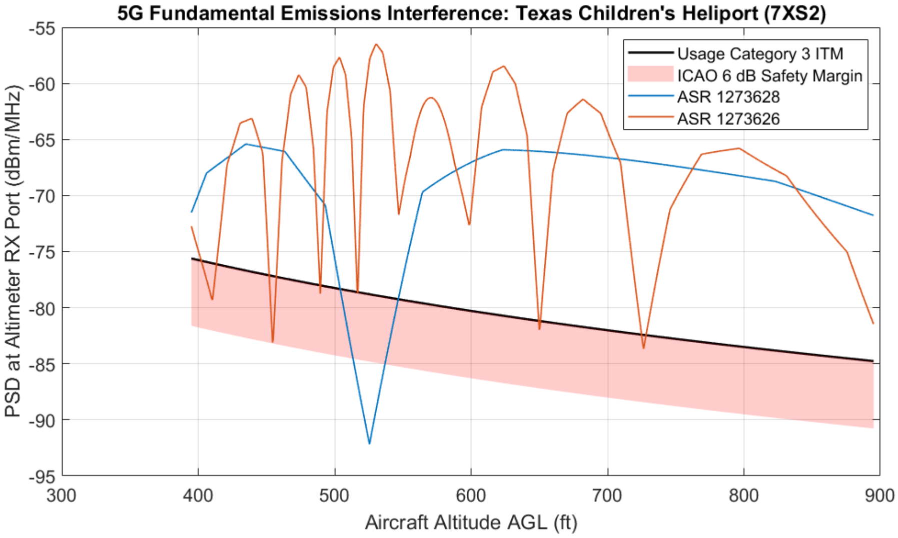

Figure 10-38: HAA Scenario Results for 5G Fundamental Emissions: Heliport 7XS2

For all four heliports, the Usage Category 3 ITM is significantly exceeded throughout the entire approach. The worst case is in the approach to the Houston Methodist heliport, in which the interference exceeds the ITM by nearly 40 dB just prior to the aircraft reaching the landing zone. Interference this far in excess of the tolerance threshold would render the radar altimeter(s) on the HAA aircraft completely inoperable, greatly limiting the capabilities of these aircraft to operate safely and dispatch quickly to those in urgent need of medical attention.

The interference levels from both base stations in all four approaches also exceed the Rec. ITU-R M.2059 Receiver Overload protection criterion of -73 dBm/MHz (based on the -53 dBm limit given in Table 6-1 and an assumed signal bandwidth of 100 MHz).

10.3.2 5G Spurious Emissions in the 4.2–4.4 GHz Band

Results for the 5G spurious emissions interference case along the each of the HAA approaches into the Texas Medical Center are shown in Figure 10-39 for the Memorial Hermann heliport, Figure 10-40 for the Houston Methodist Hospital heliport, Figure 10-41 for the Baylor St. Luke's Medical Center heliport, and Figure 10-42 for the Texas Children's Hospital heliport. As with the fundamental emissions case, the computed interference levels from both base stations are shown throughout each approach as a function of the landing aircraft altitude, as well as the ITM for Usage Category 3 and a shaded region indicating the 6 dB ICAO safety margin.

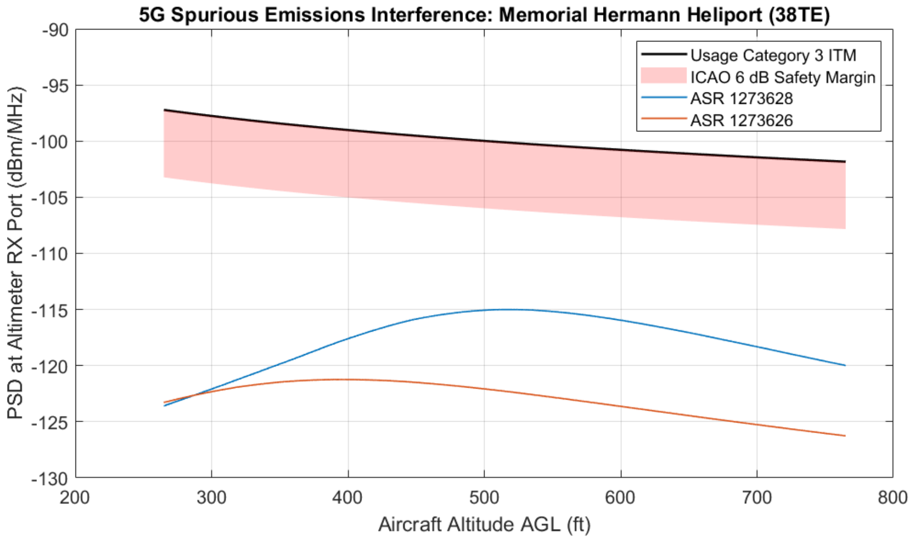

Figure 10-39: HAA Scenario Results for 5G Spurious Emissions: Heliport 38TE

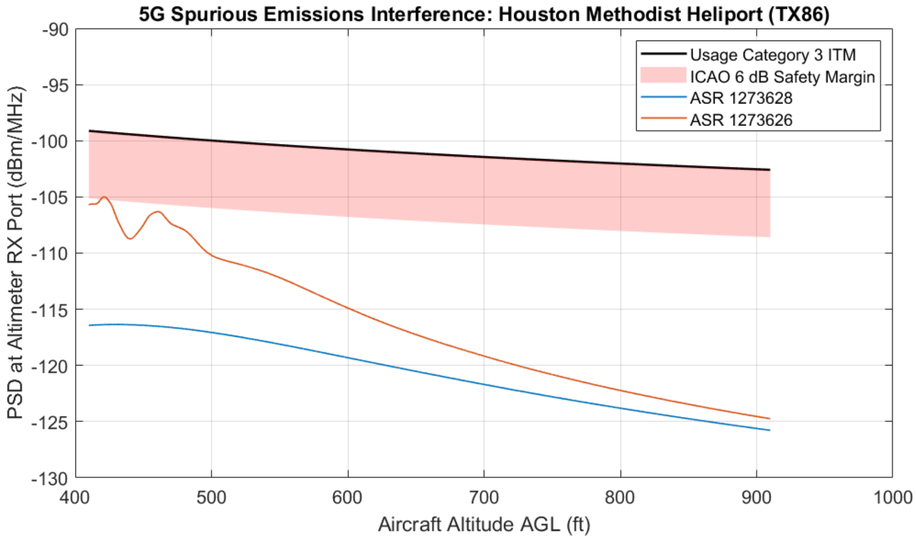

Figure 10-40: HAA Scenario Results for 5G Spurious Emissions: Heliport TX86

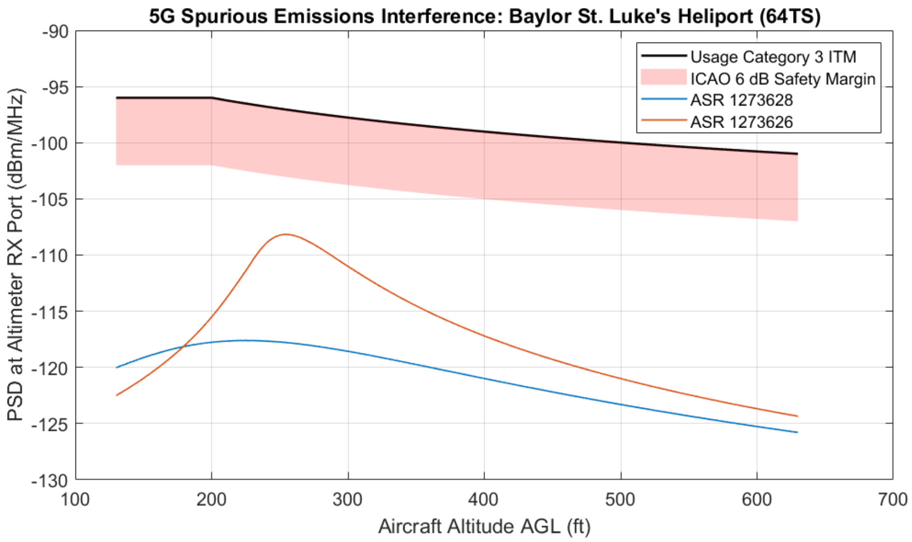

Figure 10-41: HAA Scenario Results for 5G Spurious Emissions: Heliport TX86

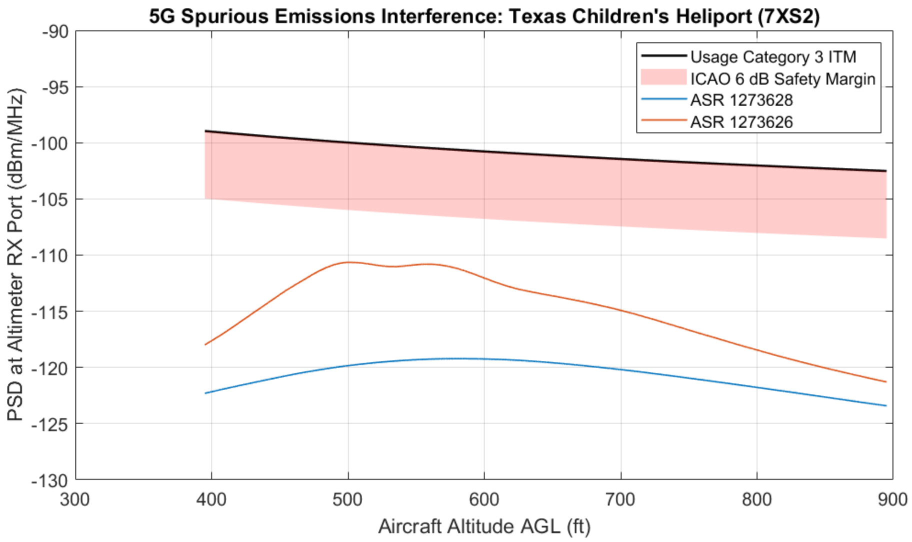

Figure 10-42: HAA Scenario Results for 5G Spurious Emissions: Heliport 7XS2

For the case of 5G spurious emissions, the 6 dB safety margin is violated only in one instance for the approach into the Houston Methodist heliport. However, the Rec. ITU-R M.2059 Receiver Desensitization protection criterion of -117 dBm/MHz (given in Table 6-2) is exceeded by at least one of the base stations in all four approaches.

10.4 User Equipment on the Ground

10.4.1 5G Fundamental Emissions in the 3.7–3.98 GHz Band

The analysis of 5G UEs on the ground beneath an overflying aircraft was carried out for aircraft altitudes ranging from 200 feet to 7,500 feet. The results for the 5G fundamental emissions in the 3.7–3.98 GHz band are shown in Figure 10-43, along with the ITMs[46] for all three Usage Categories and shaded areas showing the ICAO 6 dB safety margin.

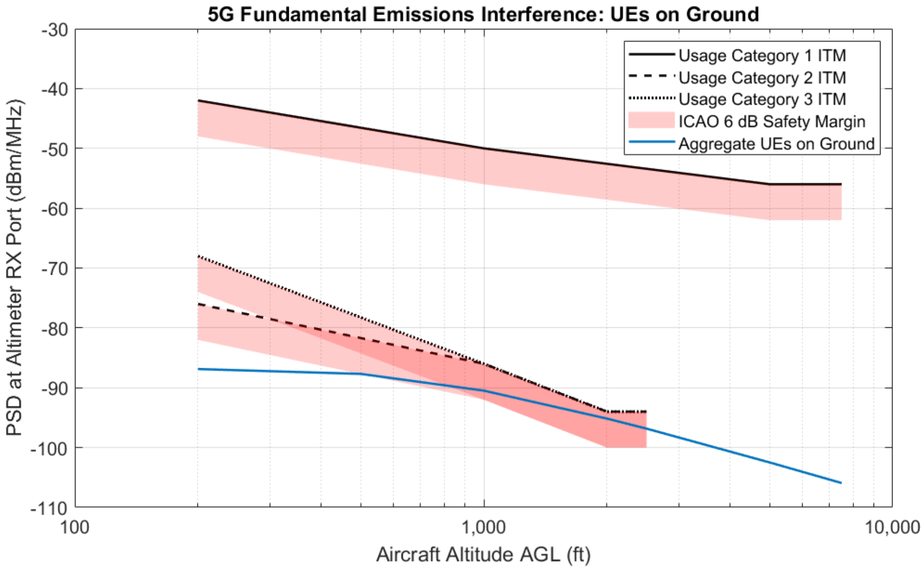

Figure 10-43: UEs on Ground Results for 5G Fundamental Emissions

The aggregate interference PSD received by the radar altimeter does not exceed the ITMs for any of the usage categories at any altitude. Further, the interference does not exceed the Rec. ITU-R M.2059 Receiver Overload protection criterion of -73 dBm/MHz (based on the -53 dBm limit given in Table 6-1 and an assumed signal bandwidth of 100 MHz).

Above 500 feet altitude, the received aggregate interference violates the 6 dB safety margin for Usage Category 2 and Usage Category 3. However, given the worst-case assumptions made in the analysis, and the fact that in practice, UEs will employ transmit power control resulting in less than the maximum allowed radiated power being emitted most of the time, it is not anticipated that the aggregate 5G fundamental emissions interference will result in significant operational impacts for civil and commercial aircraft.

10.4.2 5G Spurious Emissions in the 4.2–4.4 GHz Band

The analysis of 5G UEs on the ground beneath an overflying aircraft was carried out for aircraft altitudes ranging from 200 feet to 7,500 feet. The results for the 5G spurious emissions in the 3.7–3.98 GHz band are shown in Figure 10-44, along with the ITMs for all three Usage Categories and shaded areas showing the ICAO 6 dB safety margin.

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[46] As with the other analysis cases, the ITMs shown here are taken as the minimum across the three center frequencies, since no specific assumptions are made regarding the actual 5G center frequency.

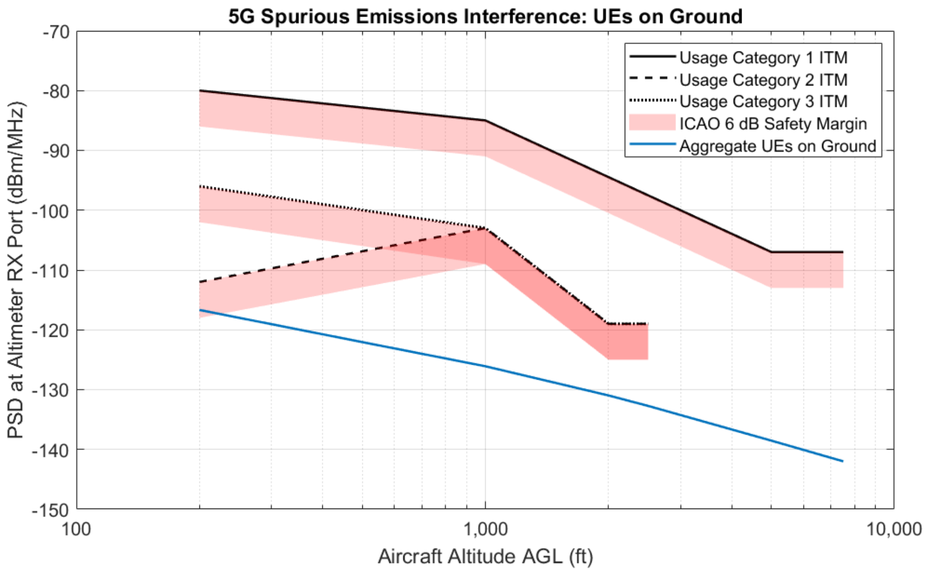

Figure 10-44: UEs on Ground Results for 5G Spurious Emissions

The aggregate interference PSD received by the radar altimeter does not exceed the ITMs for any of the usage categories at any altitude. The aggregate interference does exceed the Rec. ITU-R M.2059 Receiver Desensitization protection criterion of -117 dBm/MHz (given in Table 6-2), but only at 200 feet altitude, and only by a small amount (less than 1 dB). This point also corresponds to the aggregate interference level violating the safety margin for Usage Category 2. However, as with the fundamental emissions case, it is not anticipated that the aggregate 5G spurious emissions from UEs on the ground will result in significant operational impacts for civil and commercial aircraft.

10.5 User Equipment Onboard Aircraft

10.5.1 5G Fundamental Emissions in the 3.7–3.98 GHz Band

The results of the analysis of 5G fundamental emissions interference from UEs onboard an aircraft are presented in Table 10-1. The overall minimum ITM (taken across all 5G center frequencies and altitudes) for each Usage Category, along with the applicable protection criteria from Rec. ITU-R M.2059, are also listed.

Table 10-1: UEs Onboard Aircraft Results for 5G Fundamental Emissions

Usage Category	Aggregate UE Interference	Overall ITM Minimum	Rec. ITU-R M.2059 Receiver Overload Protection Criterion[47]
1	-70.8 dBm/MHz	-56 dBm/MHz	-73 dBm/MHz
2	-60.8 dBm/MHz	-94 dBm/MHz	
3	-47.8 dBm/MHz	-94 dBm/MHz	

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

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[47] Computed assuming a total signal bandwidth of 100 MHz.

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.

10.5.2 5G Spurious Emissions in the 4.2–4.4 GHz Band

The results of the analysis of 5G spurious emissions interference from UEs onboard an aircraft are presented in Table 10-2. The overall minimum ITM (taken across all altitudes) for each Usage Category, along with the applicable protection criteria from Rec. ITU-R M.2059, are also listed.

Table 10-2: UEs Onboard Aircraft Results for 5G Spurious Emissions

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

In all cases, the aggregate interference exceeds the Rec. ITU-R M.2059 Receiver Desensitization 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 6 dB safety margin. Even if the spurious emissions from just a single UE are considered, resulting in $N = 1$ in Equation 6-4 and thus decreasing the computed interference PSD by 7 dB in each case, both the protection criteria and the empirical interference tolerance thresholds are still exceeded for Usage Category 2 and Usage Category 3.

11 FINDINGS AND CONCLUSIONS

11.1 Likely Impacts to Aircraft Operations Due to 5G Interference

11.1.1 5G Base Stations

5G base stations present a risk of harmful interference to radar altimeters across all aircraft types, with far-reaching consequences and impacts to aviation operations.

For Usage Category 1, which covers most commercial airplanes used for passenger travel and cargo transport, the impact is limited to specific scenarios—with only the AAS base stations producing interference above the safe interference limit, and only for certain combinations of aircraft altitude and lateral distance between the aircraft and base station. However, although the interference impacts for Usage Category 1 only arise in certain scenarios, the extent and safety consequences of those impacts are extreme, as seen in the CAT II/III Instrument Approach Procedure Scenario discussed in Section 8.1 and Section 10.2. In the worst case, the safe interference limit is exceeded by nearly 14 dB for the 5G fundamental emissions in the 3.7–3.98 GHz band. For the 5G spurious emissions in the 4.2–4.4 GHz band, the safe interference limit is not exceeded by any base station configuration.

For Usage Category 2, which covers commercial airplanes used for regional air transport as well as business and general aviation airplanes, the impact of 5G interference from base stations is inescapable. Every base station configuration produces harmful interference both from fundamental emissions in the 3.7–3.98 GHz band and spurious emissions in the 4.2–4.4 GHz band, across virtually all operational scenarios and relative geometries between the aircraft and base station. In the worst case, the safe interference limit for the fundamental emissions is exceeded by over 47 dB, and the safe interference limit for the spurious emissions is exceeded by over 27 dB.

For Usage Category 3, which covers both transport and general aviation helicopters, the impact of interference from 5G base stations is nearly as broad as for Usage Category 2. Every base station configuration produces harmful interference both from fundamental emissions in the 3.7–3.98 GHz band and spurious emissions in the 4.2–4.4 GHz band, across virtually all operational scenarios and relative geometries between the aircraft and base station. In the worst case, the safe interference limit for the fundamental emissions is exceeded by over 45 dB, and the safe interference limit for the spurious emissions is exceeded by nearly 12 dB.

11.1.2 5G User Equipment on the Ground

As shown in Section 10.4, 5G UEs operating on the ground are not expected to cause harmful interference to radar altimeters. Therefore, no operational impacts for aircraft are anticipated in this case.

11.1.3 5G User Equipment Onboard Aircraft

As shown in Section 10.5, 5G UEs which may be operating, even unintentionally, onboard Usage Category 2 or Usage Category 3 aircraft introduce a significant risk of harmful interference to the radar altimeters used on these aircraft. When accounting for the 6 dB ICAO safety margin, the computed aggregate worst-case interference levels on Usage Category 2 aircraft exceed the safe interference limit by 39 dB for the 5G fundamental emissions in the 3.7–3.98 GHz band, and by 20 dB for the 5G spurious emissions in the

4.2–4.4 GHz band. On Usage Category 3 aircraft, the aggregate worst-case interference levels exceed the safe interference limit by 52 dB for the 5G fundamental emissions in the 3.7–3.98 GHz band, and by 33 dB for the 5G spurious emissions in the 4.2–4.4 GHz band.

11.2 Mitigating the Risk of Harmful Interference to Radar Altimeters

The results presented in this report reveal a major risk of harmful interference to radar altimeters on all types of civil and commercial aircraft caused by 5G telecommunications systems in the 3.7–3.98 GHz band in a broad range of operational scenarios. This risk is widespread and has the potential for broad impacts to aviation operations in the United States, including the possibility of Catastrophic failures leading to multiple fatalities. Further, this risk cannot be adequately mitigated by the aviation industry acting alone. As stated in the ICAO *Handbook on Spectrum Requirements for Civil Aviation* at paragraph 9.2.17, in cases where a non-aeronautical service produces harmful RF interference to an aeronautical safety service, “it would be assumed that an aeronautical safety service would be permitted to continue to operate, with the prime obligation being on the interfering service to adjust, close down or take other immediate action to resolve the situation.” [17]

While the aviation industry has recognized that changes to the RF environment in which radar altimeters operate are inevitable and performance standards must be updated accordingly, this necessarily takes a significant amount of time given the extreme rigor and caution with which aviation systems manufacturers, aircraft manufacturers, aircraft operators, and Civil Aviation Authorities (CAAs) work to develop and implement such changes for safety-critical systems like radar altimeters. Even a technical solution which may be viable for retrofit installations, which to this point remains unexplored and may not even exist, would take several years to properly validate and deploy across all affected civil aircraft operating in the United States. Therefore, it is critical that the performance of radar altimeters which are currently in service across tens of thousands of civil aircraft be understood and the risks and operational impacts due to interference be appreciated based on the characterization provided in this report. Given the planned timeline for deployment of 5G systems in the 3.7–3.98 GHz band, these radar altimeters will be exposed to such risks and operational impacts if proper mitigations are not put in place.

In some cases, such as for Usage Category 1, the operational impacts may be narrow enough in scope (although they are still severe in consequence) to allow for mitigations such as proper base station placement and deployment planning, improved base station antenna designs, or minor operational limitations which are not restricted by current regulations (such as limiting AAS scan angle ranges) to be sufficient. In other cases, such as for Usage Category 2 and Usage Category 3, the impacts are so widespread that mitigation will likely require significant action to be taken by both the aviation industry and the mobile wireless industry, along with the applicable regulators for each.

11.3 Continued Work and Ongoing Aviation Industry Activities

11.3.1 Updates to Radar Altimeter MOPS

The first step to improving the resilience of future radar altimeter designs to RF interference in the 3.7–3.98 GHz band is updating the MOPS. This process is underway with the creation of SC-239, and the updated MOPS—with additional performance requirements for RF interference rejection—are expected to be completed and approved for release by RTCA by October 2022. The new MOPS will be developed jointly with EUROCAE Working Group 119 (WG-119).

After the MOPS are updated, it is anticipated that they will be referenced by CAAs, such as the FAA in the United States, to define new performance standards that must be met for equipment-level design approvals of radar altimeters. After this point, new radar altimeter designs which seek such approvals from CAAs for use on certified aircraft are expected to be capable of safe operation in the presence of the anticipated RF interference from 5G systems operating in the C-band (or upper S-band). However, as noted in Section 11.2, radar altimeters exhibiting the performance described in this report will continue to operate on commercial and civil aircraft for many years into the future.

11.3.2 Development of Mitigations and Technical Recommendations

The SC-239 membership will work with interested parties, both regulatory authorities and industry representatives, to develop any further analysis efforts or discussion of interference mitigation approaches as needed.

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14 DEFINITIONS

Availability — The percentage of time that a navigational aid or other system is usable by the operator.

Aviation safety margin — Aeronautical safety applications are required to have continued operation through worst case interference, so all factors which contribute to harmful interference should be considered in analyses involving those applications. An aviation safety margin is included in order to address the risk that some such factors cannot be foreseen (for example impacts of differing modulation schemes). This margin is applied to the system protection criteria to increase the operational assurances to the required level. Traditionally for aviation systems/scenarios an aviation safety margin of 6–10 dB is applied. Until established on the basis of further study on a case-by-case basis, an aviation safety margin of not less than 6 dB should be applied. [17]

Catastrophic — Failure conditions that are expected to result in multiple fatalities of the occupants, or incapacitation or fatal injury to a flight crewmember normally with the loss of the airplane. Catastrophic failure condition would prevent continued safe flight and landing. [12][13][14][15]

Continuity — The ability of a navigational aid or other system to perform its function without interruption during intended operation, generally expressed as the probability that the specified system performance will be maintained for the duration of a phase of operation.

Hazardous/Severe Major — Failure conditions that would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be the following:

(a) A large reduction in safety margins or functional capabilities;

(b) Physical distress or higher workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; or

(c**)** Serious or fatal injury to an occupant other than the flight crew. [12][13][14][15]

Integrity — The measure of trust that can be placed in the correctness of information provided by a navigational aid or other system, including the ability of the system to provide timely warnings when it should not be used.

Major — Failure conditions that would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be a significant reduction in safety margins or functional capabilities. In addition, the failure condition has a significant increase in crew workload or in conditions impairing crew efficiency; or a discomfort to the flight crew or physical distress to passengers or cabin crew, possibly including injuries. [12][13][14][15]

Category I — A precision instrument approach and landing with a decision height not lower than 60 m (200 ft) and with either a visibility not less than 800 m (2400 ft), or a runway visual range not less than 550 m (1800 ft). [36]

Category II — A precision instrument approach and landing with a decision height lower than 60 m (200 ft) but not lower than 30 m (100 ft) and a runway visual range not less than 300m (1000 ft). [36]

Category III — A precision instrument approach and landing with a decision height lower than 30 m (100 ft) (or with no decision height, or with an alert height) and a runway visual range less than 300m (1000 ft). [36]

Development Assurance Level (DAL) — The Development Assurance Level, or DAL, is described in SAE ARP4754A and provides a top-level characterization of the integrity, availability, and continuity of a system for use in aviation safety applications. The highest is DAL A, meaning that the system can generally support operating conditions with Catastrophic failure severity. DAL B systems can generally support operating conditions with, at most, Hazardous/Severe Major failure severity, and DAL C systems can generally support operating conditions with, at most, Major failure severity. [42]

Decision Height — A specified height in the precision approach at which a missed approach must be initiated if the required visual reference to continue the approach has not been established. For CAT II/III precision approach and landing, the DH is determined using the radar altimeter output. [36]

External loop loss — Defined in RTCA DO-155, *Minimum Performance Standards for Low-Range Radar Altimeters*, Appendix B as the ratio of the available power entering the receiving antenna aperture to the power leaving the transmitter antenna aperture. [4]

Interference Tolerance Mask (ITM) — A set of Interference Tolerance Thresholds defined across a range of operating conditions, such as the center frequencies of the interfering signal, or the initial state of the victim receiver or system (e.g. the altitude being tracked by a radar altimeter).

Interference Tolerance Threshold — The maximum allowable level of a specified RF interference signal, under a particular set of operating conditions, which will not lead to certain failure of the victim receiver or system. May be determined based on empirical measurement, or an established protection criterion.

Predictive Wind Shear — An avionics system onboard aircraft that senses and identifies a windshear threat before the phenomenon is encountered. Height above ground is determined using the radar altimeter output.

Terrain Awareness Warning Systems (TAWS) — An avionics system onboard aircraft that predicts a potential conflict between the aircraft's future flight path and terrain. TAWS look-ahead capability provides warnings and alerts well in advance of potential hazards, allowing time for the pilot to make the necessary maneuvers or data corrections for terrain avoidance. Height above ground is determined using the radar altimeter output.

Traffic Alert and Collision Avoidance Systems (TCAS) / Airborne Collision Avoidance Systems (ACAS) — An avionics system onboard aircraft that performs collision avoidance. An airborne collision avoidance system that uses interrogations on 1030 MHz to track other aircraft, possibly in addition to other methods of tracking other aircraft, and uses 1030/1090 MHz to coordinate avoidance maneuvers in collision risk encounters with other Active TCAS/ACAS. The Height above ground for TCAS/ACAS inhibition near the ground is determined using the radar altimeter output.

15 ACRONYMS AND ABBREVIATIONS

3GPP	3rd Generation Partnership Project
4G	4th Generation Cellular Telecommunications
5G	5th Generation Cellular Telecommunications
AAS	Advanced Antenna System (or Active Antenna System)
AC	Advisory Circular
ACAS	Airborne Collision Avoidance System
AFGCS	Automatic Flight Guidance and Control System
AGL	Above Ground Level
AH	Alert Height
AID	Aircraft Installation Delay
AMJ	Advisory Material Joint
ARNS	Aeronautical Radionavigation Service
ASR	Antenna Structure Registration
AUT	Altimeter Under Test
AVSI	Aerospace Vehicle Systems Institute
AWGN	Additive White Gaussian Noise
BS	Base Station
CAA	Civil Aviation Authority
CAT I	Category I Precision Instrument Approach
CAT II	Category II Precision Instrument Approach
CAT III	Category III Precision Instrument Approach
CFIT	Controlled Flight into Terrain
CFR	Code of Federal Regulations
DAL	Development Assurance Level
dB	Decibels
dBi	Decibels Relative to Isotropic Radiator
dBm	Decibels Relative to One Milliwatt
DC	Direct Current
DH	Decision Height
ECAM	Electronic Centralized Aircraft Monitoring
ED	EUROCAE Document
EICAS	Engine-Indicating and Crew-Alerting System
EIRP	Effective Isotropic Radiated Power
EUROCAE	European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FCC	Federal Communications Commission
FDR	Frequency Dependent Rejection
FMCW	Frequency-Modulated Continuous Wave
FS	Fixed Service
FSS	Fixed-Satellite Service
ft	Feet
GHz	Gigahertz
HAA	Helicopter Air Ambulance
HTAWS	Helicopter Terrain Awareness Warning System
Hz	Hertz
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IF	Intermediate Frequency

ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
ITM	Interference Tolerance Mask
ITU	International Telecommunications Union
ITU-R	ITU Radiocommunication Sector
km	Kilometer
LRRA	Low-Range Radar Altimeter
LTE	Long Term Evolution
m	Meter
MHz	Megahertz
MOPS	Minimum Operational Performance Standards
NASA	National Aeronautics and Space Administration
NCD	No Computed Data
NM	Nautical Mile
NR	New Radio
NR-FR1-TM1.1	New Radio-Frequency Range 1-Test Model 1.1 (5G Test Waveform)
NTIA	National Telecommunications and Information Administration
OFDM	Orthogonal Frequency Division Multiplexing
OOBI	Out-of-Band Interference
PED	Portable Electronic Device
PSD	Power Spectral Density
PWS	Predictive Wind Shear
QPSK	Quadrature Phase-Shift Keying
RA	Radar Altimeter
RF	Radio Frequency
Rx	Receive (or Receiver)
SC	Special Committee
SINR	Signal-to-Interference-Plus-Noise Ratio
SNR	Signal-to-Noise Ratio
TAWS	Terrain Awareness Warning System
TC	Type Certificate
TCAS	Traffic Alert and Collision Avoidance System
TSO	Technical Standard Order
TWG	Technical Working Group
Tx	Transmit (or Transmitter)
UE	User Equipment
USB	Universal Serial Bus
VAC	Volts Alternating Current
VDC	Volts Direct Current
VCO	Voltage-Controlled Oscillator
VSG	Vector Signal Generator
WCLS	Worst-Case Landing Scenario

16 MEMBERSHIP

RTCA Special Committee SC-239

Low Range Radar Altimeter

Chairs	**Organization**
Seth Frick	Honeywell International Inc.
Jean-Luc Robin	Airbus

Secretary	**Organization**
Sai Kalyanaraman	Collins Aerospace

Government Authorized Representative	**Organization**
Charisse Green	Federal Aviation Administration (FAA)

RTCA Program Directors	**Organization**
Karan Hofmann	RTCA, Inc.
Rebecca Morrison	RTCA, Inc.

Members	**Organization**
Hamza Abduselam	Federal Aviation Administration (FAA)
Oreoluwa Ajayi	NeuralVol Inc.
Mohandas Amarnathan	Honeywell International Inc.
Laurent Azoulai	Airbus
Gregory Baker	Aviation Spectrum Resources, Inc. (ASRI)
Miles Bellman	Federal Aviation Administration (FAA)
Craig Brandt	The Boeing Company
Adrian Cioranu	European Organisation for Civil Aviation Equipment (EUROCAE)
Joseph Cramer	The Boeing Company
Max Fenkell	Aerospace Industries Association (AIA)
Bryce Fenton	Textron Aviation Inc.
Fred Fisher	Aerospace Vehicle Systems Institute (AVSI)
Thomas Googe	American Airlines, Inc.
Charisse Green	Federal Aviation Administration (FAA)
Edward Hahn	Air Line Pilots Association (ALPA)
Shane Happs	Collins Aerospace
Kim Kolb	The Boeing Company
Zhimin Li	Collins Aerospace
Ladislas Loughin	Airbus
Ivan Martin	Thales Group
Samh Menshawy	Thales Group
Donny Morrow	Air Line Pilots Association (ALPA)
Lee Nguyen	Federal Aviation Administration (FAA)
Jesse Oltrogge	Collins Aerospace

Ted Peterson	Collins Aerospace
Behlul Poonawalla	FreeFlight Systems
Nayyar Rao	Honeywell International Inc.
David Redman	Aerospace Vehicle Systems Institute (AVSI)
Nicolas Rico	Textron Aviation Inc.
Andrew Roy	Aviation Spectrum Resources, Inc. (ASRI)
Dave Sambrano	United Airlines, Inc.
James Stanley	Collins Aerospace
Charles Stewart	United Airlines, Inc.
Eddie Straub	Garmin Ltd.
Stephane Tallet	Thales Group
Christopher Tourigny	Federal Aviation Administration (FAA)
Michael Tran	The MITRE Corporation
Jessie Turner	The Boeing Company
Long Vo	Bell Textron Inc.

Appendix A AVSI TEST SETUP AND METHODOLOGY DETAILS

A.1 Introduction

The Aerospace Vehicle Systems Institute (AVSI) performed laboratory testing of radar altimeter (RA) susceptibility to out-of-band interference (OOBI) as part of AVSI Project AFE 76s2. This appendix describes the test apparatus and procedures used to characterize RA performance in the presence of simulated interference signals. The objective was to empirically determine the interference power thresholds at which RA performance is adversely affected by representative 5G signals in the 3.7–3.98 GHz frequency band and representative 5G spurious signals in the 4.2–4.4 GHz frequency band for a broad sample of commercially available RA models.

AVSI is an aerospace industry research cooperative based at Texas A&M University that facilitates collaborative research and technology projects for its members. Project AFE 76s2 included representatives from Airbus, Aviation Spectrum Resources Inc. (ASRI), Collins Aerospace, Embraer, FAA, Garmin, Honeywell, the International Air Transport Association (IATA), Lufthansa Technik, the National Aeronautics and Space Administration (NASA), Texas A&M University, Safran, and Thales. The research team brought together subject member experts in RA equipment design and RA system integration, along with input from 5G experts, to design the test conditions and procedures necessary to accurately determine the interference power thresholds useful for analyzing the potential interference arising from 5G implementations in the 3.7–3.98 GHz frequency band.

A.2 AVSI Test Setup Detailed Description

A.2.1 General

The general approach to empirically determine interference tolerance thresholds was introduced in Section 7. The laboratory test apparatus was configured to allow commercial off-the-shelf RAs to operate normally using an altitude simulator while various sources of RF interference were directly coupled into the RA return signal path, all while monitoring the altitude reported on the standard RA output. In this way, testing is limited to black-box testing of commercial altimeters in that stimuli are applied to the standard RA input and effects are observed on the standard RA output, without detailed knowledge of the internal operation of the specific altimeter under test. This method of testing thus allows a general assessment of the susceptibility of an altimeter to interference without considering design details of the RA's receiver and signal processing algorithms.

Figure A-1 presents a block diagram of the AVSI test apparatus. The test apparatus was designed to be operated either in a laboratory setting or installed in an aircraft for possible testing during actual flight conditions. All tests described in this report were conducted in a laboratory setting under standard environmental conditions. The main features of the apparatus include connections for the altimeter under test, an altitude simulator, simulation of FMCW interference sources operating in the 4.2–4.4 GHz band, simulation of 5G interference sources, data acquisition, and computer control. Each of these are described in detail below.

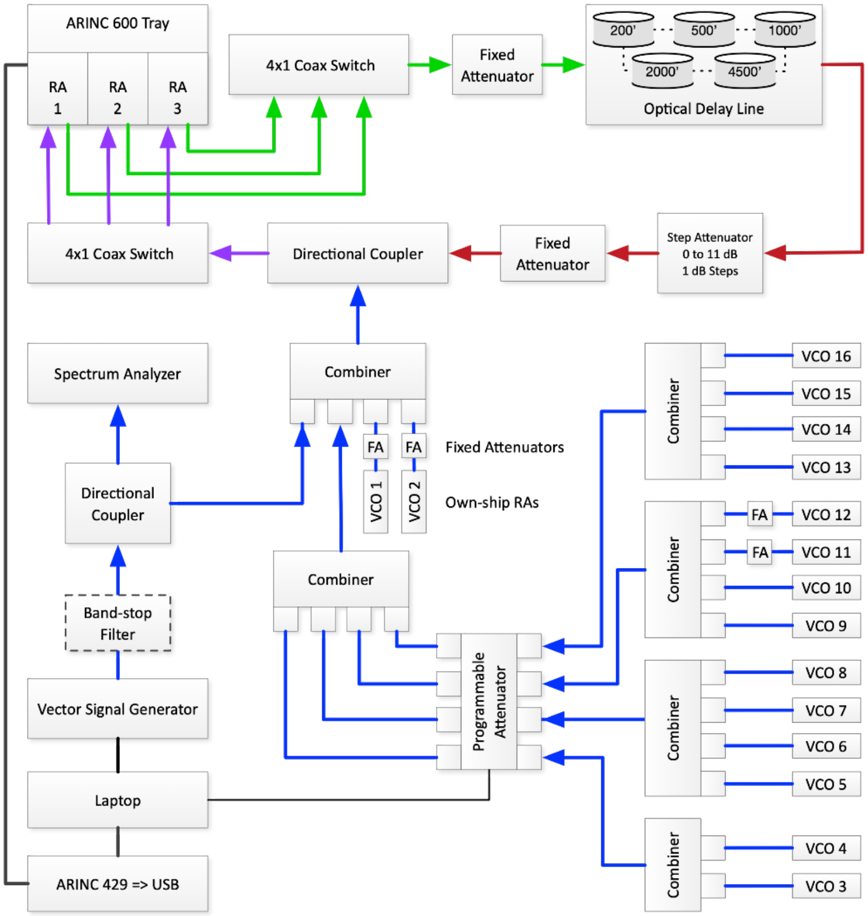

Figure A-1: Block Diagram of AVSI Test Setup

A.2.2 Altimeter Under Test

AVSI obtained a total of nine radar altimeter models from five different manufacturers, as described in Section 7.2 and summarized in Table 7-1. The specific altimeter under test was mounted per recommended installation procedures provided by each RA manufacturer.

RAs in Usage Category 1 were mounted in a standard ARINC 600 avionics tray with the recommended avionics connector. This connector is used to pin configure the RA for a specific installation assignment, which is used for configuring RAs in multiple-unit installations. The RAs have a System Select input (typically pin configured, but some have a voltage input) to internally configure operating parameters that allow multiple RAs of the same model on the same aircraft to operate simultaneously without operationally significant mutual interference. Each RA was set to System Select 2. A test rack was constructed to allow three different RAs to be mounted with the altimeter under test (AUT) selected with a panel switch. This switch operated a Teledyne CCR-38S SP4T coax switch whose inputs were connected to the three RA transmit outputs (Tx) and whose output was connected to the altitude simulator using manufacturer recommended, aircraft-grade coaxial cabling. A second equivalent RF switch was used in the RA signal return path, connecting the altitude simulator output to the receive inputs (Rx) of the RA mounted in the test rack. The standard output, which for Usage Category 1 altimeters is an ARINC 429 digital output, was connected to the control computer via a Ballard Technology USB 429 interface adapter connected to the test laptop computer. The test rack also provided 115 VAC 400 Hz power or 28 VDC power to the AUT as required.

RAs in Usage Categories 2 and 3 were mounted directly on the benchtop. Type 6, 7, and 9 were connected to the ARINC 429 interface using a pigtailed connector that provided connections to power and the standard output. The standard output for the Type 8 altimeter is a precision analog output which provides a calibrated voltage proportional to the altitude and two additional discrete signals that indicate error conditions equivalent to the NCD and Failure Warning status indications reported on the ARINC 429 bus for all other altimeters. The precision analog altitude and discrete output signals from the Type 8 altimeter were monitored using a National Instruments USB-6211 analog-to-digital converter connected to the test laptop computer.

A.2.3 Altitude Simulator

As specified by DO-155, the “altitude simulator consists of variable and fixed RF attenuators, and coaxial cables or other suitable delays to simulate the various altitudes. The simulator must accept the altimeter energy, attenuate and delay this RF energy and present the delayed signal of the altimeter receiver.” [4] In the case of the AVSI test apparatus, the altitude simulator consisted of fixed and step variable attenuators and a fiber optic delay line comprised of an Emcore 5021TR-B-1309-FA fiber optic transceiver and optical fiber spools providing calibrated delays representing round trip propagation for altitudes of 200, 500, 1000, 2000, and 4500 feet. The individual spools can be daisy-chained to provide additional test altitudes. A 20 dB fixed attenuator was inserted prior to the optical transceiver to protect the transceiver input. Note that RAs are calibrated to account for aircraft installation delays (AID) arising from the coaxial cable propagation delay between the RA and the antennas. This fixed delay is usually compensated during installation to set the reported altitude to zero while the aircraft is on the ground by adjusting the AID setting that is externally accessible on the RA. However, AVSI testing did not compensate for AID, as this simply adds a fixed altitude offset to the nominal height above ground level (AGL) that is removed when considering differential changes to the reported altitude caused by external stimuli on the Rx input. While cable delays do not impact the AVSI testing, additional losses imposed by installation cabling were considered when establishing the total loop loss at each altitude.

The external loop loss for the full RA Tx-to-Rx signal path was determined by adding additional attenuation to the intrinsic losses of the fiber optic delay line and then measuring the total attenuation using a calibrated network analyzer over the 4.2–4.4 GHz frequency band. A 0–11 dB step attenuator was used to bring the total loop loss to the value specified by the MOPS for the altitude being simulated plus an additional 6 dB to account for cable losses between the RA Tx and Rx ports and the RA Tx and Rx antennas as described in Section 6.3.4.2. Additional information concerning external loop loss values is provided in Section 7.3.1.

A.2.4 Simulation of FMCW Interference Sources

Most RAs experience FMCW interference from other RAs operating in same the 4.2–4.4 GHz frequency band. As described in Section 7.3.2, such interference can originate from on board the same aircraft in the case of duplex or triplex radar altimeter installations, or from other aircraft operating nearby the victim altimeter. The complexity and cost of replicating in-band interference scenarios using additional RAs to generate interference signals was prohibitive, so these signals were generated using Mini-Circuits ZX95-4403-S+ voltage-controlled oscillators (VCOs) that were tuned to a set of representative linearly chirped FMCW waveforms appropriate for each RA Type and operating scenario.

Each VCO was controlled by an independent function generator that supplied the proper waveform to the voltage tuning input in order to assure that individual FMCW sources were uncorrelated. Most of the FMCW RAs use a continuous triangle-wave linear up/down chirp, however some used a sawtooth frequency modulation waveform. Each VCO was calibrated to determine the direct current (DC) voltage that established a center frequency of 4.3 GHz and the minimum/maximum voltages necessary to cover the specific RA sweep range (160 MHz or less). The function generator DC offset, waveform peak voltages, sweep repetition frequency, and sweep waveform were set according to the RA specifications.

A.2.5 Own-Ship FMCW Interference

For RAs that are intended for multiplex installations, 1 or 2 VCOs were configured to replicate the frequency sweep characteristics of the AUT, adjusted for any changes caused by setting the System Select input to 1 or 3.

Altimeter manufacturers specify a minimum isolation between the Tx antenna of one RA to the Rx antenna of another own-ship RA. The own-ship VCOs’ RF output was attenuated such that the power measured at the AUT Rx input matches the nominal AUT Tx output power attenuated by the specified isolation plus 6 dB for cable losses. This attenuation between the VCO RF output and the AUT Rx input was then verified using a network analyzer over the 4.2–4.4 GHz frequency band.

A.2.6 Off-Board FMCW Interference

AVSI conducted an extensive analysis of potential operating scenarios to determine the greatest potential risk to RA-equipped aircraft. As indicated in Table 5-1, loss of RA function during the landing phase of flight can be catastrophic. This situation is exacerbated by the fact that airports present the highest concentration of FMCW interference sources due to the RAs on other aircraft at the holding bay, on the taxiway, and at the gate area. Note that RAs are always active whenever an aircraft is powered and are subject to interference from other aircraft due to reflections off the tarmac and airport structures. ICAO aerodrome design requirements contained in Annexes 10 and 14 to the Convention on International Civil Aviation as well as the IATA Airport Development Reference Manual specify minimum separation distances required to safely operate aircraft in the vicinity and on the surface of an aerodrome [44] [45] [46]. Analysis of these aerodrome considerations led to the definition of a Worst-Case Landing Scenario (WCLS), which is worst-case in the sense that triplex RA-equipped aircraft are placed in the densest allowable geometry and the altitude of a landing aircraft containing the victim altimeter is positioned above the runway at an AGL that maximizes the aggregate interference power from the aircraft on the ground.

The WCLS defines a set of sixteen aggressor aircraft, of which five aircraft are in the taxiing phase in proximity to the landing victim aircraft, and eleven aircraft are farther away on the aerodrome’s apron, as illustrated in Figure A-2.

The separation between each of the aggressor aircraft and the victim aircraft as well as the associated free-space path loss at 4.3 GHz was modeled in a dynamic simulation of the victim aircraft's final landing phase to determine a worst-case height above the runway just prior to landing[48]. This allowed for the calculation of an aggregate interference level of all sixteen aircraft as seen by the RA receiver on the victim aircraft. In order to expose the AUT to the interference characteristics experienced as a consequence of the geometries specified in the WCLS, the interference path loss values between the various aggressor aircraft and the victim aircraft were then used to derive the power levels for RA interference signals.

The geometry of the WCLS includes the separation distances d_1, d_2, d_3 and d_4 relevant for parameterization of the WCLS. These are summarized in Table A-1.

Table A-1: Worst-Case Landing Scenario Geometry Explanation

Distance	Description
d_1	**Separation between two taxiing aircraft** The separation distance d_1 depends on aircraft type. For the assessments carried out in this test campaign, large aircraft with triplex RA installations were assumed. For these types of aircraft, a separation distance of d_1 = 80 m is considered reasonable.
d_2	**Lateral separation between two parking aircraft** The separation d_2 = 80 m is the width of a standard parking box.
d_3	**Separation between centerline of runway and parallel taxiway** The minimum separation distance between the centerline of a runway and a taxiway on airport types 2B and 3B is specified as 87 m. (see Annex 14 to the Convention on International Civil Aviation, section 3.9.8 Table 3-1 [45]).
d_4	**Separation between runway centerline and closest aircraft on the apron** For protection of ILS operation for precision approach CAT II/III, the localizer critical and sensitive area is defined in Annex 10 to the Convention on International Civil Aviation, Attachment C [44]. The minimum separation between runway centerline and the RA transmit antenna location of an aircraft on the apron parking area is d_4 = 300 m, as derived from Figure C-4A of Annex 10.

---

[48] Note that although Figure A-2 shows the aircraft crossing the runway threshold at 200 feet AGL, this worst-case altitude need not correspond to the actual threshold crossing height. Other situations may also lead to the same WCLS geometry, for example if the ends of the taxiway and apron are not aligned with the runway threshold.

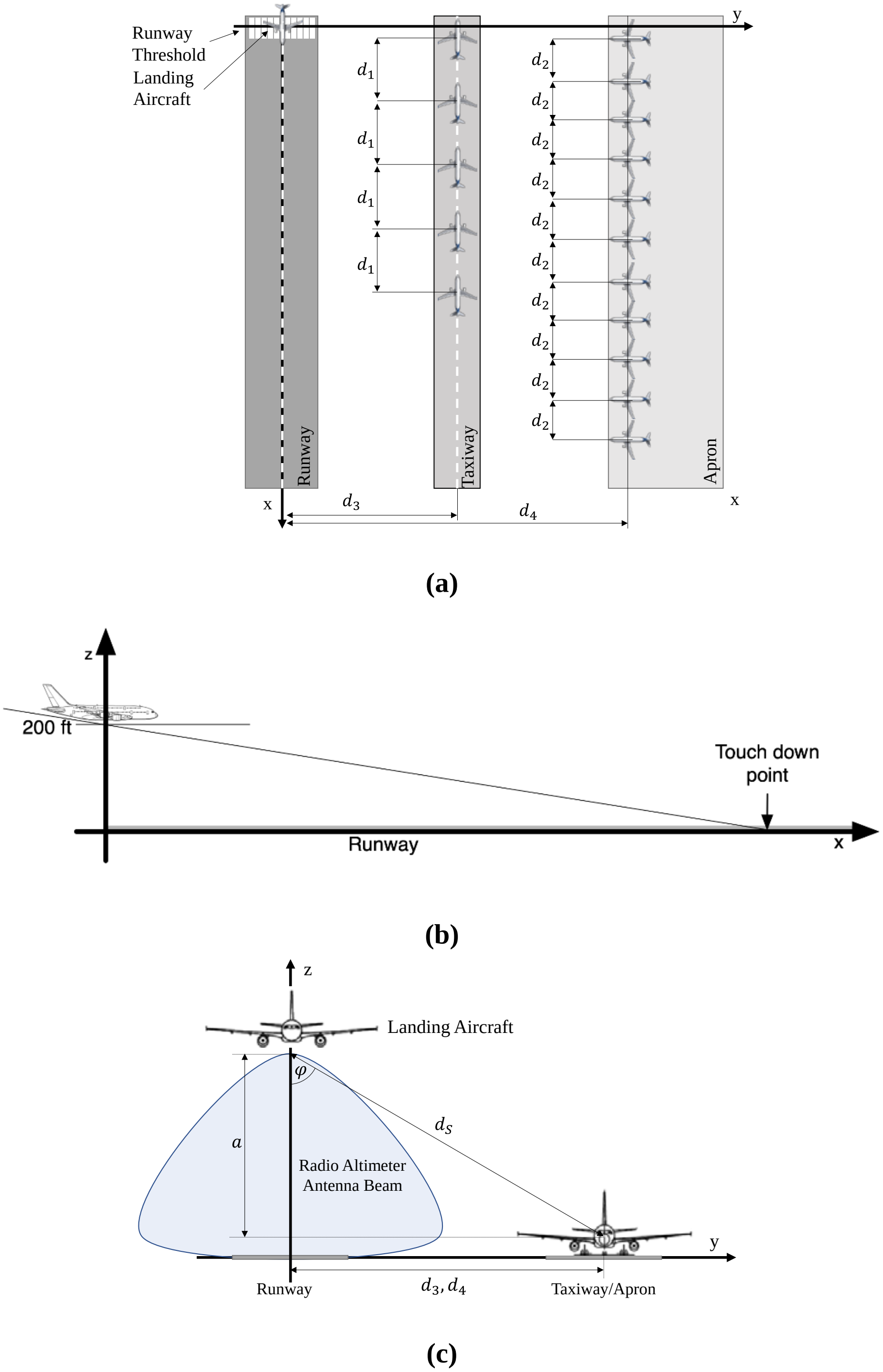

Figure A-2: Worst-Case Landing Scenario Geometry Diagrams

(a) Distribution of aggressor aircraft on taxiway and apron, (b) victim aircraft 200 ft above runway approaching the touchdown point, (c) vertical and lateral separation of victim and aggressor aircraft.

The worst-case aggregate FMCW interference power at the victim RA is determined assuming that the aircraft on the ground in the WCLS geometry are equipped with RAs that transmit at one watt average power and with each aircraft having a triplex RA installation. These 48 individual FMCW emission sources sum incoherently at the victim altimeter input, and thus the path loss between the aggressor Tx antennas and the victim Rx antenna was calculated assuming that all Tx and Rx antennas are at the geometric center of the aircraft, a single specular bounce off the tarmac, and a simple free-space propagation model, taking into account the antenna patterns of the aggressor Tx and victim Rx antennas. Table A-2 shows the path loss for each of the 16 aggressor aircraft, where T1–T5 are the aircraft on the taxiway as indicated in Figure A-2(a) with T1 at the top of the figure and A1–A11 are the aircraft on the apron with A1 similarly at the top of the figure, sorted in order of increasing path loss.

Table A-2: Path Losses Between Victim and Aggressor Aircraft in the WCLS

WCLS Aircraft	Computed Path Loss (dB)
T1	87.93
T2	112.45
A1	118.45
T3	132.81
A2	141.33
T4	142.81
T5	147.68
A3	160.09
A4	169.12
A5	173.25
A6	177.77
A7	180.43
A8	182.22
A9	184.74
A10	187.19
A11	187.98

The AVSI experimental apparatus was limited to 16 VCOs, 2 for own-ship signals (see Section 7.1) and 14 for off-board signals. VCOs 3–16 were configured subject to the constraints of the experimental apparatus to present the highest aggregate interference at the AUT Rx input. This represents triple installations on aircraft T1, T2, A1, and T3 and a dual installation on aircraft A2. Chirp rates and bandwidths were set to match different commercial RA models that have a nominal output power of one watt. Each VCO has a nominal output power of 4 dBm, and combinations of fixed and programmable attenuators were used to set the interference power at the AUT Rx input according to the values in Table A-3. The WCLS aggregate FMCW interference power at the Rx input of the AUT from VCOs 3–16 was thus -54.2 dBm.

Table A-3: WCLS VCO Settings

VCO	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**units**
Output Power	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	dBm
Fixed Attenuation	-18	-18	0	0	0	0	0	0	0	0	-23	-23	0	0	0	0	dB
Programmable Atten.	n/a	n/a	-56	-56	-26	-26	-26	-26	-26	-26	-26	-26	-49	-49	-49	-49	dB
Other Circuit Losses	-16	-16	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40	dB
Power at RA Rx	**-30**	**-30**	**-92**	**-92**	**-62**	**-62**	**-62**	**-62**	**-62**	**-62**	**-85**	**-85**	**-85**	**-85**	**-85**	**-85**	dBm
Sweep Repetition Rate			143	111	133	133	133	118	118	118	111	129	129	129	143	143	Hz
Sweep BW			133	131	131	124	132	135	132	132	124	130	129	131	131	132	MHz
Sweep Waveform			/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/\/\/	/|/|/|	/|/|/|	/|/|/|	/\/\/	/\/\/	

A.2.7 Simulation of 5G Interference Sources

As described in Section 7.5, two types of potential 5G signals were simulated: the fundamental emissions in the 3.7–3.98 GHz frequency band and spurious emissions in the 4.2–4.4 GHz frequency band. To accommodate the differences in these signals and to provide fidelity in the simulation of the 5G emissions, a Rohde & Schwarz SMW200A vector signal generator (VSG) configured with the SMW-K144 5G NR and SMW-K62 software options was used to generate 3GPP-compliant 5G NR test waveforms between 3.7–3.98 GHz and additive white Gaussian noise (AWGN) signals between 4.2–4.4 GHz to simulate 5G fundamental emission and 5G spurious emissions, respectively.

A.2.7.1 5G Fundamental Emissions in the 3.7–3.98 GHz Band

The Rohde & Schwarz SMW-K144 5G NR software provides a full library of 3GPP-compliant test models. The waveform used for 5G fundamental emission testing, as described in Section 7.5.1, was the 5G NR Frequency Range 1 (FR1) test model 1.1 (NR-FR1-TM1.1), which is an Orthogonal Frequency-Division Multiplexing (OFDM) waveform using Quadrature Phase-Shift Keying (QPSK) subcarrier modulation and 30 kHz subcarrier spacing. The bandwidth was set to 100 MHz and thresholds were determined for three center frequencies (3.75, 3.85, and 3.93 GHz) providing full coverage of the frequency band proposed in the FCC Report and Order [5]. Previous AVSI testing had reported thresholds measured using 100 MHz wide OFDM signals configured with only 52 subcarriers using Binary Phase-Shift Keying (BPSK) modulated random data. While both waveforms were OFDM, use of the NR-FR1-TM1.1 waveform in the testing described herein provides greater fidelity in the simulation of possible 5G fundamental emissions.

The intent of the 5G interference tolerance testing is to determine interference power thresholds at which RA performance is measurably affected, and since the response of the RA receivers to RF signals inside the 4.2–4.4 GHz band is significantly different to the response from signals outside the band, the experimental apparatus was configured with a band-stop filter between the 5G signal source and the AUT Rx input to separate the effects from the two types of emissions. The filter response shows non-zero attenuation in the 3.7–3.98 GHz frequency band (see Section A.3.1), thus the filter's frequency-dependent insertion loss must thus be considered when deriving the interference power threshold at the AUT Rx input from the commanded power output from the VSG. The necessary compensation was determined by measuring the 100 MHz channel power at the VSG output and also at the AUT Rx input for each of the 3.75 GHz, 3.85 GHz, and 3.93 GHz center frequencies. These compensation values are added to the attenuation measured without the filter in place to determine the 5G emission power at the AUT Rx input. Table A-4 summarizes the compensation values rounded to the nearest dB.

Table A-4: Band-Stop Filter Correction Values for 5G Fundamental Emissions

Center Frequency	Filter Correction Value
3.75 GHz	1 dB
3.85 GHz	2 dB
3.93 GHz	5 dB

A.2.7.2 5G Spurious Emissions in the 4.2–4.4 GHz Band

Section 7.5.2 describes that a suitable waveform for simulating 5G spurious emissions is an

AWGN signal of sufficient bandwidth to cover the full receive bandwidth of the AUT. The Rohde & Schwarz SMW200A VSG configured with the SMW-K62 software option used to generate the AWGN waveform for testing of the interference tolerance thresholds in the 4.2–4.4 GHz band was limited to a maximum bandwidth of 160 MHz, which was sufficient to cover the maximum receive bandwidth of all RAs tested. The band-stop filter was removed and the VSG configured to produce a 160 MHz AWGN signal centered at 4.3 GHz for 5G spurious emission threshold measurements.

A.2.8 Data Acquisition and Experiment Control

The AVSI test apparatus employed computer-controlled automation to implement the test procedures described in Section A.3 and to collect data from the AUT. A laptop computer (PC) was connected to the VSG via Ethernet. Custom Python software was used to issue SciPy commands from the PC to the VSG to control the RF output state, including output power, waveform, bandwidth, and center frequency. Commands issued to the VSG that changed the RF output state of the VSG were time stamped and logged along with the RF output state data. The AUT was not under computer control but instead had to be manually powered up and allowed to warm up prior to running any tests.

For RAs with ARINC 429 digital output, the ARINC output was connected to a Ballard USB 429 ARINC 429 to USB interface, which was connected to the PC’s USB input. Ballard Co-Pilot software was used to control the interface and acquire ARINC 429 data. The Co-Pilot software ran asynchronously with the Python code and timestamped ARINC 429 altitude data was stored in a separate file. The timestamped VSG output state data and the timestamped altitude data were then post-processed to correlate VSG stimuli to the AUT response.

A.3 AVSI Test Procedures

A.3.1 Calibration and Characterization Tests

The attenuation in all RF signal paths, including the simulated altitude loop, the paths from the VCOs to the radar altimeter receiver input, and the path from the VSG to the radar altimeter receiver input, was calibrated using a network analyzer.

In addition, to characterize the spurious output of the VSG in the 4.2–4.4 GHz band, several channel power measurements were made across this whole band using a Rohde & Schwarz FSV7 spectrum analyzer while the VSG was configured for the 5G fundamental emissions NR-FR1-TM1.1 waveform in the 3.7–3.98 GHz band. These measurements were made at the RF port normally connected to the radar altimeter receiver input and without the band-stop filter in place in order to maximize the measurement sensitivity. At low VSG output power levels, the spurious levels in the 4.2–4.4 GHz band were below the noise floor of the spectrum analyzer, which was found to be -90 dBm/MHz[49], based on a measured channel power of -67 dBm across the 200 MHz bandwidth. This measurement is shown in Figure A-3.

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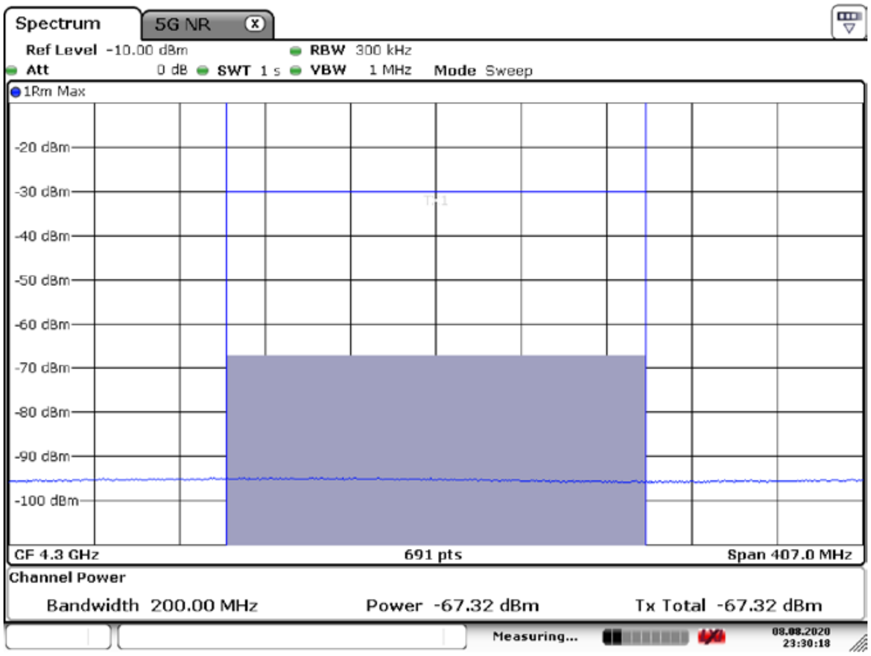
[49] This measurement is consistent with the datasheet specification for the Rohde & Schwarz FSV7 spectrum analyzer, which lists a maximum displayed average noise level of -88 dBm/MHz, and a typical level of -91 dBm/MHz [48].



Ref Level -10.00 dBm
Att 0 dB SWT 1 s RBW 300 kHz VBW 1 MHz Mode Sweep

CF 4.3 GHz 691 pts Span 407.0 MHz

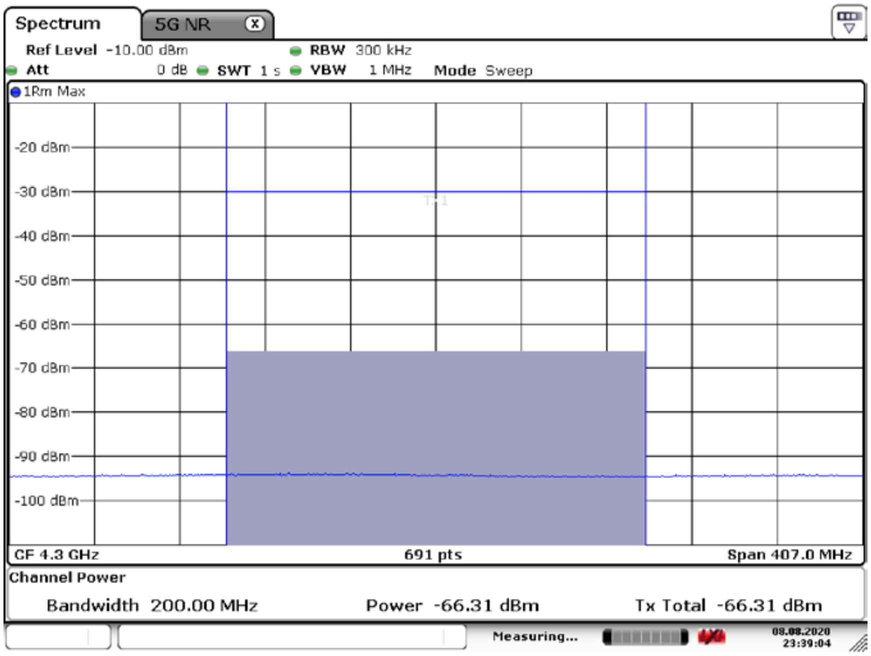
Channel Power
Bandwidth 200.00 MHz Power -67.32 dBm Tx Total -67.32 dBm

08.08.2020
23:30:18

Date: 8.AUG.2020 23:30:19

Figure A-3: Spurious Channel Power Measurement with Low VSG Output Power

Increasing levels of VSG output power were tested until the measured channel power rose to 1 dB above the spectrum analyzer noise floor, corresponding to an average spurious level of -89 dBm/MHz across the 4.2–4.4 GHz band. This occurred with a VSG output power of +5 dBm, and the measurement is shown in Figure A-4.



Ref Level -10.00 dBm
Att 0 dB SWT 1 s RBW 300 kHz VBW 1 MHz Mode Sweep

CF 4.3 GHz 691 pts Span 407.0 MHz

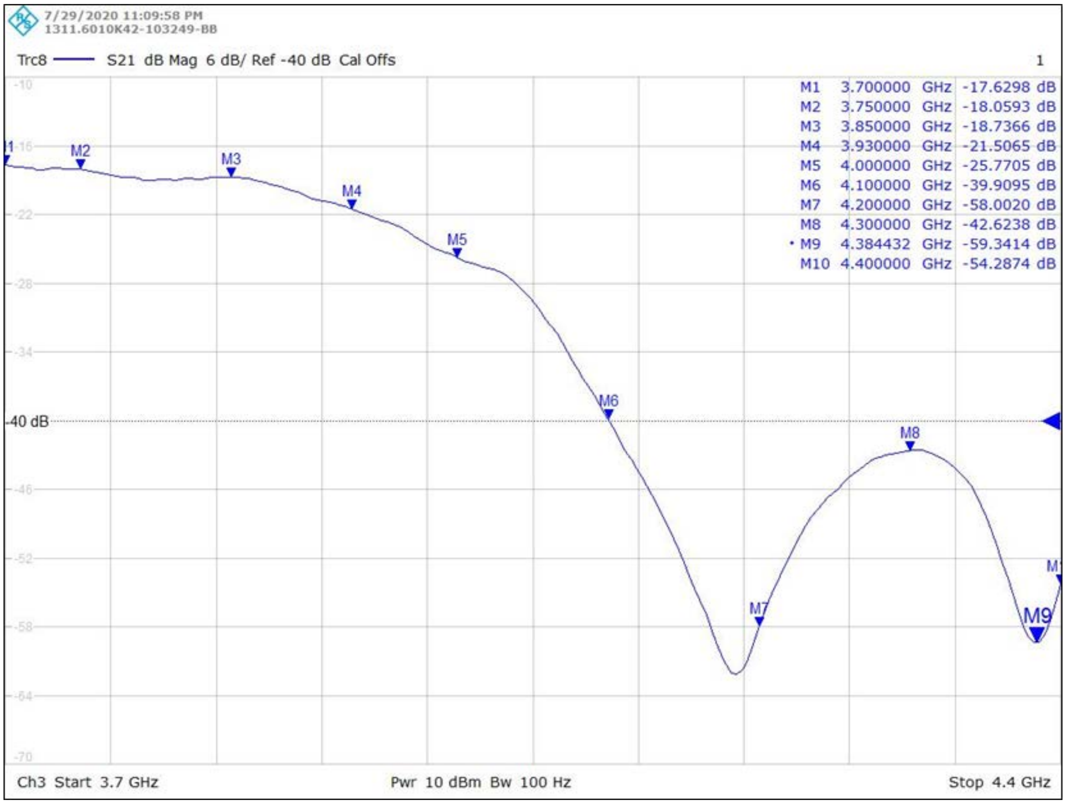
Channel Power
Bandwidth 200.00 MHz Power -66.31 dBm Tx Total -66.31 dBm

08.08.2020
23:39:04

Date: 8.AUG.2020 23:39:05

Figure A-4: Spurious Channel Power Measurement with +5 dBm VSG Output

The band-stop filter was also characterized using a network analyzer to evaluate the stopband attenuation. The measured filter response is shown in Figure A-5, which illustrates the S21 magnitude (i.e. insertion loss) measured with the network analyzer between the VSG output and the AUT Rx input.



```
  M1  3.700000 GHz -17.6298 dB
  M2  3.750000 GHz -18.0593 dB
  M3  3.850000 GHz -18.7366 dB
  M4  3.930000 GHz -21.5065 dB
  M5  4.000000 GHz -25.7705 dB
  M6  4.100000 GHz -39.9095 dB
  M7  4.200000 GHz -58.0020 dB
  M8  4.300000 GHz -42.6238 dB
• M9  4.384432 GHz -59.3414 dB
  M10 4.400000 GHz -54.2874 dB
```

Figure A-5: Band-Stop Filter Insertion Loss from 3.7 to 4.4 GHz

A.3.2 Interference Tolerance Threshold Tests

A single experiment consisted of increasing the 5G interference power in steps of 1 dBm while the reported altitude was continuously recorded. Each power step included a period during which the RF output was turned off at the VSG, followed by a period during which the RF power at the VSG was turned on. The initial period with the RF power turned off provided the baseline height reading used as a reference to measure the effects of interference with the interference RF power turned on. Altimeters were turned on prior to testing to allow them sufficient time to stabilize.

The reported altitude was recorded using the Ballard Co-Pilot software, which included an independent time stamp generated by the bus converter. The software stored the time-stamped readings in a database. This was subsequently post-processed as described in Section A.2.8. Measured attenuation values were used to scale the interference power output by the VSG to that at the receive port of the RA.

A typical "power sweep" plot obtained by this process is shown in Figure A-6 for a typical interference signal. This plot shows the reported altitude (blue trace corresponding to values on left vertical axis) superimposed on the time-varying interference power (green trace corresponding to values on right vertical axis). It also shows the standard ±2% error limits (red horizontal lines) defined in ARINC 707 [47]. Data points at which the altimeter was unable to reliably report a computed altitude were captured as red points along the blue trace when they occurred. These unreliable altitude readings are output on the ARINC 429 bus along with an error flag that indicates No Computed Data (NCD) or indicated by an equivalent discrete output signal. Criteria for reporting NCD can vary with the specific signal processing in different altimeters, but is generally indicative of a condition in which the signal-to-noise ratio of the received FMCW signal is insufficient to compute an altitude with the required level of confidence.

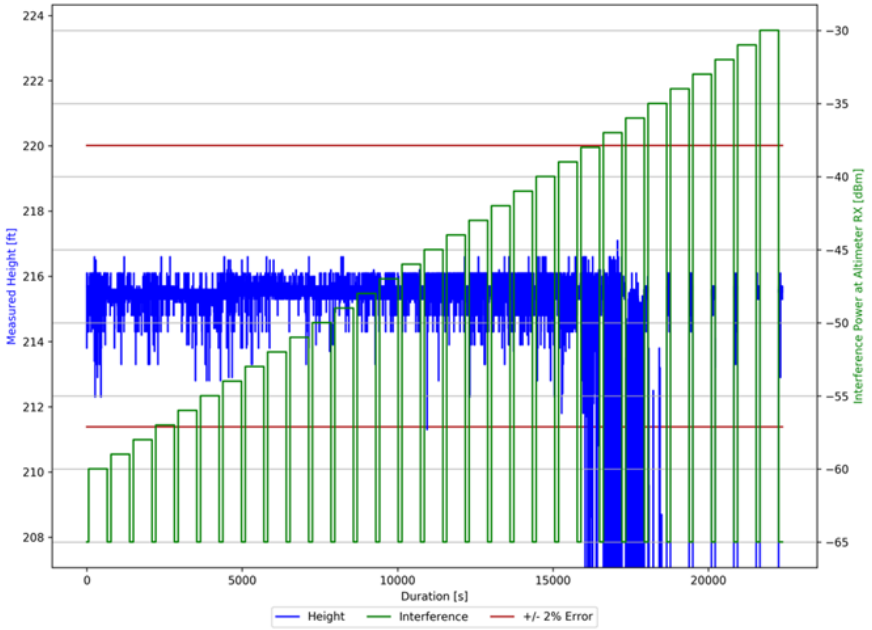


Figure A-6: Typical Power Sweep Plot

A power sweep was repeated for each center frequency that was tested and all results recorded in a single data base for post-processing.

A.3.2.1 5G Fundamental Emissions

All 5G fundamental emissions measurements were performed using a 100 MHz NR-FR1-TM1.1 waveform at three center frequencies (3.75, 3.85, and 3.93 GHz) under computer control. The AUT was allowed to settle for 30 seconds after each change in center frequency before starting a corresponding power sweep. All measurements were made with the band-stop filter in the RF circuit as described in Section A.2.7.1.

A.3.2.2 5G Spurious Emissions

All 5G spurious emissions measurements were performed using a 160 MHz AWGN signal centered at 4.3 GHz under computer control. All measurements were made without the band-stop filter in the RF circuit as described in Section A.2.7.2.

A.4 Radar Altimeter Interference Tolerance Threshold Criteria

The reported altitudes were statistically analyzed to determine the point at which the AUT performance became unacceptable. The criteria that were used to determine this point included at least one of the following conditions:

1. A mean height error greater than 0.5%,

$$\frac{|Average\ Height(RF\ on) - \ Average\ Height(RF\ off)|}{Average\ Height(RF\ off)} * 100\% > 0.5\%$$

   where $Average\ Height(RF\ on)$ and $Average\ Height(RF\ off)$ are the mean height values measured during the period where the 5G RF power at VSG is turned on and off.

2. Fewer than 98% of all data points in the RF power on interval fall within the 2% or 1.5 foot limits specified by ARINC 707 [47],

$$H_{1\%} < (Average\ Height(RF\ off) - 2\%) \quad \text{or}$$

$$H_{99\%} > (Average\ Height(RF\ off) + 2\%)$$

   (where $H_{1\%}$ and $H_{99\%}$ are defined as 1st and 99th percentiles, i.e. the values for which 1% and 99% of all heights reported during the measurement interval fall below that height)

3. Any height reading labeled NCD.

These criteria provided a uniform evaluation of the effects of interference on RA performance regardless of the interference waveform.

Appendix B TWG-3 INFORMATION EXCHANGE

B.1 Question Responses and Data Provided by Aviation to Mobile Wireless Industry

The exchange of technical information between the mobile wireless and aviation industries within TWG-3 is presented here in a question and answer format. Note that the information exchange conducted within TWG-3 was subject to the agreement that the use of the information in technical analyses would not reflect any judgment or support of the findings of such analyses.

In this section, the questions were issued by the mobile wireless industry experts, and the answers were provided by the aviation industry experts. For additional clarity, the questions provided by the mobile wireless industry experts are shown with red text, and the answers provided by the aviation industry experts are shown with blue text. Each of the questions and answers are marked with the date on which they were submitted.

Question 1 (June 16, 2020):

Can you provide an altimeter link budget, including the following:

a. Altimeter instantaneous transmit bandwidth: _____ MHz

b. Altimeter peak antenna gain: _____ dBi

c. Loop loss versus altitude:

    i. 200 ft: _____ dB

    ii. 1000 ft: _____ dB

    iii. 2000 ft: _____ dB

d. Altimeter receiver noise figure: ____ dB

e. Altimeter SINR requirement: ____ dB

f. Altimeter instantaneous receive bandwidth: ____ MHz

g. Cable loss: _____ dB

Answer 1 (July 1, 2020):

We have a few general comments on "link budgets" as they pertain to radar altimeters. In the context of radar systems this is more commonly referred to as loop sensitivity analysis, although the principles are similar. First, please refer to the Background section AVSI Preliminary Report on the Behavior of Radio Altimeters Subject to Out-Of-Band Interference, available here, for a high-level overview of the design and operation of FMCW altimeters.

Second, note that the loop sensitivity performance of FMCW altimeters may not be dictated purely by the thermal noise in the receiver across the full altitude range. Because there is always some source of RF leakage directly from the transmitter into the receiver (usually due to imperfect isolation between the TX and RX antennas), and FMCW altimeters transmit continuously with 100% duty cycle, a transmit leakage signal will be continuously present in the receiver with very little propagation delay. This transmit leakage signal will further include a phase noise skirt. As the transmit leakage signal is mixed with the receiver LO, which is itself an undelayed copy of the transmit signal, a spectral impulse at near-zero beat frequency is observed in the baseband section of the receiver. Further, the phase noise skirt of the transmit signal is superimposed on this impulse, leading to received energy throughout the full IF bandwidth. Since reflected signals received from farther ranges are generally much weaker, the baseband section of the receiver typically includes a frequency response that applies more gain at higher frequencies, and thus while the fundamental component of the transmit leakage signal may be attenuated, the spectral content of the phase noise skirt at large offset frequencies may be amplified. Since the receiver LO signal is the same as the transmit signal, the phase noise is highly correlated with that of the transmit leakage signal, and thus some rejection of the phase noise is achieved in the mixing process. However, the correlation factor depends on the time delay of the transmit leakage path, as well as on beat frequency. At high frequencies, corresponding to high altitudes, the net effect may be that the receiver noise floor is set not by thermal noise (i.e. receiver noise figure), but instead by the residual phase noise of the transmit leakage signal. Further, these transmitter phase noise impacts are intrinsic parameters of the design trade space for FMCW radar altimeters, and thus may not be fully eliminated from all designs.

As a first approximation, it is reasonable to base loop sensitivity analysis upon receiver thermal noise. However, due to the factors described above, in FMCW radar altimeters the observed sensitivity performance may not agree fully with these results in all conditions. Typically, the transmit leakage phase noise effects may increase the receiver noise floor by up to a few dB, primarily at the highest altitudes. However, this may not be the case for all FMCW altimeters, depending on how they are designed and the characteristics of their installation on a particular aircraft.

a. For pulsed altimeters, the instantaneous transmit bandwidth is dictated simply by the pulse width and pulse envelope shape. For examples of this bandwidth from several different commercially-deployed altimeter models, refer to the Pulsed-type listings in Table 1 (p. 12) and Table 2 (p. 15) of Recommendation ITU-R M.2059-0, Annex 2. Both the pulse width and the 3 dB emission bandwidth are provided. Note that any analysis based on M.2059 should consider all altimeter models contained therein, and conclusions should be based upon the most conservative or worst case among these results.

   For FMCW altimeters, which are more common in commercial use than pulsed altimeters, the *instantaneous* transmit bandwidth is generally very narrow—less than the resolution bandwidth or equivalent noise bandwidth of the receiver—and may be treated as such in loop sensitivity analysis. The full swept bandwidth of the FMCW transmitter will typically be anywhere from 100 MHz to 180 MHz. For examples of this swept bandwidth from several different commercially-deployed altimeter models, refer to the FMCW-type listings in the same tables referenced from M.2059 above. The “Chirp bandwidth excluding temperature drift” row gives the most direct indication of the total swept transmit bandwidth.

b. Antennas used with both pulsed and FMCW commercial radar altimeters will typically have a boresight gain ranging from 9 to 11 dBi, although in some cases this may be as low as 6 dBi or as high as 13 dBi. Further, the full half-power beamwidth of such antennas is typically between 45° and 60° (i.e. ±22.5° to ±30° from the boresight). For examples of the peak gain and beamwidth of the antennas used with several different commercially-deployed altimeter models, refer to the same tables referenced from M.2059 above.

   Although there may be a range of antenna gain and radiation pattern characteristics used with radar altimeters as indicated in M.2059, a reasonable simplification is to assume the same characteristics that have been used in past work by AVSI, and apply these to all altimeter models. For reference, these characteristics include a boresight gain of 10.8 dBi and a full half-power beamwidth of 60°.

c. Loop loss will vary based on installed RF cable losses, TX and RX antenna gains and beamwidths, pulse width or effective range resolution (as applicable), and terrain reflectivity characteristics in addition to the height above the terrain. In the testing conducted to-date at AVSI, the assumptions used to determine loop losses have been 6 dB of total cable loss (3 dB in the TX path and 3 dB in the RX path), 10.8 dBi antennas with 60° beamwidth, beamwidth-limited conditions for all FMCW altimeters, and a terrain reflection coefficient of 0.01. This reflection coefficient is the minimum specified in the radar altimeter Minimum Operational Performance Standards (MOPS), EUROCAE ED-30, corresponding to the highest loop losses at which the altimeters must meet their performance requirements. The DO-155 external loop loss curves below are calculated assuming a reflection coefficient of 0.006 (a minimum value which has been superseded by the introduction of the ED-30 MOPS), resulting in loop losses that are 2 dB higher than with a reflection coefficient of 0.01. Therefore, the curves are adjusted downward by 2 dB, and then upward by 6 dB to account for the cable loss assumptions. This leads to the following total loop loss values (referenced to the TX and RX ports on the altimeter) used by AVSI for testing of FMCW altimeters:

   i. **96 dB** at 200 ft altitude

   ii. **110 dB** at 1000 ft altitude

   iii. **116 dB** at 2000 ft altitude

   Simplified methods for estimating loop loss are given in RTCA DO-155, Appendix B. The plot shown below, Figure 5 in this appendix[50], gives the resulting loop loss values for a frequency of 4.3 GHz, antenna gain of 10.8 dBi (linear power gain of G = 12), and antenna beamwidth of 60°. Note that this plot shows **external loop loss** only, which is defined in reference to the TX and RX antenna RF ports. Therefore, it does not include the RF cable losses that are encountered in a radar altimeter installation on an aircraft. To compute the **total loop loss** in reference to the TX and RX ports on the altimeter, the total cable losses must be added to the external loop loss.

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[50] From DO-155, *Minimum Performance Standards-Airborne Low Range Radar Altimeters* ©RTCA, 1974. Used with permission. All Rights Reserved.

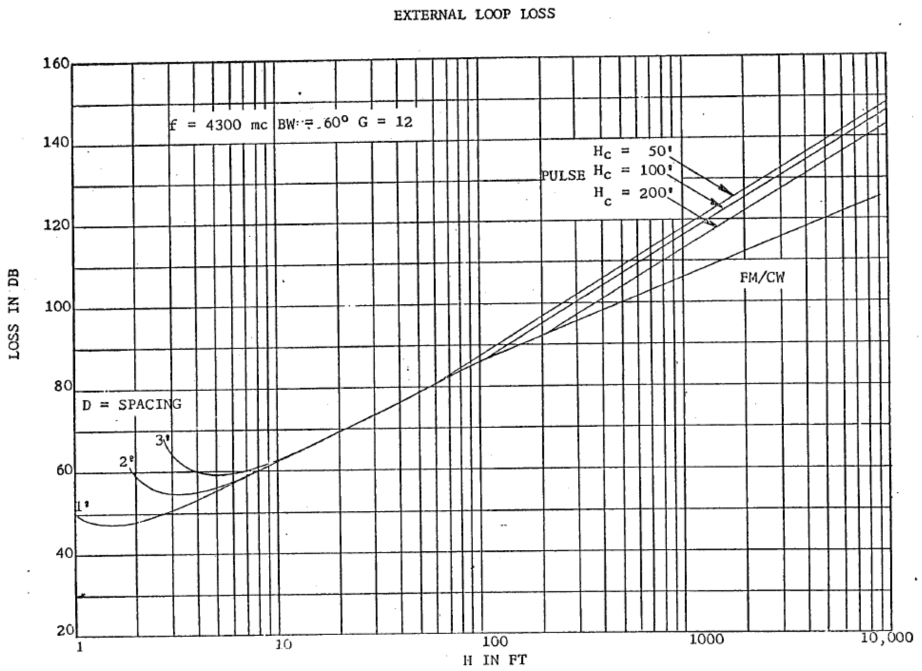

FIGURE 5

There are four separate loop loss curves shown on the plot, corresponding to a beamwidth-limited case (the curved denoted “FM/CW”) and pulse-limited cases for three different pulse widths. In monostatic radar systems, the loop loss associated with the return signal from a point target increases by 40 dB per decade of distance between the radar and the target, due to the inverse-square law acting both on the signal propagating from the radar to the target, and on the signal propagating from the target back to the radar. In radar altimeters, the desired return signals come not from point targets but from a large distributed area of terrain. The altimeter may therefore integrate the received signal throughout some or all of this area to increase the signal level (and effectively decrease the loop loss). In a beamwidth-limited case, it is assumed that the altimeter will integrate the return signal energy throughout the entire antenna illumination footprint on the terrain. The integration of this full area leads to the net effect of a 20 dB increase in loop loss per decade of distance between the radar and the terrain (i.e. altitude), rather than the 40 dB per decade response from a point target. In a pulsed altimeter, the portion of the antenna illumination footprint over which the return signal may be integrated is effectively limited by the pulse width. The transmitted pulse will illuminate the terrain beginning at nadir and spreading outward, but the extent of this spread for a single pulse may be less than the full illumination footprint. As a result, the rate of change of loop loss versus altitude is somewhere between that of the point target case and that of the beamwidth-limited case. The value of 30 dB of loop loss per decade of altitude is typically used.

In DO-155, the pulse-limited loop loss curves are determined by initially using the beamwidth-limited curve at low altitudes, and altering the response from 20 dB/decade to 30 dB/decade above some critical height. This critical height is computed based on the pulse width and antenna gain, as follows:

$$H_c = \frac{c\tau G}{4}$$

In this formula, c is the speed of light, τ is the pulse width in seconds, and G is the linear antenna gain (i.e. absolute power ratio, rather than gain in dBi).

Note that whether or not a particular radar altimeter design operates in a beamwidth-limited or pulse-limited regime depends on the specific design characteristics of that altimeter. Depending on the design, it is possible for a FMCW altimeter to be effectively pulse-limited (in which case it is not truly limited by a pulse width, but rather by an effective range resolution or gate width), or for a pulsed altimeter to be effectively beamwidth-limited (even above the critical height computed above). However, as a first approximation it is reasonable to assume that FMCW altimeters typically contend with beamwidth-limited loop loss characteristics, and pulsed altimeters typically contend with pulse-limited loop loss characteristics.

d. The noise figure achieved in both FMCW and pulsed radar altimeter receivers typically ranges from 6 to 10 dB. For examples of the noise figure of several different commercially-deployed altimeter models, refer to the same tables referenced from M.2059 above.

e. The typical detection SNR in both FMCW and pulsed radar altimeter receivers is around 10 dB, although values of anywhere from 6 to 13 dB are common. The SNR required for signal detection is not explicitly given in the tables in M.2059.

f. The IF bandwidth of FMCW altimeter receivers typically ranges from a few hundred kHz up to a few MHz. The IF bandwidth of pulsed altimeter receivers typically ranges from a few MHz up to a few tens of MHz. For examples of the IF bandwidth of several different commercially-deployed altimeter models, refer to the same tables referenced from M.2059 above.

Further, note that the full IF bandwidth of altimeter receivers typically does not determine the receiver noise bandwidth. More often, the noise bandwidth is dictated by the resolution bandwidth or detector bandwidth of the receiver, which is much narrower than the full IF bandwidth—typically ranging from about 100 Hz up to a few kHz. This is particularly true for FMCW altimeters.

RF cable losses will vary based on the specific radar altimeter installation on a given aircraft. Total round-trip cable losses will typically be around 5-7 dB, but may be as high as 10-12 dB. In some installations, either on small airframes or with the use of low-loss cables, the total cable losses may be as low as 2-3 dB. For examples of the cable losses in the installations of several different commercially-deployed altimeter models, refer to the same tables referenced from M.2059 above.

As noted above, in previous AVSI testing and studies a representative cable loss value of 6 dB (3 dB in the TX path and 3 dB in the RX path) has been assumed.

Question 2 (June 16, 2020):

Altimeter antennas provide a peak response within 4200-4400 MHz.

a. What is the frequency response of altimeter antennas below 4200 MHz?

b. What are the antenna patterns for frequencies below 4200 MHz?

Answer 2 (July 1, 2020):

We are coordinating amongst the radar altimeter manufacturers to obtain relevant antenna measurements for multiple different antenna models which are representative of what is commonly used in commercial radar altimeter applications.

a. The following information represents the data that the aviation industry currently considers in its analysis, while we wait for additional measured data to become available. This data is based on preliminary antenna frequency response measurements obtained by AVSI for use in past analysis and testing.

    i. At boresight, the frequency-dependent rejection factor is 0 dB at 4.2 GHz, and increases linearly versus frequency to 5 dB at 3.7 GHz. That is, signals received at 3.7 GHz are attenuated by 5 dB relative to signals received in the 4.2-4.4 GHz band.

    ii. At 30° off boresight, the frequency-dependent rejection factor is 0 dB at 4.2 GHz, and increases linearly versus frequency to 1.5 dB at 3.7 GHz. That is signals received at 3.7 GHz are attenuated by 1.5 dB relative to signals received in the 4.2-4.4 GHz band.

   Because most interference scenarios between potential 5G emissions sources in the 3.7-3.98 GHz band and radar altimeters will involve coupling into the altimeter receive antenna at incidence angles far from boresight, AVSI concluded from this data that the antenna itself cannot be relied upon as a significant source of frequency-dependent rejection. The analysis efforts underway within SC-239 will be reevaluating this conclusion as necessary once more detailed data becomes available.

   Work is ongoing within the aviation industry to obtain more complete data. We anticipate being able to provide updated antenna frequency response measurements across the 3.7-3.98 GHz band for multiple antenna models no later than July 15th.

b. As a first approximation, it is suggested that the altimeter antenna pattern in the 3.7-3.98 GHz band be estimated by taking the radiation pattern at 4.3 GHz, and adding the frequency-dependent rejection of the antenna (that is, assuming the same pattern shape, but with the gain uniformly decreased based on the antenna frequency response). To determine the antenna radiation patterns at 4.3 GHz, the method described in Report ITU-R M.2319-0, Annex 3 can be used (see Equation A-3.6 at page 28). This is the same approach currently used by the aviation industry to produce representative antenna patterns while we wait for the new measured data to be made available.

Work is ongoing within the aviation industry to obtain more complete data. We anticipate being able to provide antenna pattern measurements taken at 3.85 GHz for multiple antenna models no later than July 15th.

Question 3 (June 16, 2020):

We understand that helicopters and aircraft use the 4 GHz altimeter band.

a. Do UAVs also use 4 GHz, or other bands?

b. Or does the UAV altimeter operating band vary by size of UAV?

Answer 3 (July 1, 2020):

There is an Aeronautical Radionavigation Service (ARNS) allocated globally to radar altimeters in the 4.2-4.4 GHz band by the ITU. In the United States, such altimeters are often used on general aviation aircraft operating under Federal Aviation Regulations Part 91 rules. Further, many commercial aircraft operations under Part 121 domestic or flag air carrier rules, as well as all commercial helicopter operations under Part 135 rules, *require* at least one FAA-approved radar altimeter.

a. All current FAA-approved radar altimeters use the 4.2-4.4 GHz band. This exact band is not explicitly required, but the MOPS (EUROCAE ED-30) specify that the altimeter must operate “within a frequency band allocated for the operation of airborne radio altimeters as provided in the International Telecommunications Union regulations.” This could potentially be interpreted to include other ARNS bands, but that has not previously been done. However, it is highly unlikely that the FAA would grant approval under Technical Standard Order C87a (TSO-C87a), which governs commercial radar altimeters, to any altimeter which operates outside of the 4.2-4.4 GHz band, even if a different ARNS allocation is used.

   There are other non-FAA-approved commercially available radar altimeters which operate in other bands, such as the 24.125 GHz ISM band, and the 77 GHz band (although note that use of the 77 GHz band from an airborne platform is forbidden in the United States). However, such altimeter models are very low-end, consumer-grade devices that are not suitable for use on commercial or civil aircraft. They may be used in hobbyist-type applications such as on consumer drones (Part 107) or model aircraft (Part 103). In these applications the radar altimeter is not to be considered a critical safety-of-flight sensor, as it is in other use cases.

b. Concerning Unmanned Aircraft Systems (UAS): consumer drones and other sUAS operated under Part 107 rules typically do not use radar altimeters. However, UAS operated commercially under Part 135 rules require FAA-approved radar altimeters, unless an exemption is granted by the FAA.

Question 4 (June 16, 2020):

A receiver's overload threshold depends on the desired signal level, because the low noise amplifier in the receiver decreases its gain when the desired signal is strong, and increases gain when the desired signal is weak. As a result, the receiver is most susceptible to overload from an out-of-band strong signal when the desired signal is weakest, and is more robust to out-of-band signals when the desired signal is strong. What is the altimeter receiver overload threshold for each altimeter model as a function of altitude:

a. 200 ft

b. 1000 ft

c. 2000 ft

(we are assuming the same altitude thresholds as AVSI in their testing, given that some altimeters do not state a supported altitude above 2500 ft; if higher altitudes should be included, please provide).

Answer 4 (July 1, 2020):

For examples of the receiver overload threshold of several different commercially-deployed altimeter models, refer to the same tables referenced from M.2059 above. These overload thresholds are not specified versus altitude, and for the reasons below it cannot be determined how (or if) the overload threshold will vary across altitude for the altimeter models described in M.2059. Therefore, initial analysis should assume that the thresholds specified in M.2059 must be met at all altitudes. Ongoing testing by AVSI and analysis by SC-239 may be able to provide a better characterization of interference tolerance of commercial radar altimeters versus altitude, and this data will be shared with TWG-3 as necessary. However, note that it is not feasible in the AVSI testing to isolate receiver overload thresholds from the overall interference tolerance observed.

Note that not all radar altimeter designs utilize Automatic Gain Control (AGC) as described in the question. That is, the receiver gain may not necessarily be adjusted based on received signal strength. Some altimeter designs may use AGC in this manner ahead of the mixer (i.e. at the LNA), some altimeter designs may use AGC after the mixer (i.e. at IF or baseband), some may use both, and some may use no AGC at all, maintaining a fixed receiver gain at all times. In the case of the final option (no AGC), the receiver obtains the full dynamic range needed to track return signals across all altitudes and terrain types using some form of Sensitivity Time Control (STC). In a pulsed altimeter, this would entail increasing the receiver gain over time after each pulse is transmitted to ensure that signals received from farther ranges are amplified more. In a FMCW altimeter, the implementation may be even simpler—since at baseband (after the homodyne downconversion) there is a linear relationship between frequency of the received signals and the radar range of these signals, a high-pass filter response with an increasing gain slope versus frequency can be used to apply the necessary amplification of signals from farther ranges.

In general, even with STC a pulsed altimeter will often still require some form of AGC to achieve the required dynamic range. However, some FMCW altimeter designs will use no AGC at all if the instantaneous dynamic range of the receiver is sufficient to handle the signal strength variation caused by changes in terrain reflectivity and aircraft pitch/roll (which changes the antenna gain in the nadir direction towards the terrain), and the high-pass filter response of the baseband stages is sufficient to compensate for range losses. The total signal strength variation encountered due to the terrain and aircraft attitude factors is typically 30-40 dB at a given altitude. The additional signal strength variation due to range losses across the functional measurement range of radar altimeters is typically 60-70 dB.

Question 5 (June 16, 2020):

What is the frequency dependent rejection of each altimeter model outside of the altimeter operating band of 4200-4400 MHz?

Answer 5 (July 1, 2020):

As a first approximation, please refer to the RF selectivity characteristics provided in Table 3 of Annex 3 of M.2059. This is the same receiver frequency-dependent rejection that has been considered in analysis by the aviation industry to-date while we wait for additional measured data to become available from the radar altimeter manufacturers.

We are coordinating amongst the radar altimeter manufacturers to obtain measurements of receiver frequency-dependent rejection of several altimeter models that see widespread commercial use. These particular altimeter models may include some of the models tested by AVSI, but they will not be explicitly identified. Some additional models which have not been tested by AVSI may also be included. We anticipate being able to provide the frequency-dependent rejection data for the altimeter receivers no later than July 15th.

Note that some of the data may be provided as a total combined system, accounting for both the antenna frequency response and the altimeter receiver frequency-dependent rejection. This approach is beneficial since not all altimeter models will be used in practice with all antenna models (and thus applying the worst-case antenna frequency response along with the worst-case receiver frequency-dependent rejection may be overly conservative). Any data provided in this manner will be clearly indicated as such.

Question 6 (June 16, 2020):

Since the desired signal strength plays an important role in whether interference is impactful to receiver function, what level of in-band interference power (meaning interference due to out-of-band 5G emissions within 4200-4400 MHz) could cause errors in altitude reporting for each altitude:

a. 200 ft

b. 1000 ft

c. 2000 ft

Answer 6 (July 1, 2020):

For the general tolerance of radar altimeters to interference within the 4.2-4.4 GHz band, refer to the Receiver Desensitization and False Altitude criteria described in Annex 3 of M.2059. Such criteria have been established through the ITU as being the official protection criteria requirements to be used in sharing studies when considering in-band interference against radar altimeters. Note that the definitions given in M.2059 are based on the worst-case interference tolerance, which generally occurs when the altimeter receiver is most sensitive, i.e. at the maximum altitude of its functional measurement range and with a weak return signal from the terrain. As indicated in the question, radar altimeters will generally exhibit improved interference tolerance at lower altitudes and/or when the return signal from the terrain is stronger, such that the receiver is less sensitive. Since the interference tolerance dependency on signal strength is not accounted for directly in M.2059, the AVSI testing has focused explicitly on testing of multiple altitudes throughout the full functional measurement range to better characterize the performance of radar altimeters.

As a first approximation, a reasonable approach is to calculate the interference tolerance thresholds in accordance with the Receiver Desensitization and False Altitude criteria as described in M.2059 for each altimeter model listed therein, and consider this to be directly applicable to the maximum reported altitude of each altimeter (see the row "Range of reported altitude" in Table 1 and Table 2 of Annex 2). Then, the tolerance thresholds may be adjusted for lower altitude cases by accounting for the difference in received signal strength expected based on the applicable loop loss curve versus altitude (e.g. curves calculated in accordance with DO-155, for either beamwidth-limited or pulse-limited cases).

For example, if a particular FMCW altimeter model has an in-band interference tolerance threshold of -100 dBm at a maximum altitude of 8,000 feet, then at an altitude of 200 feet the expected signal strength will be $20\log_{10}\frac{8000}{200} = 32$ dB higher (assuming a beamwidth-limited case, providing a 20 dB change in loop loss per decade of altitude change). Therefore, a simple approximation is that the in-band interference tolerance threshold at 200 feet would also be 32 dB higher, or -68 dBm.

Note that this approach provides an approximation only, and due to various factors the actual observed interference tolerance versus altitude of a given altimeter model may not match this approximation.

Question 7 (June 16, 2020):

Are the altimeter characteristics on commercial aircraft, helicopters, etc. similar or different than altimeters on UAVs/drones? Are the receiver masks and power thresholds similar?

Answer 7 (July 1, 2020):

Refer also to the response to Question 3 regarding usage of radar altimeters on different aircraft types.

In order to be granted TSO approval by the FAA, a radar altimeter must meet the MOPS requirements. The MOPS do include separate performance categories, although this is only applicable to the altitude accuracy requirements, altitude range, and the performance envelope (i.e. aircraft pitch and roll angles, and maximum horizontal and vertical velocities). The MOPS do not specify any requirements for receiver masks or interference tolerance. Therefore, these performance characteristics may vary drastically across radar altimeter models even if they meet the same MOPS performance category.

In general, it is expected that higher-end altimeters targeted towards the commercial air transport market will exhibit the best interference tolerance, lower-end altimeters targeted towards general aviation will exhibit the worst interference tolerance, and altimeters targeted towards the business aviation and regional air transport markets will land somewhere in the middle. However, this will not always hold true, since these specific performance characteristics are not governed by any applicable industry standards or regulatory requirements.

Question 8 (June 16, 2020):

What are the operational scenarios under consideration for evaluating altimeter performance? Are we focusing on the aircraft's final approach and landing, or are we also evaluating cruising altitudes?

Answer 8 (July 1, 2020):

Radar altimeters operate continuously throughout all phases of flight, even when outside of their functional measurement range. Further, erroneous operation of radar altimeters may impact the safe operation of aircraft during any phase of flight. For example, when the radar altimeters in a commercial airliner cruising at 27,000 feet detected a signal reflection from an underflying aircraft and erroneously reported this as an altitude reading, a Ground Proximity Warning System (GPWS) alert was issued to the pilots which required the execution of an abrupt pull-up maneuver, as described in this NTSB incident report. As a result of the unexpected maneuver, two flight attendants suffered serious injuries and another two were minorly injured.

Although erroneous operation of the radar altimeters may have a negative impact on the safe operation of an aircraft during any phase of flight, the criticality of such an occurrence may vary based on aircraft type and operational scenario. The process of assigning criticality levels to all such scenarios is referred to as a Functional Hazard Assessment (FHA), which is completed by the radar altimeter manufacturer as part of the FAA approval process. In all applicable operational scenarios for a given radar altimeter model, each failure mode will be classified as either No Effect, Minor, Major, Hazardous/Severe Major, or Catastrophic. In general, across all operational scenarios which take place within the functional measurement range of the radar altimeter, any undetected erroneous altitude output or unexpected loss-of-track from the altimeter would be considered at least a Major failure condition. Erroneous operation of radar altimeters outside of the functional measurement range can still have an impact to aviation safety, however, as described in the example above. The allowable occurrence rate of each failure mode is determined by the failure condition classification. Major failure conditions must be shown to occur at a rate of no more than 1 x 10^{-5} per flight hour or per event (e.g. a landing sequence), Hazardous/Severe Major failure conditions must be shown to occur at a rate of no more than 1 x 10^{-7} per flight hour or per event, and Catastrophic failure conditions must be shown to occur at a rate of no more than 1 x 10^{-9} per flight hour or per event.

In addition, operational scenarios other than just those applicable to fixed-wing commercial aircraft must also be evaluated. Fixed-wing commercial aircraft typically follow predefined flight paths, particularly for low-altitude operations within the functional measurement range of radar altimeters, such as takeoff and climb-out or approach and landing. This allows for the likelihood of interference from any fixed terrestrial emissions sources (e.g. 5G base stations) to be reduced through proper planning and analysis of the deployment of such emissions sources relative to those flight paths. However, rotorcraft are not similarly restricted in their operations, and thus a much more thorough analysis of the potential for harmful interference is required. Further, all helicopters which operate under Part 135 rules (i.e. all helicopters operating for commercial purposes) are required to have a radar altimeter unless an exemption is granted. Certain use cases, including Helicopter Air Ambulance (HAA) operations, are further required to utilize a Helicopter Terrain Awareness Warning System (HTAWS) which often utilizes input from the radar altimeter(s). Additional helicopter use cases such as firefighting and utility infrastructure construction and maintenance also rely on the radar altimeter for safe operation. These scenarios must therefore also be considered in a thorough analysis on the risk of potential harmful interference.

Question 9 (June 16, 2020):

Are there differences in operation or sensitivity for the pulsed versus frequency modulated CW altimeters? Are both in common use today?

Answer 9 (July 1, 2020):

In general, all modern commercial radar altimeter designs employ the FMCW architecture. However, there are still a fair number of pulsed altimeters in widespread commercial use, particularly on general aviation and low-end business aviation aircraft, as well as helicopters. Further, pulsed altimeter designs are very common on military aircraft.

It is anticipated that pulsed altimeters may exhibit different interference tolerance characteristics than FMCW altimeters. In addition some element are also provided in the answer of question 1.c. Initial analysis on this can be conducted using the performance parameters given in M.2059, which includes several commercial altimeters with both pulsed and FMCW architectures. Further, AVSI has obtained a commercial pulsed altimeter for additional testing to support the interference analysis conducted by RTCA SC-239.

Question 10 (June 16, 2020):

Are there any studies to determine any additional safety margins needed for performance of the radio altimeters?

Answer 10 (July 1, 2020):

The SC-239 interference testing results will be used to determine the pass thresholds for a broader sampling of RA's that are representative of the fielded solutions. This includes the impacts due to variations in temperature, vibration etc. across the airborne operating conditions that are applicable to the radar altimeter.

Additional margin is applied to account for radar altimeter integrity and availability requirements. Per international standards[51, 52], guidelines and precedent suggest that a minimum of 6 dB aeronautical safety margin should be applied to account for uncertainties in the interference analysis.

In addition to the safety margin, the interference analysis will apply margin based on the applicable failure rates for specific operational scenarios. The margin will be based on statistical analysis and will account for the variance of the 5G/LTE interference power received by the altimeter (in the 3.7 to 3.98 GHz range) given the specific interference signal waveform characteristics and the signal propagation model. This will be characterized with a mean aggregate value and a corresponding variance at the appropriate cumulative distribution function (CDF) cutoff. This margin is expected to reflect a path loss variance approximately up to 6dB and depends on several factors including laydown of base stations, line of sight to radar altimeter antenna, fading and multipath.

As an example, these safety margins apply to the operational scenario for a fixed-wing commercial aircraft performing a Category III approach and landing (the most extreme autoland condition, in which the pilots have near-zero or zero visibility and must rely solely on their instruments). Radar altimeter failures in this scenario would be considered catastrophic and thus must occur at a rate of less than 1×10^{-9} per landing sequence. This 1e-9 criteria will be reflected in the CDF cut off threshold. Refer to the response to Question 8 for more information on the applicable failure rates.

Question 11 (June 16, 2020):

Test Setup Questions/Suggestions

1. The vector signal generator has an out-of-band emissions level that may differ from that of 5G equipment. A band reject filter for 4200-4400 MHz, or a low pass filter

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[51] From ITU R-REC-M.1903-1, Section 2; "A safety margin (which may also be called a public safety factor), is critical for safety-of-life applications in order to account for risk of loss of life due to radio-frequency interference that is real but not quantifiable. To support safety-of-life applications, all interference sources must be accounted for"
[52] ICAO 9718, Section 9.2.23

attenuating frequencies above 4200 MHz, should be placed in-line with the signal generator output to ensure the test setup only measures receiver overload effects and is not influenced by in-band emissions.

2. The AVSI test setup does not include the altimeter antenna, which will provide some frequency rejection of the 3700-3980 MHz band. AVSI should account for this effect in the results.

3. Measuring the input power for receiver threshold overload and the receiver mask for frequency dependent rejection will be helpful in determining potential receiver impacts.

4. A separate test of interference energy within 4200-4400 MHz could help identify potential receiver impacts from 5G out-of-band emissions, and the results may be applied to operational scenarios with typical separation distances, antenna gains, and path loss.

Answer 11 (July 1, 2020):

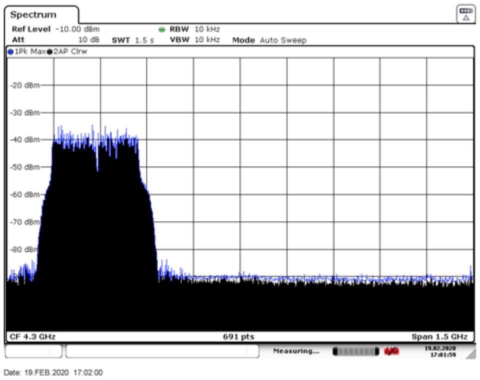
Test Setup Questions

1. Please see the question from aviation to the wireless industry regarding the VSG emissions characteristics and request for identifying or loaning appropriate filtering equipment to better represent 5G systems. Further, this question also considers whether additional filtering of spurious output from the VSG would be required for accurate representation of User Equipment (UE) uplink emissions.

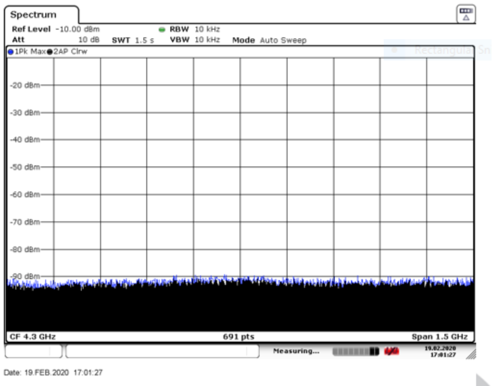
   For context, the FCC Report & Order on Expanding Flexible Use of the 3.7 to 4.2 GHz Band defines base station emissions limits of 65 dBm/MHz EIRP (rural) and 62 dBm/MHz EIRP (non-rural), and mobile device emissions limits of 30 dBm EIRP. Further, the out-of-band emissions limits are -13 dBm/MHz conducted power for both base stations and mobile devices. For a mobile device emitting at the maximum power limit of 30 dBm with a 0 dBi antenna and 20 MHz bandwidth, the conducted power spectral density (PSD) of the fundamental emissions is 17 dBm/MHz. Therefore, the out-of-band/spurious emissions limit is only 30 dB down from the peak of the PSD envelope.

   In the AVSI test setup, the VSG output was characterized using the same OFDM waveform that was used to represent 5G emissions. Plots of the spectrum of this waveform had been included in early AVSI test reports, but these were taken with a large resolution bandwidth (RBW) setting on the spectrum analyzer, meaning that the instrument noise floor was too high to display the true spurious content of the VSG. To investigate further, additional tests were conducted with reduced RBW, as low as 10 kHz, to reduce the spectrum analyzer noise floor. The plots below show the test results with a 10 kHz RBW. The OFDM waveform tested had a 280 MHz bandwidth, the largest considered in any of the AVSI tests.

VSG RF out ON



VSG RF out OFF



By comparing the observed spectrum with the VSG turned on and off, it can be determined if there is any spurious content output from the VSG which is above the spectrum analyzer noise floor. As seen above, this is not the case—instead, this test confirms that the VSG output contains no spurious content greater than 50 dB below the peak of the OFDM PSD envelope. The spurious output from the VSG is likely even lower than this, but no additional tests have been carried out to-date since additional steps would need to be taken to ensure sufficient dynamic range is available on the spectrum analyzer to support such a measurement.

The testing described above demonstrates that the AVSI test setup is certainly capable of avoiding any undesired spurious content within the 4.2-4.4 GHz band, at least to the level required for mobile devices operating within the limits of the FCC Order.

As described in the response to Test Setup Question #4 below, previous AVSI studies suggest that spurious emissions into the 4.2 – 4.4 GHz band from the laboratory signal generator being used to produce representative 5G waveforms in the 3.70 – 3.98 GHz band will not significantly contribute to in-band RA interference. Thus the > 50 dB suppression of spurious emissions shown above should be sufficient to eliminate concerns that energy leaking into the RA band from the signal generator is degrading RA performance. However, we are open to working with 5G experts to determine if additional measures must be implemented in the experimental setup to produce more representative waveforms.

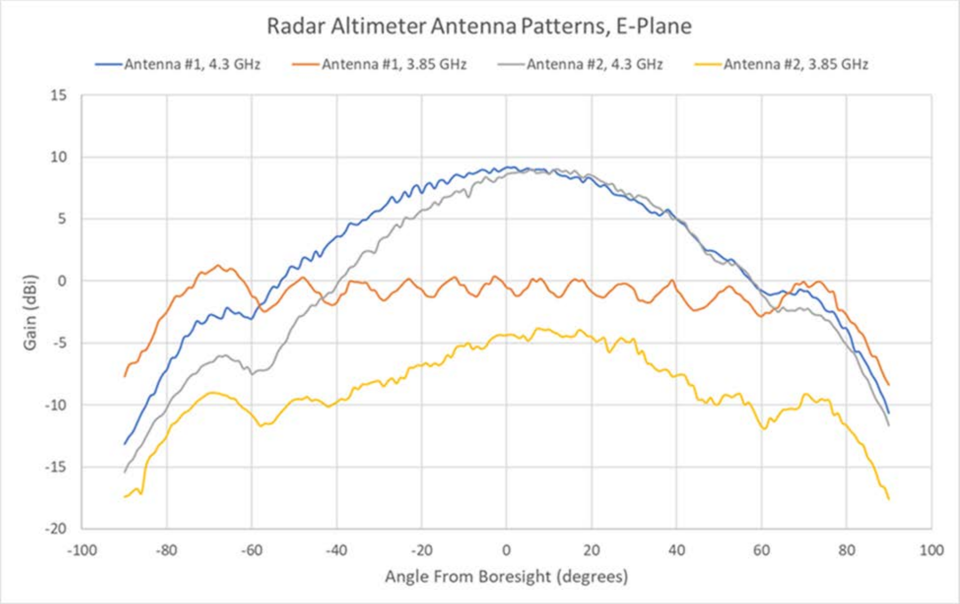
2. In past analysis, AVSI did look at some examples of radar altimeter antenna frequency selectivity and found it to be minimal across the 3.7-4.2 GHz band, as described in the response to Question 2 above. In particular, when accounting for interference signals that may arrive at the antenna at the edges of the main lobe rather than at boresight, there may be very little frequency-dependent rejection provided by the antenna. Therefore, it was not explicitly accounted for. However, additional antenna measurements will be taken to furnish the data requested in Question 2 above. This data will also be accounted for in interference scenario analysis conducted by SC-239, considering antenna selectivity and/or changes to the radiation patterns observed in the 3.7-3.98 GHz band as necessary.

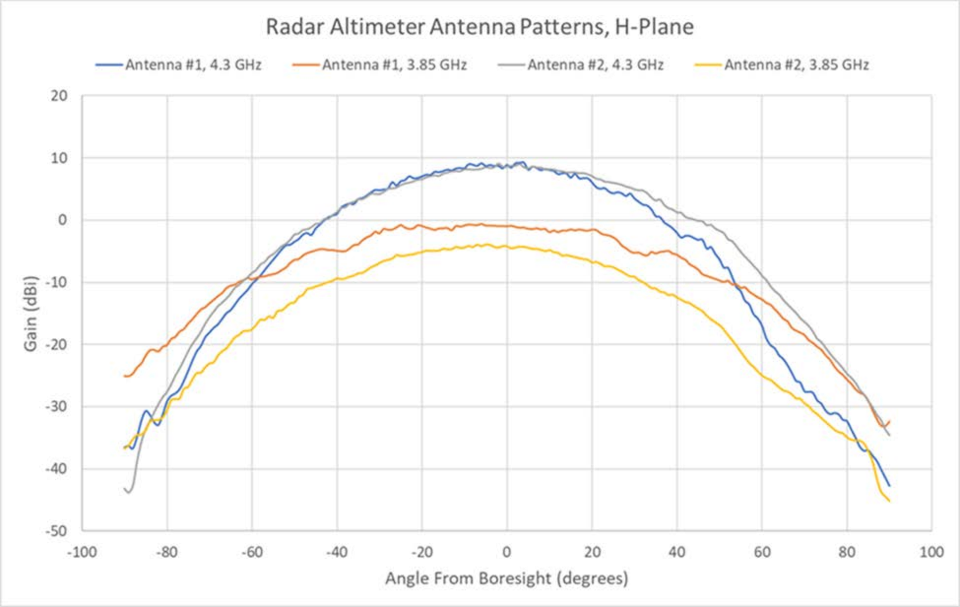
3. Additional testing and analysis is being conducted by the radar altimeter manufacturers to furnish the data on receiver selectivity requested in Question 5 above. However, it should be noted that AVSI testing is “black box” testing that measures the combined effects of all sources of interference present at the receive port of the RA on the height

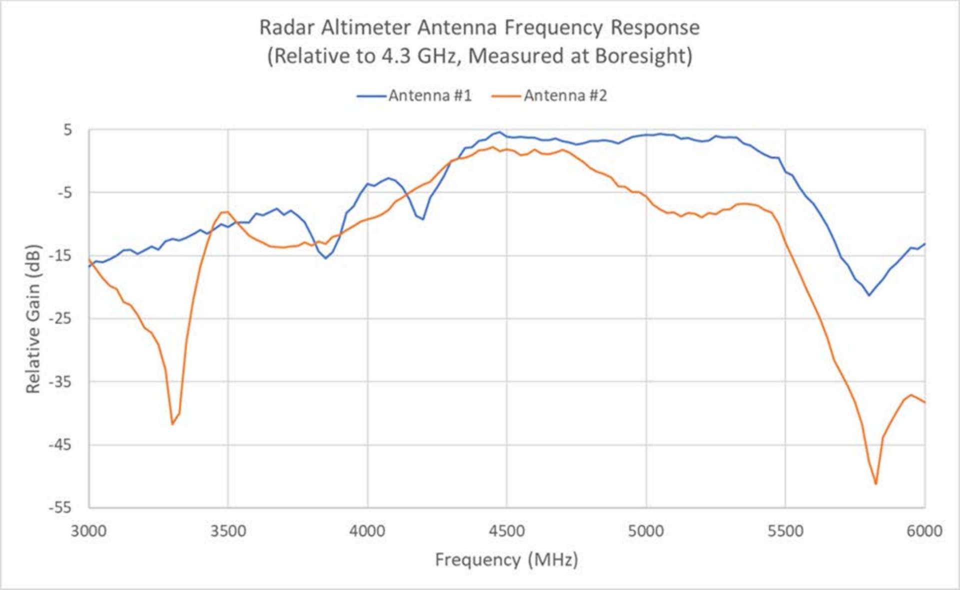
above ground as reported on the standard output. Such testing cannot discern specific failure mechanisms or receiver characteristics without additional proprietary information. Thus, the selectivity masks show box-level FDR characteristics (antenna FDR is not accounted for in the testing, only antenna directivity). In the meantime, please refer to M.2059 as indicated.

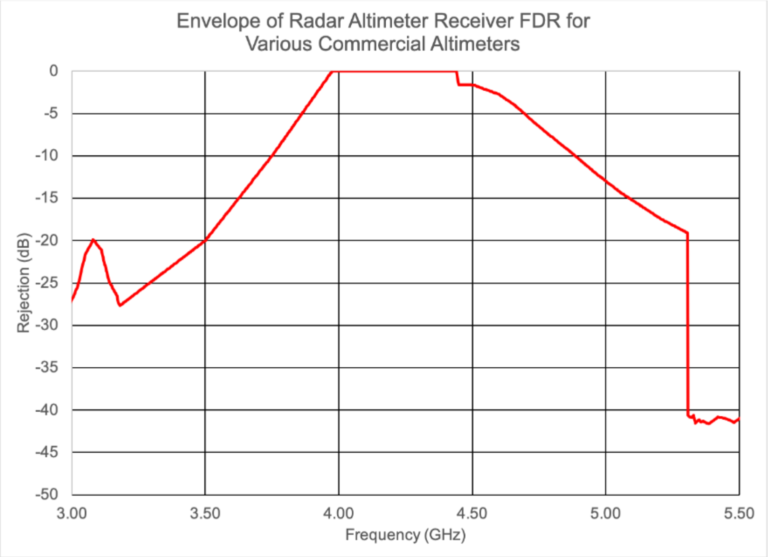
4. AVSI has previously conducted similar tests of radar altimeters with interference signals within the 4.2-4.4 GHz band to evaluate compatibility with Wireless Avionics Intra-Communications (WAIC) systems. The WAIC interference was modeled as a wideband OFDM signal covering the full sweep bandwidth of the FMCW altimeters under test, such that a more or less uniform PSD would be observed within the receive bandwidth of the altimeters at all times. Further, tests were conducted with both this in-band WAIC interference and interference within the 3.7-3.98 GHz band to represent 5G emissions present simultaneously. There was very little difference observed in the empirical interference tolerance thresholds of the altimeters with the in-band interference present in addition to the out-of-band interference, compared to the thresholds with out-of-band interference only. This suggests that the primary interference mechanism for the out-of-band 5G emissions is not spurious signals which land within the 4.2-4.4 GHz band.

Additional data provided by aviation industry experts (July 13, 2020):




Radar Altimeter Antenna Patterns, H-Plane
Antenna #1, 4.3 GHz
Antenna #1, 3.85 GHz
Antenna #2, 4.3 GHz
Antenna #2, 3.85 GHz
Gain (dBi)
20
10
0
-10
-20
-30
-40
-50
-100
-80
-60
-40
-20
0
20
40
60
80
100
Angle From Boresight (degrees)


Radar Altimeter Antenna Frequency Response
(Relative to 4.3 GHz, Measured at Boresight)
Antenna #1
Antenna #2
Relative Gain (dB)
5
-5
-15
-25
-35
-45
-55
3000
3500
4000
4500
5000
5500
6000
Frequency (MHz)



Question 12 (August 6, 2020):

FDR Envelope [Refers to plot above titled "Envelope of Radar Altimeter Receiver FDR for Various Commercial Altimeters]

TWG-3 conference calls in July noted that this envelope curve is an analytical result reflecting the minimum rejection across a collection of altimeters, developed by reviewing the manufacturer-provided design data, measurements, specifications and extracting from the underlying set of available data the lowest rejection performance level as a function of frequency.

Altimeter performance varies. Data for the underlying altimeters is needed to determine the performance for each as a function of frequency separation, operational environment, and accompanying equipment specifications, such as operational altitude, antenna selectivity, cable loss, etc. Please provide FDR performance vs. frequency information for each altimeter assessed in the study, anonymized if necessary but identifiable across input information sets/test studies. Individual variations are critical to accurately evaluating overall performance.

Answer 12 (August 12, 2020):

Please see complete response below which also addresses this point. [Refers to Answer 13]

Question 13 (August 6, 2020):

ITU-R M.2059 Receiver Overload. Aviation identified ITU-R M.2059 as a source for altimeter receiver overload threshold, as defined in the document's Tables 1 and 2. The M.2059 altimeter overload thresholds are summarized below and converted to a dBm/MHz level, assuming a 100 MHz interfering transmission bandwidth.

ITU-R M.2059 Table 1 Receiver Overload Threshold

	Analog Altimeters						
	A1	A2	A3	A4	A5	A6	
Receiver Overload Threshold	-30	-53	-56	-40	-40	-40	dBm
Threshold per MHz	-50	-73	-76	-60	-60	-60	dBm/MHz

ITU-R M.2059 Table 2 Receiver Overload Threshold

	Digital Altimeters				
	D1	D2	D3	D4	
Receiver Overload Threshold	-30	-43	-53	-40	dBm
Threshold per MHz	-50	-63	-73	-60	dBm/MHz

Per ITU-R M.2059, the worst performing altimeter's receiver overload threshold is -76 dBm/MHz, and the best-performing altimeter's threshold is -50 dBm/MHz.

The Envelope FDR curve above indicates that altimeter FDR at 3900 MHz is less than 5 dB. Combining this FDR with the ITU guidance indicates that altimeter receivers will overload if the input signal is in the range of -45 (for A1 and D1) to -71 dBm/MHz (for A3).

Answer 13 (August 12, 2020):

This is the correct application of the Receiver Overload protection criterion from M.2059. For the question regarding the altimeter receiver FDR characteristics, please refer to the following:

1. The agreed-upon methodology for analytically evaluating interference against radar altimeters from adjacent band sources is established by the ITU in M.2059. In this case, only the Receiver Overload protection criterion is directly applicable to interference sources outside of the 4.2-4.4 GHz band (spurious emissions from these sources that land within the 4.2-4.4 GHz band would also need to meet the False Altitude and Receiver Desensitization protection criteria, however). M.2059 specifies a *single representative receiver FDR characteristic*, which is considered to be applicable to all altimeter models listed in the Recommendation.

   In lieu of using the FDR characteristic provided in M.2059, the aggregate FDR characteristic provided by AVSI could be used, and applied in the same manner. The goal here is not to exactly characterize the performance of *specific* altimeter models such as those explicitly listed in M.2059, but instead to characterize the performance of *all* FAA-approved radio altimeters (even those not listed in M.2059), using representative data.

2. The wireless stakeholders expressed an interest in obtaining the exact performance characteristics, including receiver FDR and overload thresholds, for several different altimeter models. This data would be considered proprietary by the individual altimeter manufacturers, and there is no mechanism to obtain or distribute it through AVSI or RTCA. Therefore, the wireless stakeholders would need to work with the individual altimeter manufacturers to set up NDAs and determine what data could be shared. However, if this approach is taken, *all* FAA-approved altimeter models must be

considered in order for the analysis to sufficiently characterize the current deployment of radar altimeters in the civil and commercial aviation markets. This is understandably a difficult task to achieve, which is why the aviation stakeholders (and the ITU) have instead taken the approach of using representative datasets.

3. Interference tolerance threshold tests of 9 different altimeter models spanning the full civil and commercial aviation market, including those used on helicopters, business and general aviation aircraft, and commercial air transport and regional aircraft, are underway at AVSI. It is the intention of the aviation stakeholders to share the test results not only with RTCA SC-239, but also with TWG-3, as soon as the data is available. These results will consist of empirical interference tolerance thresholds against representative 5G waveforms in the 3.7-3.98 GHz band (generated in accordance with standard 3GPP test practices), determined at the black-box level (only looking at altimeter data outputs; not having access to internal altimeter RF parameters). The data will be provided in a format which aggregates the results for all altimeter models applicable to each market segment and aviation use case, e.g. helicopters, business and general aviation, and commercial air transport.

   Once this data is available, the aviation stakeholders suggest that it be used in any interference analysis in place of the M.2059 Receiver Overload criterion. Therefore, this data will eliminate the need for any specified altimeter receiver FDR characteristics, since these characteristics would be incorporated into the overall interference tolerance thresholds. The other protection criteria in M.2059 will still be applicable for any spurious 5G emissions which land within the 4.2-4.4 GHz band, however. Additional testing may be done to obtain more detailed interference tolerance thresholds for spurious emissions within the 4.2-4.4 GHz band. If this data becomes available, it may be used in place of the Receiver Desensitization and False Altitude criteria in M.2059.

Question 14 (August 6, 2020):

AVSI Test Data. AVSI provided laboratory test data to the FCC proceeding. The October 2019 test report included a table reporting the worst-performing altimeter out of Types 1-6, reproduced below:

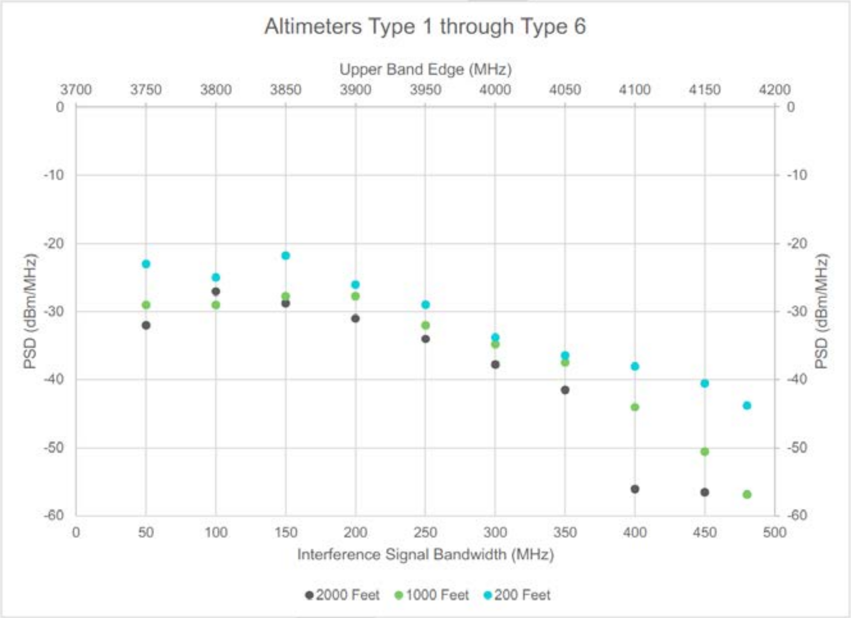


Figure 10: Minimum Break Points of Altimeter Types 1 – 6 for Each Altitude Tested.

At 3900 MHz, the worst altimeter of the six tested showed an interference threshold of -31 dBm/MHz, 14 dB better than the best-performing altimeter in M.2059, and 40 dB better than the worst-performing altimeter in M.2059. As a function of altitude, the threshold varies by 5 dB from 2000 ft to 200 ft, with 200 ft being the best-performing altitude.

We wish to make a careful analysis. However, the amalgamation of six altimeters into one set of data obscures frequency selective behavior of each altimeter. The variations in individual altimeter performance are essential to understand to ensure the studies assess real-world situations, and are not focused on the worst of several specifications that would never be deployed together in practice.

AVSI provided an additional graph of test data for altimeter Type 7:

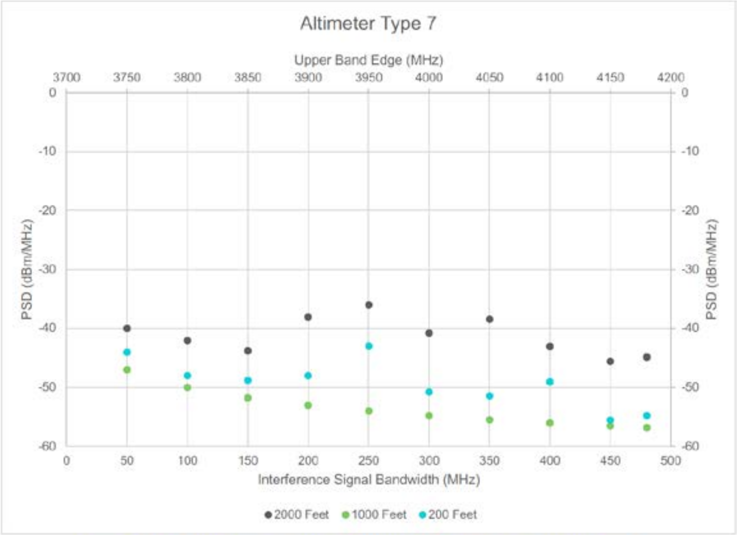


Figure 11: Minimum Break Points of Altimeter Type 7 for Each Altitude Tested.

Altimeter Type 7 shows odd frequency selectivity, with little change as a function of frequency separation. At 3900 MHz, the interference threshold varies by 15 dB as a function of altitude, with 2000 ft being the best-performing. The 200 ft altitude is second-best. Altimeter type 7 provides 17 dB better performance than the worst M.2059 altimeter.

- How and to what extent is the AVSI test environment impacting Altimeter Type 7 performance? AVSI should test Type 7 without the external interference sources (remove other RAs, and no WAIC) to assess the impact that the test setup has on Type 7's poor performance.
- Does Altimeter Type 7 contain any RF filtering?
- Please provide the actual Altimeter receiver front end overload thresholds (or best estimate) associated with each of the underlying data used in developing the Altimeter FDR envelope, similarly anonymized if necessary and identifiable across input information sets/test studies. Correctly matching FDR and overload characteristics are critical to accurately evaluating overall performance.
- Please provide insights into the peculiar frequency selectivity of Altimeter 7.

Answer 14 (August 12, 2020):

The aggregation of AVSI test results for multiple altimeter models still allows for a complete and thorough analysis of potential interference, since the tests are conducted at a black-box level. There is therefore no need to account for any specific design characteristics of individual altimeter models in subsequent interference analysis that utilizes these results.

The only feature of actual altimeter operation that is not explicitly accounted for in the AVSI test setup is the altimeter antenna. However, as indicated below, altimeter antennas are generally "mix-and-match" with different altimeter models, and thus there is no concern regarding the altimeter antenna data provided not being applicable to any of the altimeter models tested by AVSI. In other words, a given antenna model can be, and often is, used with a broad range of altimeters. Likewise, a given altimeter model can be, and often is, used with a broad range of antenna models.

The AVSI test data that is currently being collected to support the interference analysis will be aggregated into three groups: one which only considers altimeter models used on commercial air transport aircraft, one which only considers altimeter models used in all other fixed-wing applications (regional air transport, business aviation, and general aviation), and one which only considers altimeter models used on helicopters. This will give a sufficient breakdown of the altimeter performance by platform type, allowing only the directly applicable altimeter models to be considered when analyzing specific operational scenarios that may not be encountered by all types of aircraft. Further breakdowns within each performance category (e.g. to specific altimeter models) are unnecessary, and will not result in any difference in interference analysis results.

Further interference tolerance threshold testing is ongoing at AVSI which now includes two additional altimeter models that primarily serve the same market segments as Altimeter Type 7 (primarily general aviation and helicopters, as well as low-end business aviation).

Early results with these additional models suggest that Altimeter Type 7 is not necessarily an outlier, but is instead reasonably representative of the performance of FAA-approved altimeter models used in these market segments. The other six altimeter models previously tested by AVSI primarily serve the commercial air transport, regional air transport, and high-end business aviation market segments, although some of these models also see use in helicopter and general aviation applications.

The AVSI interference tolerance threshold test setup does not include WAIC interference (some preliminary tests included WAIC, but all subsequent testing and analysis have excluded it). Further, the existing in-band interference from other altimeters that is modeled in the setup only accounts for the interference encountered in dual or triple RA installations aboard the same aircraft (as applicable to the limitations of each altimeter model), as well as interference from RAs installed onboard other aircraft located on the ground when the victim aircraft is operating at a very low altitude near an airport (i.e. in the Worst-Case Landing Scenario). For all higher altitude test cases, no interference from RAs on the ground is included. Further, for low altitude test cases meant to represent aircraft operations that are not at or near an airport (e.g. a low-flying helicopter), no interference from RAs on the ground is included. Since Altimeter Type 7 only supports a single unit installation, no own-ship RA interference is included when testing this model. Since no interference from RAs on the ground is included in higher altitude testing, AVSI has already assessed the performance of Altimeter Type 7 without the external interference sources.

We are unable to provide any specific design details or proprietary characteristics of Altimeter Type 7. Our interaction with this particular altimeter model is limited to black-box testing at AVSI.

Question 15 (August 6, 2020):

Antenna Selectivity. Aviation provided the below graphs of measured antenna selectivity as a function of frequency: [Refers to plots shown above titled “Radar Altimeter Antenna Patterns, E-Plane” and “Radar Altimeter Antenna Patterns, H-Plane”]

Boresight antenna selectivity appears to provide a frequency rejection of 8 to 12 dB at the frequencies measured here.

Should we consider these results to be representative of antennas used by aviation altimeters?

Answer 15 (August 12, 2020):

Yes, these results can be considered representative of typical antennas that are used with a variety of different altimeter models across a wide range of aircraft types (commercial air transport aircraft, business and general aviation aircraft, and helicopters).

Question 16 (August 6, 2020):

Receiver Desensitization. Aviation's July 1 answers to wireless industry questions noted that the receiver performance will vary as a function of altitude:

"Then, the tolerance thresholds may be adjusted for lower altitude cases by accounting for the difference in received signal strength expected based on the applicable loop loss curve versus altitude (e.g. curves calculated in accordance with DO-155, for either beamwidth-limited or pulse-limited cases)."

The last conference call in July, Aviation discussed using the 20 dB/decade as an approximation of this improvement in receiver performance, using the maximum reported altitude from M.2059 as the starting point. As an example, is the following approach correct?

- Altimeter D3's maximum reported altitude is 6,000 m
- D3 IF bandwidth: 2 MHz
- D3 Noise Figure: 8 to 12 dB
- Desensitization threshold of -109 dBm/MHz at 6000 m
- Threshold at 600 m = (-109 + 20) = -89 dBm/MHz
- Threshold at 60 m = (-89 + 20) = -69 dBm/MHz

Answer 16 (August 12, 2020):

This is the correct approach, although once again note that this is a first-order approximation and may not exactly capture the true behavior of every altimeter. In addition, this approach is meant only to give a rough approximation of expected altimeter behavior and does not constitute an acceptable means of altering the protection criteria established in ITU M.2059 for use in interference studies. The protection criteria in M.2059 should be adhered to in their current form whenever possible.

Additional empirical test results of in-band interference tolerance may be provided by AVSI in the near future, which will give a more accurate indication of the altitude dependence. This data may potentially be suitable as a substitute for the protection criteria in M.2059 for use in interference studies.

Further, note that in the example calculations the Desensitization Threshold appears to just be the noise floor of altimeter D3, and does not account for the -6 dB I/N protection criterion. The actual threshold should be -115 dBm/MHz at the maximum altitude, and thus -95 dBm/MHz at 600 m, and -75 dBm/MHz at 60 m.

B.2 Question Responses and Data Provided by Mobile Wireless Industry to Aviation

The exchange of technical information between the mobile wireless and aviation industries within TWG-3 is presented here in a question and answer format. Note that the information exchange conducted within TWG-3 was subject to the agreement that the use of the information in technical analyses would not reflect any judgment or support of the findings of such analyses.

In this section, the questions were issued by the aviation industry experts, and the answers were provided by the mobile wireless industry experts. For additional clarity, the questions provided by the aviation industry experts are shown with blue text, and the answers provided by the mobile wireless industry experts are shown with red text. Each of the questions and answers are marked with the date on which they were submitted.

Answers 1 through 5 were submitted (on July 1, 2020) by CTIA on behalf of the mobile wireless industry experts with the following introduction:

> *In the interests of advancing the discussion within Working Group #3—5G/Aeronautical Coexistence, the wireless and aviation industries agreed to exchange questions and provide information regarding the general operating parameters for 5G networks to be deployed in the 3.7 GHz Service and altimeter and other aeronautical operations in the 4.2-4.4 GHz band, respectively. The information that the wireless industry provides here is in response to questions from RTCA on behalf of the aeronautical industry. This information is provided solely for the purposes of the work of Working Group #3 in response to Federal Communications Commission GN Docket No. 18-122, and reflects the unique environment and network characteristics within the United States. Neither the information nor studies or analyses thereof may be used for any other purposes or made available in any other fora. By making this information available, the wireless industry does not endorse or support any analyses or studies that the aeronautical industry may perform.*

CTIA has provided the following statement giving RTCA permission to include their responses from the TWG-3 information exchange in this report:

> *CTIA does not object to RTCA publication of the information into the public domain, but CTIA disputes the report's analysis and conclusions.*

Question 1 (June 12, 2020):

What is an appropriate signal waveform to use in interference tolerance bench testing of radar altimeters that will be reasonably representative of potential 5G emissions in the 3.7-3.98 GHz band?

Clarifying points and follow-on questions:

Are there any additional frequency-dependent characteristics of the transmission path (e.g. bandpass filters) which should also be accounted for in the interference signals to be injected into the receiver input of each radar altimeter under test? If yes, could you assist with obtaining relevant equipment to account for these frequency-dependent characteristics?

How do the waveforms and/or frequency-dependent characteristics differ between base station emissions and user equipment emissions? It would be helpful in creating our tests to have additional details in support of the same.

For the representative 5G waveforms indicated above, is there guidance on the peak-to-average power ratio (PAPR) characteristics, such that these may be considered in statistical analysis of the interference power received by radar altimeters in various operational scenarios?

Any additional guidance relative to simulating potential 5G emissions for these testing efforts, as appropriate, would be helpful.

Context on previous efforts:

Previous testing conducted by AVSI has used a single OFDM signal with 52 BPSK-modulated subcarriers (using random baseband data). The modulation clock rate (and thus the subcarrier spacing) was adjusted to produce each desired total signal bandwidth (ranging from 20 MHz to 280 MHz). While AVSI is confident in the previous test results which have been submitted to the FCC, there admittedly may be room for improvement in representing the potential 5G emissions as accurately as possible.

Answer 1 (July 1, 2020):

5G transmission signals:

- Baseline assumption: 100 MHz.
- Upper bound: 160 MHz, assumes licensees are co-located.
- Factors reducing energy density include various network factors such as scheduling, network loading, etc.
- To simplify modeling and testing, the worst-case maximum EIRP can be used with the baseline and upper bound bandwidths above, to account for network factors. In practice the signal will be beamformed to the users, and the in-band emissions in the direction of the radio altimeter can vary based on the antenna patterns.
- Maximum base station EIRP per FCC is 1640 W/MHz for non-rural and 3280 W/MHz for rural.
- The waveform should use QPSK. BPSK modulation is not included in the 5G NR air interface forward link.
- The OFDM test signal will capture an appropriate PAPR as part of the testing. For statistical analysis, we should discuss how that would be applied to better understand how best to answer.
- The FCC rule for conducted emissions above 3980 MHz is -13 dBm/MHz for the base station and user equipment. Generally, equipment emissions roll off significantly as a function of frequency separation. Therefore, a base station emissions sensitivity analysis could be performed with values other than -13

dBm/MHz, such as -20 to -40 dBm/MHz. For the user equipment, 3GPP further defines a spurious emissions requirement of -30 dBm/MHz[53].

<u>Question 2 (June 12, 2020):</u>

What are the possible signal bandwidths, for both base station downlink emissions and user equipment uplink emissions, which will be reasonably representative of potential 5G emissions in the 3.7-3.98 GHz band?

<u>Clarifying points and follow-on questions</u>:

What would a reasonable spectrum utilization layout (including spectrum reuse), possibly including multiple network operators, look like for:

a) Densely populated regions?

b) Rural and suburban regions?

c) In and around airports?

It is assumed that all 280 MHz of available spectrum can be used simultaneously in a given geographical area. Details of representative spectrum segmentation across network operators (downlink/uplink and slot scheduling as applicable) throughout the 3.7-3.98 GHz band are requested.

<u>Context on previous efforts</u>:

Previous testing conducted by AVSI has considered 20 MHz and 100 MHz interference signal bandwidths (under guidance from the FCC's Office of Engineering and Technology), as well as a full 280 MHz bandwidth as a worst case. Further, it is acknowledged that the FCC R&O defines fourteen 20 MHz sub-blocks throughout the 3.7-3.98 GHz band which may be individually licensed, and thus the final contiguous bandwidths for each network operator will ultimately depend on the auction results. However, reasonable assumptions must be established such that various scenarios may be evaluated, and worst-case conditions relevant to aircraft operations can be identified.

<u>Answer 2 (July 1, 2020):</u>

From a practical perspective given tower space and loading constraints, it is reasonable to assume that no more than 100 to 160 MHz will be in use at a single location. Question 1 provided further details on the bandwidth.

For TDD asymmetry, typical DL:UL split is 2:1 in time. This means that within a 5G NR radio frame, the base station transmits for approximately two-thirds of the time, and the

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[53] 3GPP TS 38.101 "User Equipment (UE) radio transmission and reception", Table 6.5.3.1-2 Requirement for general spurious emission limits.

devices transmit for approximately one-third of the time. It is important to note that the base stations and devices do not transmit at the same time.

Base stations do not transmit at maximum power all of the time. This is captured in network simulations by network loading. A network loading value of 20% would normally represent a typical/average value for the loading of base stations across a network (or part thereof).

UEs are subject to transmit power control. Guidance on UE power control is provided in Recommendation ITU-R M.2101-0 "Modelling and simulation of IMT networks and systems for use in sharing and compatibility studies," February 2017.

Typical inter-site distance is 0.7 km for urban, 1.7 km for suburban, and 6 km for rural.

Sites in and around airports typically mount antennas in the clutter to avoid FAA lighting and marking requirements.

Question 3 (June 12, 2020):

What are the possible base station antenna radiation patterns or models, specifying absolute directivity, which will be reasonably representative of what will be deployed in the 3.7-3.98 GHz band?

Clarifying points and follow-on questions:

If multiple different types of antennas with different radiation patterns will be used for different purposes (e.g. rural, suburban, urban macro-cells, urban micro-cells etc.), one or more examples of each type will be needed to allow for the characterization of various scenarios such that worst-case conditions relevant to aircraft operations may be identified. Details on variations in base station deployments across geographic areas in support of the same are requested.

Ranges of possible mast heights and downtilts (electrical/mechanical as applicable) which may be utilized for each antenna type are requested.

If multiple types of antenna technologies will be utilized (e.g. passive/fixed antennas, active antenna systems/beamforming, MIMO, etc.) in the 3.7-3.98 GHz band, specify which technologies are applicable to which applications/deployment scenarios, and how this may impact the overall radiation patterns. Relevant antenna polarization pattern information in support of the same is requested.

If active antenna systems will be utilized, will there be any limitations (regulatory, operational, or practical) on the beamsteering capabilities in the elevation plane? Supporting details are requested.

Context on previous efforts:

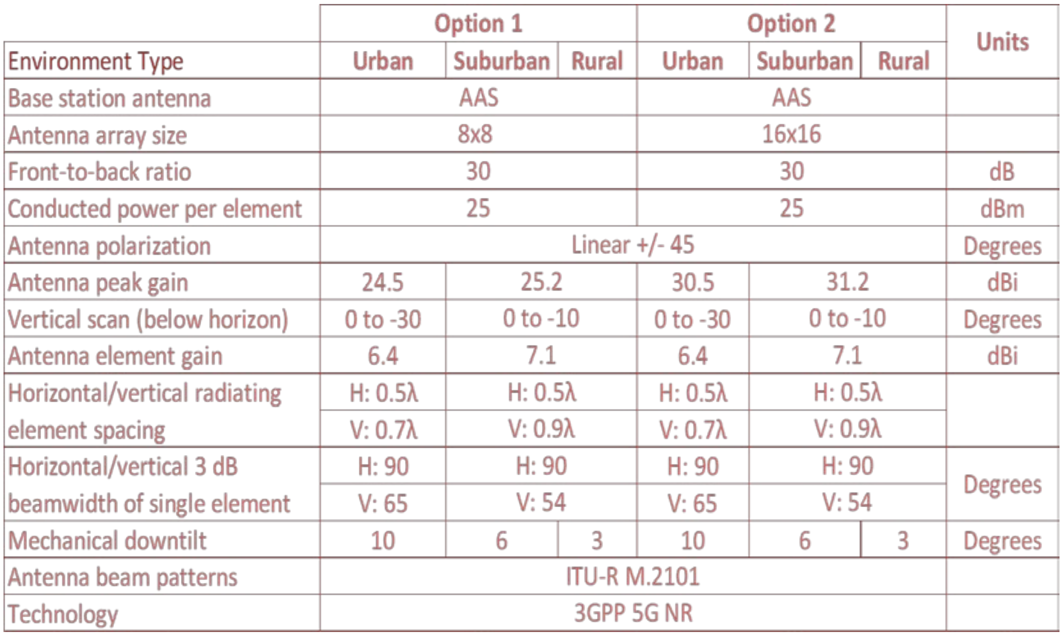
Previous analysis conducted by AVSI has considered a base station antenna pattern calculated in accordance with Recommendation ITU-R F.1336-5, with assumptions of a 7-degree elevation beamwidth, 3-degree downtilt, no beamforming, and 90 ft mast height, meant to represent a single base station in a rural deployment scenario.

Answer 3 (July 1, 2020):

Assume all base stations will use an active antenna array system with beamforming – this enhances the coverage range of the base station to better match the existing cell site footprint. The larger array size below is close to the maximum FCC EIRP. The smaller array size results in a lower EIRP.

Antenna height: 35 m for rural, 25 m for suburban areas, 20 m for urban.

Representative configurations of AAS BS are given below.



	Option 1			Option 2			Units
Environment Type	Urban	Suburban	Rural	Urban	Suburban	Rural	
Base station antenna	AAS			AAS			
Antenna array size	8x8			16x16			
Front-to-back ratio	30			30			dB
Conducted power per element	25			25			dBm
Antenna polarization	Linear +/- 45						Degrees
Antenna peak gain	24.5	25.2		30.5	31.2		dBi
Vertical scan (below horizon)	0 to -30	0 to -10		0 to -30	0 to -10		Degrees
Antenna element gain	6.4	7.1		6.4	7.1		dBi
Horizontal/vertical radiating element spacing	H: 0.5λ	H: 0.5λ		H: 0.5λ	H: 0.5λ		
	V: 0.7λ	V: 0.9λ		V: 0.7λ	V: 0.9λ		
Horizontal/vertical 3 dB beamwidth of single element	H: 90	H: 90		H: 90	H: 90		Degrees
	V: 65	V: 54		V: 65	V: 54		
Mechanical downtilt	10	6	3	10	6	3	Degrees
Antenna beam patterns	ITU-R M.2101						
Technology	3GPP 5G NR						

Array losses are included in the element gain.

Question 4 (June 12, 2020):

Are there any general comments which can be provided on the following approach to propagation modeling, or suggestions for alternative propagation models which should be considered, noting that the strongest possible interference coupling must be evaluated for relevant aircraft operational scenarios?

Clarifying points:

To evaluate the interference coupling from 5G emission sources in the 3.7-3.98 GHz band (both base stations and user equipment located on the ground), the primary consideration will be direct line-of-sight propagation, i.e. free-space path loss only from 5G terrestrial emission sources to an airborne radar altimeter, as this direct path will lead to the strongest coupling under most conditions. Further, for certain terrain conditions and interference geometries, ground-bounce propagation will also be considered to evaluate additional non-line-of-sight paths that may direct higher power levels into a radar altimeter receiver onboard an aircraft.

Answer 4 (July 1, 2020):

Recommendation ITU-R P.528 provides propagation modeling guidance for aeronautical paths. ITU-R P.528 should be used in conjunction with ITU-R P.2108, which provides a slant path clutter loss model, and ITU-R P.2109 provides building entry loss guidance for indoor UEs. The percentage of UEs operating indoors is assumed to be 70%.

Question 5 (June 12, 2020):

What are the possible reasonably representative timing patterns of uplink emissions in the 3.7-3.98 GHz band from multiple simultaneously operating UEs (e.g. passenger-carried devices) that could be located onboard an airborne platform?

Clarifying points:

Any details considering different subcarriers/resource blocks and different network operator cells, as applicable, are appreciated to assist in creating an accurate model.

Context on previous efforts:

The worst case being considered currently is that 100% of UEs located onboard an airborne platform may transmit simultaneously in the same time slot. It is also considered that UEs may emit at full power (+30 dBm) when they are located on an airborne platform, since the path losses to base stations on the ground will be significant when accounting for fuselage attenuation, propagation distance, and possibly low directivity of the base station antennas at elevation angles above the horizon. Feedback on these assumptions is requested.

Answer 5 (July 1, 2020):

Handheld cellular devices must be in airplane mode when in flight, per FCC title 47 part 22.925, which includes this notice: “The use of cellular telephones while this aircraft is airborne is prohibited by FCC rules, and the violation of this rule could result in suspension of service and/or a fine. The use of cellular telephones while this aircraft is on the ground is subject to FAA regulations.”

Since all handheld devices that support C Band will also support the cellular band, the FCC effectively prohibits airborne operation of these devices. Of further note, the C Band spectrum in 3700-3980 MHz is designated as “mobile except aeronautical mobile” which precludes use of the band for airborne devices. Since the FCC rules prohibit use of devices while airborne, the expected operating environment is that no devices would be transmitting in the C-Band onboard an aircraft.

Question 6 (July 8, 2020):

Thank you for the answers. Please find below the additional clarifications pertaining to Question 1 that are needed to reach the most accurate representativeness of our Testing

A. Do any of the wireless industry stakeholders have a filter (e.g. bandpass or lowpass filter) which could be loaned to AVSI for testing to ensure more realistic spurious levels within the 4.2 to 4.4 GHz band? If so, what are the characteristics of this filter (bandwidth, cutoff frequency or frequencies, etc.) and when could it be provided?

B. Bandwidth Upper Bound is suggested to be 160MHz:

- Please provide validation for the 160 MHz bandwidth limit. Is this the maximum bandwidth that could be utilized by a single base station, or does this assume multiple mobile network operators in close proximity? Is this full bandwidth utilized only for downlink, or would some be reserved for uplink?

- Is the expectation, therefore, that the full 280 MHz of licensed flexible use spectrum will never be utilized simultaneously in a given geographic area (i.e. within a given inter-site distance)?

- Is the 20% of network scheduling/load (20% refer to answer pertaining to question 2) explicitly accounted for in the 160 MHz bandwidth assumption?

- If yes, please provide a technical or regulatory basis for the 20% of network scheduling/load. Is this a nominal or expected value? What is the highest network load that could occur?

- Do any regulations restrict the network load to 20%? In aviation we must consider the worst-case foreseeable condition, even if this is not expected most of the time.

C. What are the possible OFDM subcarrier spacing values that may be used? Is the same spacing used regardless of total bandwidth? Is the same spacing used for both uplink and downlink emissions? Are there any conditions or operational scenarios which will utilize different subcarrier spacing values?

Is “-20 to -40 dBm/MHz” expressed in conducted or in radiated power (e.g. EIRP)? We would assume this would be conducted power, since the -13 dBm/MHz limit in the FCC Order is specified in this manner. Is this range of values simply considered to be representative of nominal performance? Are there additional regulations or industry standards beyond the FCC Order which will guarantee these lower spurious levels?

Answer 6 (August 6, 2020):

We do not have a filter available, but researched a company that could build and deliver one, if this would be of interest:

Filter Company: Microwave Filter Company (www.microwavefilter.com)

Passband: 3700-3980 MHz

Estimated cost: $1400-1800 for first custom filter

Delivery 4-6 weeks ARO

Need to specify the maximum passband insertion loss and the minimum stopband attenuation that is targeted for the filter.

- The maximum channel bandwidth defined by 3GPP for mid-band spectrum is 100 MHz. Permitting up to 160 MHz at a location addresses the case where more than one operator is co-located on a tower. The 160 MHz limit is more an expectation or an estimation, so justification is based on operator experience with real installations. This bandwidth is for a single location.

  The 5G NR systems that will be deployed in the C Band are time division duplex (TDD) meaning that the full channel size or a portion of it, is used for downlink for a portion of time, and then the full channel size or a portion of it, is used by devices to transmit in the uplink in a second portion of time. Static portions of the channel may also be configured by the operator, this is known as Bandwidth Parts (BWP). Bandwidth Parts may be up to 20 MHz in order to accommodate both legacy LTE devices that support up to 20 MHz and newer 5G devices. The split between uplink and downlink depends on the ratio statically defined by the operator for TDD operations. We expect the majority of the time to be used for downlink since there is typically more downlink traffic to deliver – for instance, 50-70% of a 10 ms radio frame will likely be downlink, with the remainder used for uplink.

- The expectation is the full 280 MHz will not be used simultaneously at a location. Non-co-located sites will not be close enough such that the energy from more than one site exceeds the single-site limit.

- Network loading is independent of the bandwidth. ITU-R M.2101 shows how to implement network loading into simulations.

- There is no regulatory mandate. The value for BS/network loading that is proposed to be used in sharing studies for outdoor environments is 20%. This represents a typical/average value for the loading of base stations within a network. In order to provide adequate quality of service, networks are dimensioned such that, across the cells within a network, most of the cells will be relatively lightly loaded most of the time.

- There is no regulatory mandate.

B. The 3GPP specifications allow for subcarrier spacing of 15 kHz, 30 kHz and 60 kHz for FR1 frequency ranges. The frame duration is 10 ms for all, but the slot duration becomes shorter as the SCS becomes larger. Smaller slot duration may be desirable for latency-sensitive applications. Each Bandwidth Part (BWP) may have a different numerology and hence sub-carrier spacing.

C. The levels are conducted. Antenna gain would be applied on top of these.

Question 7 (July 8, 2020):

Thank you for the answers. Please find below the additional clarifications pertaining to Question 3 that are needed to be sure we fully understand the assumptions you suggested.

A. The response suggests that non-active (i.e. fixed beam) antennas will not be used by base stations in the 3.7 to 3.98 GHz band. Is this correct? If not, what situations or deployment scenarios would utilize a non-active antenna? Further, what would be a representative antenna pattern in this case? Is ITU-R F.1336 an appropriate reference?

B. Is mechanical downtilt separated from the "Vertical scan (below the horizon)" parameter or is it integrated into the "Vertical scan (below the horizon)" parameter? That is, are the "Vertical scan" ranges given in the table above in reference to the antenna broadside direction, or to the Earth horizon after the antenna is installed on a mast with any applicable downtilt?

C. Can you confirm that the vertical scan (below the horizon) will always be limited to 0° below the horizon? That is, no beam steering to angles above the horizon will ever occur?

D. Is there any aperture taper applied, particularly in the elevation plane? If so, what are the characteristics of this taper? Are there specific requirements to limit the peak side lobe level?

E. A mechanical downtilt (from 3°, 6°, 10°) is provided in the above table. Is this a fixed mechanical downtilt, or a maximum mechanical downtilt (i.e if it is a maximum mechanical downtilt, then will there be cases with less downtilt than that specified)?

Are the antenna heights provided meant to be average/nominal values? In practice we expect that some antenna installations will be much higher above the ground level if they are installed, for example, atop tall buildings. Is this a valid assumption?

Answer 7 (August 6, 2020):

A. FCC is not mandating any antennas. It is very likely that this band will use active antennas, because the performance improves dramatically with AAS; however, there is no regulation preventing use of a sectorized antenna. For non AAS, ITU-R F.1336 is adequate.

B. Vertical scan is separate from mechanical downtilt. A mechanically downtilted antenna's horizon is perpendicular to the antenna face.

C. No, we cannot confirm that.

D. ITU-R M.2101 Section 5.1 provides a formula for antenna pattern characteristics.

E. Mechanical downtilt is fixed.

F. Yes, the values included in the table are typical value of antenna heights.

Question 8 (July 8, 2020):

Please provide an answer to the original question. [referring to Question 5]

Answer 8 (August 6, 2020):

No devices would be transmitting in the C-band onboard an aircraft as they are in idle or 'listen' mode, not active and connected. Studying scenarios which are explicitly against FCC rules should be outside the scope of the working group.

Furthermore, operators do not design networks to support the use of devices on board aircraft, thus there is no specific information or knowledge with regard to this question.

Inadvertent connections would not occur in-flight given network design practices. Wide-area cellular networks necessarily focus energy toward locations where majority of users are expected. Aircraft flying above a city would be visible to a large number of base stations. A device, once turned on, needs a reasonably dominant base station signal in order to connect to a network and receive permission to transmit. Devices onboard the aircraft would suffer excessive path loss, including due to the aircraft fuselage, and are not likely to be able to attach to a base station given the weak signals overall and multiple, conflicting base station signals. The device would remain in scan mode, and does not transmit unless attached to a network.

Communication systems designed for air-to-ground service, such as Gogo, use markedly different network designs – a small number of base stations nationwide to limit self-interference, with antennas pointing toward the sky.

Question 9 (August 7, 2020):

For AAS base stations, we are able to use Recommendation ITU-R M.2101 to determine antenna radiation patterns both for the fundamental emissions in the 3.7-3.98 GHz band, and for the spurious emissions in the 4.2-4.4 GHz band (which in the case of M.2101 would be a single element radiation pattern). For fixed-beam sectoral base stations, we are able to use Recommendation ITU-R F.1336 to determine antenna radiation patterns for the fundamental emissions in the 3.7-3.98 GHz band, but it is not immediately clear how the pattern may change when considering spurious emissions in the 4.2-4.4 GHz band. Please comment on the following:

1. A straightforward approach for the fixed-beam sectoral antennas would be to assume that the radiation pattern in the 4.2-4.4 GHz band has the same shape as the pattern in the 3.7-3.98 GHz band, but the absolute gain is reduced by some constant frequency-dependent rejection (FDR) factor. Is this approach reasonable, and if so, what is a reasonably representative FDR value to assume for such an antenna in the 4.2-4.4 GHz band?

2. If the above approach is not reasonable, then what approach should be taken to model the radiation pattern of fixed-beam sectoral base station antennas in the 4.2-4.4 GHz band?

Answer 9 (August 17, 2020):

A conservative approach would be to assume the same antenna pattern within 4.2-4.4 GHz as is used in the 3.7-3.98 GHz band. The sector antennas will be designed to provide the target gain over a 280 MHz span. The reduction of antenna gain above 4200 MHz is not expected be more than a few dB.

Question 10 (August 12, 2020):

1. The clarifications we received indicate that it cannot be guaranteed that AAS base stations will never be utilized with the main beam steered above the horizon. How high above the horizon could the main beam be steered for each AAS configuration?

2. Does the wireless industry envision any potential future use cases in which an Unmanned Aircraft System (UAS) or Urban Air Mobility (UAM) vehicle would be in direct communication with a mobile network in the 3.7-3.98 GHz band?

Answer 10 (August 20, 2020):

1. Beam-steering range in the vertical plane is implementation-dependent, as different BS models can provide different operation characteristics by design, including some variation on the vertical angle beam steering range. Values previously provided for BS “antenna height,” “mechanical downtilt,” and “vertical scan (below horizon)” for urban, suburban, and rural environments represent what is considered typical for sharing studies in such deployment environments.

2. The band will be used in compliance with the FCC Table of Frequency Allocations, which designates the 3.7-3.98 GHz band for “MOBILE, except aeronautical mobile.”

APPENDIX C COMMENTS AND RESOLUTIONS FROM THE PUBLIC COMMENTING PERIOD

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51783	High	Jean-Luc ROBIN (AIRBUS)	1	1	Add appendix B (TWG-3 questions/answers)	Appendix B is missing	Need to add Appendix B	Complete	Rejected - duplicate comment.	Duplicate comment - see 52013.	
51936	Editorial	Edward Hahn Air Line Pilots Association (ALPA)	1	24	Clarification of Rotorcraft Operations	Clarify that 135.160 applies to rotorcraft operations for compensation or hire.	"For example, Title 14 of the Code of Federal Regulations (CFR) ? 135.160 states that no person may operate a rotorcraft for compensation or hire unless that rotorcraft is equipped with an operable?"	Complete	Accepted	Proposal accepted as-is.	
51955	Editorial	ASRI	1	9	Introduction characterization	Clarifies that military not studied	Radar altimeters are also used on military aircraft, although the use cases and operating requirements for such aircraft vary widely and therefore not studied here.	Complete	Accepted	Proposal accepted as-is.	
51956	Editorial	ASRI	1	19	Move text	Moved up last sentence from next para to end of this para	In addition, operations such as Category II or Category III Instrument Landing System (ILS) approaches require the use of at least one radar altimeter.	Complete	Rejected	Propose to reject - this paragraph discusses systems onboard the aircraft, while the following discusses operational use cases. ILS approaches fall under the latter. Proposal accepted by commenter.	
51957	Editorial	Andrew Roy Aviation Spectrum Resources, Inc.	1	19	Add text	Need to clarify that the RA is the only system able to do this function. Add to end of paragraph	No other system on or off the aircraft replicates the functions of a radio altimeter to the necessary accuracy or resiliency.	Complete	Accepted with modification	Propose alternate text: "No other sensor or system is capable of supporting these functions with the same level of integrity, availability, and continuity that is provided by the radar altimeter." Proposal accepted by commenter.	
51958	Editorial	ASRI	1	20	Introduction characterization	Changed to make it less passive	In commercial and civil aviation, the usage of radar altimeters is ubiquitous and their presence is not solely a matter of convenience. Indeed , for many types of aircraft operations, Federal Aviation Administration (FAA) regulation or the rules of another applicable aviation authority explicitly or indirectly require radar altimeters. For example, Title 14 of the Code of Federal Regulations (CFR) § 135.160 states that no person may operate a rotorcraft (e.g., a helicopter) unless that rotorcraft is equipped with an operable FAA-approved radar altimeter.	Complete	Accepted with modification	Alternate proposed wording: "In commercial and civil aviation, the ubiquitous usage of radar altimeters is not solely a matter of convenience. For many types of aircraft operations, such usage is either explicitly or indirectly required by…" Proposal accepted by commenter.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51990	Non-Concur	CTIA dhyslop@ctia.org	1	1	Context	General comment throughout. The worst-performing altimeter in Categories 2 and 3 is significantly worse than prior measured altimeters	Test data for all altimeters is essential to understand the range of performance and potential mitigation approaches.	Complete	Unresolved	See the following from section 7.2: "These models are representative of a significant majority of radar altimeter models currently deployed on commercial air transport, regional, business aviation, and general aviation aircraft, as well as helicopters." RTCA SC-239 received summary data from AVSI and is not able to provide individual altimeter performance data. Please contact AVSI directly for more detailed information. No wording changes planned.	
52085	Medium	Jessie Turner/The Boeing Company	1	6	User Functions	It states: "Such functions include, but are not limited to, Terrain Awareness Warning Systems (TAWS), Traffic Collision Avoidance Systems (TCAS) and Airborne Collision Avoidance Systems (ACAS), and autoland systems including autothrottle and automated landing flare". Include Windshear and other edits. (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	Proposed revision: "Such functions include, but are not limited to, Terrain Awareness and Warning Systems (TAWS), Traffic-alert & Collision Avoidance Systems (TCAS) and Airborne Collision Avoidance Systems (ACAS), Wind Shear detection, flight controls, and autoland systems (including autothrottle and automated landing flare and rollout)".	Complete	Accepted	Proposal accepted as-is.	
51793	Editorial	Garmin	2	12	punctuation	missing comma after word "receiver"	Add comma	Complete	Accepted	Proposal accepted as-is.	
51794	Editorial	Garmin	2	16	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "band"	Complete	Accepted	Proposal accepted as-is.	
51959	Editorial	ASRI	2	11	Introduction characterization	Made text more definitive	As such, radar altimeters are highly susceptible to RF interference entering the receiver which can negatively impact their performance.	Complete	Accepted	Proposal accepted as-is.	
51960	Editorial	ASRI	2	15	Introduction characterization	Corrected/simplified text in sentence	Radar altimeters may be susceptible to RF interference received either within the band of operation, or within adjacent or nearby frequency bands.	Complete	Accepted	Proposal accepted as-is.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51961	Low	ASRI	2	32	Introduction characterization	Emphasized the spectrum is being reallocated	However, as the push for extended capabilities of mobile networks has continued, additional spectrum has been identified and made available for commercial mobile use, often through reallocation	Complete	Accepted	Proposal accepted as-is.	
51962	Low	ASRI	2	39	Introduction characterization	More accurate text on FCC actions throughout para	On March 3, 2020, the Federal Communications Commission (FCC) released their Report and Order of Proposed Modification in the matter of Expanding Flexible Use of the 3.7 to 4.2 GHz Band [5]. This Report and Order reallocated the spectrum from 3.7 to 3.98 GHz from FSS and FS to new flexible use licensees. The spectrum will be auctioned beginning in December of 2020, with the intent of supporting 5G telecommunications deployments in the mid-band spectrum ranges. As a result, the incumbent FSS operators in the 3.7 to 4.2 GHz band will be transitioned into the 4.0 to 4.2 GHz band, while FS incumbents will be required to move out of the 3.7-4.2 GHz Band entirely.	Complete	Accepted	Proposal accepted as-is.	
51963	Editorial	ASRI	3	2	Introduction characterization	Corrected/simplified text in sentence	Several aviation industry stakeholders actively monitored and participated in the FCC rulemaking process by submitting technical reports to the FCC and meeting with FCC technical staff with the intent of ensuring that the risk of potential harmful interference to radar altimeters would be adequately evaluated and considered	Complete	Accepted	Proposal accepted as-is.	
51964	Editorial	ASRI	3	15	Introduction characterization	Corrected/simplified text in sentence	The updates to the MOPS will primarily be focused on defining additional performance requirements and tests to ensure that new radar altimeter designs can operate in the rapidly changing RF environment around the 4.2–4.4 GHz band while minimizing the risk of harmful interference.	Complete	Rejected	Propose to reject - I think the proposed wording is less accurate/clear. Proposal accepted by commenter.	
51965	Medium	ASRI	3	18	Introduction characterization	Needs to emphasize that retrofit is a multi-decade process	However, as safety is paramount for critical aviation systems such as radar altimeters, past experience shows that the development and implementation of new standards is a necessarily slow process, let alone the implementation of those standards into new certified equipment designs, and the retrofitting of aircraft with such new equipment. The entire process can take many years, often several decades for all affected aircraft.	Complete	Accepted with modification	Proposed wording: "However, as safety is paramount for critical aviation systems such as radar altimeters, the development and implementation of new standards necessarily takes a significant amount of time—several years at a minimum. Further, additional time will be required for new equipment to be designed, certified, and deployed across all civil and commercial aircraft, as typical product lifecycles can span decades." Proposal accepted by commenter.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51966	Editorial	ASRI	3	21	Introduction characterization	More accurate description of FCC language	The FCC Report and Order encouraged interested stakeholders to establish a multi-stakeholder industry group to study and coordinate on any outstanding issues related to the reallocation of the 3.7 to 4.2 GHz band prior to the spectrum auction, including any potential coexistence issues with radar altimeters	Complete	Accepted	Proposal accepted as-is.	
51967	Low	ASRI	3	28	Introduction characterization	New sentence to clarify MSG status and public access	RTCA announced this multi-stakeholder process publicly and invited public participation in late April 2020.	Complete	Accepted	Proposal accepted as-is.	
51968	Low	ASRI	3	41	Introduction characterization	Corrected/simplified text in sentence	The primary role of TWG-3 has been to facilitate the exchange of technical information between subject matter experts in the aviation and mobile industry (see Appendix B). The analysis conducted by the 5G Task Force and reported here was informed by the technical information exchanged by the mobile industry and the aviation industry regarding their respective systems.	Complete	Accepted with modification	Alternate proposed wording for second sentence: "The analysis performed by the RTCA SC-239 5G Task Force and reported here was informed by this technical information exchange." See also the response to Comment 52003. Proposal accepted by commenter.	
51999	High	CTIA kgraves@ctia.org	3	43961	Context	This section misrepresents the Commission's position on this matter as expressed in the R&O and incorrectly states that no regulatory action was taken by the FCC to protect altimeters. To the contrary, the FCC expressly said that the spectral separation and technical rules it adopted were sufficient to prevent against interference, let alone harmful interference. This section should acknowledge that the FCC determined that no interference would occur and should make clear that the FCC considered the submissions by AVSI, along with other technical filings, in making its determination.	Replace the two sentences at lines 5-10 with the following. These efforts included interference testing and technical analysis conducted by the Aerospace Vehicle Systems Institute (AVSI) [cites], as well as technical data and information provided by T-Mobile and Alion, among other commenters. Based on the record before it, the FCC determined "that the AVSI study does not demonstrate that harmful interference would likely result under reasonable scenarios (or even reasonably 'foreseeable' scenarios to use the parlance of AVSI). We find the limits we set for the 3.7 GHz Service are sufficient to protect aeronautical services in the 4.2-4.4 GHz band. Specifically, the technical rules on power and emission limits we set for the 3.7 GHz Service and the spectral separation of 220 megahertz should offer all due protection to services in the 4.2-4.4 GHz band." The FCC "nonetheless agree[d] with AVSI that further analysis is warranted on why there may even be a potential for some interference given that well-designed equipment should not ordinarily receive any significant interference (let alone harmful interference) given these circumstances" and it encouraged the aviation industry to participate in the C-Band multi-stakeholder group.	Complete	Accepted with modification	SC-239 will remove lines 7-10 as written and replace with: "The FCC Report and Order acknowledged that further analysis is warranted to evaluate the potential for interference to radar altimeters."	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52000	High	CTIA kgraves@ctia.org	3	21-24	Context	This section lacks specificity. The FCC did not encourage the C-Band MSG to "coordinate on any outstanding issues"; it referenced four specific areas for further discussion in paragraphs 333 and 395. The RTCA Report should quote from the Report and Order to note with specificity the four areas for MSG engagement.	Replace the sentence at lines 21-24 with the following. The FCC Report and Order encouraged a multi-stakeholder industry group to be established to address "the complex coexistence issues in this band," including "a framework for interference prevention, detection, mitigation, and enforcement in the 3.7-4.2 GHz band," "best practices and procedures to address issues that may arise during the various phases of the C-band transition," "why there may even be a potential for some interference" to aeronautical operations above 4.2 GHz "given that well-designed equipment should not ordinarily receive any significant interference (let alone harmful interference)" as a result of the spectral separation and rules the FCC adopted, and "coexistence issues related to terrestrial wireless operations below 3.7 GHz."	Complete	Accepted with modification	Alternate text: "The FCC Report and Order encouraged interested stakeholders to establish a multi-stakeholder industry group to study and address the complex coexistence issues in the 3.7-4.2 GHz band, including with aeronautical services." See also Comment 51966.	
52001	Non-Concur	CTIA kgraves@ctia.org	3	21-32	Context	CTIA does not agree with the characterizations in the paragraph and requests correction of the misnomers therein. This paragraph suggests that RTCA represents the multi-stakeholder group called for by the FCC in the R&O as noted in the above point. This is incorrect and must be amended. The multi-stakeholder group evaluating the issues raised in the R&O is the C-Band Multi-Stakeholder Group Technical Working Group 3, which is co-chaired by representatives from the aviation and wireless industries.	Add the following sentences after line 32. The RTCA SC-239 effort is separate and apart from the C-Band Multi-Stakeholder Group and TWG-3. RTCA is an aviation organization, not a cross-industry multi-stakeholder group. In contrast, the C-Band Multi-Stakeholder Group is comprised of representatives from approximately 60 different companies and associations across a dozen different industry sectors, and Technical Working Group 3, which is the forum for discussion of 5G and aeronautical coexistence, is comprised of 27 different companies and associations across the aviation industry, wireless service providers and manufacturers, cable providers, Wireless Internet Service Providers, and others.	Complete	Unresolved	No changes to the text at this time. SC-239 believes the characterization is accurate and in-line with FCC guidance. SC-239 agrees to disagree with CTIA.	
52002	Medium	CTIA kgraves@ctia.org	3	28-32	Context	The RTCA Report should include here a factual statement regarding the participation in SC-239, including the number of companies/associations included in the membership and the general break-down among industry of participating representatives	The RTCA Report should include here a factual statement regarding the participation in SC-239, including the number of companies/associations included in the membership and the general break-down among industry of participating representatives	Complete	Rejected - comment already addressed by current text	Participants of SC-239 (representative names and their companies) are listed in the Membership section of the report. This is aligned with the style guide maintained by RTCA.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52003	High	CTIA kgraves@ctia.org	3	34-38	Context	The C-Band Multi-Stakeholder Group (MSG) is incorrectly characterized here. The C-Band MSG was formed shortly after the C-Band Order was released. The C-Band MSG also was not "established primarily by mobile wireless industry representatives and associations." The language here implies that the C-Band MSG was created in reaction to the RTCA effort, which is not correct. It was formed by stakeholders across numerous industry groups and is comprised of approximately 60 different companies and associations across a wide range of stakeholder interests. The RTCA Report should accurately reflect the development and membership of the C-Band MSG.	Replace the two sentences at lines 34-38 with the following. The C-Band Multi-Stakeholder Group was formed shortly after the FCC Report and Order was released. The C-Band MSG was formed by stakeholders across numerous industry groups, including aviation, and is comprised of approximately 60 different companies and associations across a wide range of stakeholder interests—including aviation, broadcasters and content programmers, cable providers, satellite operators and filter manufacturers, Wi-Fi proponents, Wireless Internet Service Providers, Citizens Broadband Radio Service stakeholders and Spectrum Access System providers, wireless services providers (nationwide, rural, and regional) and manufacturers, and other entities and representative associations. The C-Band MSG includes four Technical Working Groups that were formed to assess the four categories of issues identified by the FCC in the Report and Order. One of those groups, Technical Working Group 3 (TWG-3) is dedicated to the issue of coexistence between 5G and aviation systems—specifically, "why there may even be a potential for some interference given that well-designed equipment should not ordinarily receive any significant interference (let alone harmful interference)" given the spectral separation and rules the FCC adopted. TWG-3 is co-chaired by representatives from the aviation and wireless industries.	Complete	Accepted with modification	SC-239 proposes to replace the entirety of section 2.3.2 with the following: "Following the formation and announcement of the RTCA multi-stakeholder group (SC-239 5G Task Force), a separate group contacted RTCA leadership about another multi-stakeholder group being established. This group, called the C-Band Multi-Stakeholder group, established Technical Working Group 3 (TWG-3) to address the issue of coexistence with aeronautical services. While it is understood that TWG-3 does not plan on submitting any technical reports of its own, it has served as a forum for parts of the aviation and mobile wireless industries to better understand the respective industries' operational requirements and technical parameters. This included the facilitation of a technical information exchange (provided in Appendix B). The analysis performed by the RTCA SC-239 5G Task Force reported here was informed by this technical information exchange."	
52004	High	CTIA kgraves@ctia.org	3	39-41	Context	This statement incorrectly characterizes TWG-3. RTCA should update this language to appropriately and factually discuss the TWG-3 membership.	Replace the sentence at lines 39-41 with the following. TWG-3 participants include representatives from 27 different companies and associations, including: 11 representatives from the aviation industry (including RTCA) who are also active participants in SC-239 and its 5G Task Force; 10 representatives from wireless service providers and manufacturers; four representatives of cable providers; one Wireless Internet Service Provider representative; and one Spectrum Access System administrator.	Complete	Rejected	Refer to Comment 52003.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52086	Low	Jessie Turner/The Boeing Company	3	18	Wording Modification	It states: "However, as safety is paramount for critical aviation systems such as radar altimeters, the development and implementation of new standards is a necessarily slow process". (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	Proposed revision: "However, as safety is paramount for critical aviation systems such as radar altimeters, the development and implementation of new standards will take a significant amount of time". It is also recommended to make a similar change on Page 84, line 45.	Complete	Rejected - duplicate comment.	Duplicate comment - see 51965.	
51969	Medium	ASRI	4	39	Introduction characterization	New sentence to further emphasis the need for worst case parameters throughout study	In all assessments, the analysis must account for the potential worst case operating conditions of all parameters involved to adequately assure aviation safety. Unless compensated for, use of typical or average parameters should be avoided.	Complete	Rejected - duplicate comment.	Duplicate comment. See 51668.	
52087	Medium	Jessie Turner/The Boeing Company	4	30	Analysis Considerations for Combination of Threats	It states: "For each 5G emissions source, the analysis will individually consider both the fundamental emissions - that is, the wanted emissions within the necessary bandwidth of the source—as well as the spurious emissions falling within the 4.2–4.4 GHz band". (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	Does the analysis consider the potential combination of the 3 listed sources of interference occurring at the same time? If so, this should be stated. If not, this should also be stated, with a rationale of why a combination of sources is not considered.	Complete	Accepted	The testing resources and analysis tools available are not capable of simultaneously considering both fundamental and spurious emissions. The point is to characterize these individually to help identify specific operational scenarios which can be targeted for mitigations. As stated in the existing text, "the analysis will individually consider…" Proposed added text: "The potential combination of the two types of interference emissions is not explicitly considered due to the additional complexity of accurately modeling and analyzing such a scenario. Instead, each type of interference is evaluated individually against the interference tolerance thresholds to identify all possible operating conditions in which harmful interference may occur due to either emissions type." Proposal accepted by commenter.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51668	Medium	Seth Frick	5	5	Clarify Worst-Case Analysis Approach	Section 3.2 does not clearly state that all analysis is performed using worst-case assumptions, in accordance with the ICAO Handbook on Radio Frequency Spectrum Requirements for Civil Aviation (Doc 9718).	Add additional text in Section 3.2 after Figure 3-1 stating that all analysis will use worst-case assumptions per guidance from ICAO. Include reference to ICAO Doc 9718, para. 9.4.8.	Complete	Accepted		
51970	Editorial	ASRI	5	11	Introduction characterization	Remove the sentence, seems premature in its intent.	However, the 5G operations allowed by the FCC Report and Order lead to the most urgent potential threat to radar altimeter usage on civil and commercial aircraft, with the broadest possible impact on aviation safety.	Complete	Alternate wording accepted	Proposed alternate wording: "However, the reallocation of the 3.7–3.98 GHz band for 5G operations in the United States has led to the most immediate concern in the aviation industry regarding the potential for harmful interference to radar altimeters used on civil and commercial aircraft."	
51981	High	Andrew Roy Aviation Spectrum Resources, Inc.	5	34	Incorporation of mobile industry data	Need to fully clarify that state of the data provided and why the full responses from the mobile industry are not included. May need further work once the concerns are clarified.	Appendix B contains the questions provided to the commercial mobile industry to further understand how 5G is intended to be implemented in the US. These were used for correspondence between the aviation industry and the mobile industry conducted within TWG-3 for the exchange of technical information related to 5G mobile network operations and radar altimeter characteristics. However, immediately prior to making a draft of this report available for public review, the mobile industry through CTIA, asked that their full responses not be shared publicly in this report. While the full responses are not included, the data provided in the corresponding mobile industry responses has been incorporated into the report in order to provide a meaningful assessment (referenced to Appendix B).	Complete	Rejected with clarification	Propose to reject - Appendix B will get added in final report. Also, text added in Section 2.3.2 for Comment 51968 clearly indicates how this information is used in the analysis. No further clarification is necessary here. Proposal accepted by commenter.	
52006	Non-Concur	CTIA dhyslop@ctia.org	5	44148	Context	CTIA does not agree that "[t]he 5G operations allowed by the FCC Report and Order lead to the most urgent potential threat to radar altimeter usage on civil and commercial aircraft, with the broadest possible impact on aviation safety." The RTCA report does not provide an adequate evidentiary basis to make this claim.	CTIA suggests deletion of this conclusion.	Complete	Rejected with clarification	Statement will not be deleted. However, wording was changed to address Comment 51970. New wording is as follows: "However, the reallocation of the 3.7–3.98 GHz band for 5G operations in the United States has led to the most immediate concern in the aviation industry regarding the potential for harmful interference to radar altimeters used on civil and commercial aircraft."	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52020	Medium	Jim McClay/AOPA	5	25-29	support of general aviation inclusion and data	AOPA supports and appreciates the consideration of, and inclusion of, general aviation aircraft and equipment in this study.	AOPA supports and appreciates the consideration of, and inclusion of, general aviation aircraft and equipment in this study.	Complete	Acknowledged		
51982	Editorial	Andrew Roy Aviation Spectrum Resources, Inc.	6	18	Introduction characterization	Clarified that 5G service changes will also need to be assessed	However, the specific implementation of 5G services, operational use cases, industry standards, or government regulations may change in the future and lead to some of these assumptions or parameters no longer being appropriate	Complete	Accepted	Proposal accepted as-is.	
52008	Non-Concur	CTIA dhyslop@ctia.org	6	7, 10, 12	Context	CTIA does not agree with the characterizations and conclusions in these statements.	Remove the word “thorough” from “a thorough assessment of the resulting risk…”; remove the word “fully” from “fully understand…”; and replace “critical aviation systems will be protected…” with “altimeters functioning in 4.2-4.4 GHz continue to safely operate."	Complete	Accepted with modification	"Thorough" changed to "detailed", and word "fully" removed. No change to final line.	
52088	Medium	Jessie Turner The Boeing Company	6	35	Clarify Situational Awareness Statement	The following sentence "runs-on" and should be clarified: "The radar altimeter plays a critical role in providing situational awareness in these operating conditions in particular, not only by providing a displayed indication of height above terrain to the flight crew, but also by forming the basis of auditory altitude callouts during terminal landing procedures, as well as traffic and ground proximity advisories and warnings". Note: Although radio altitude is not used in the TCAS/ACAS collision avoidance logic (uncorrected barometric altitude is used), radio altitude is used to adjust the sensitivity level of Traffic Advisories (TAs) and Resolution Advisories (RAs) and for providing inhibits at low altitudes. (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	Proposed revision: "The radar altimeter plays a critical role in providing situational awareness by providing: a displayed indication of height above terrain to the flight crew, auditory altitude callouts during approach & landing, and altitude inputs that support TCAS/ACAS and TAWS advisories and warnings".	Complete	Accepted with modification	Alternate proposed wording: "The radar altimeter plays a critical role in providing situational awareness in these operating conditions in particular. Not only do radar altimeters provide a displayed indication of height above terrain to the flight crew, they also form the basis of auditory altitude callouts during terminal landing procedures, as well as TCAS/ACAS and TAWS advisories and warnings." Proposal accepted by commenter.	

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51926	Medium	Hamza Abduselam, FAA	7	44020	CFIT	Not clear how the loss of situational awareness leads to CFIT. This is not consistent with the classifications in table 5-1. Undetected erronous output is the one that leads to CFIT.	Change situation awareness to undetected errouneous output	Complete	Rejected	Table 5-1 is not exhaustive. Loss of situational awareness could indirectly lead to CFIT, for example, if radar altimeter output is lost when operating in low-visibility conditions close to the terrain. Propose to make no changes to the text. Proposal accepted by commenter.	
52021	Medium	Jim McClay/AOPA	7	22-29	recognition of unique risks to general aviation	AOPA recognizes that general aviation is at potentially higher risk from interference resulting generated by 5G base stations, since GA aircraft operate at low altitudes more often.	AOPA recognizes that general aviation is at potentially higher risk from interference resulting generated by 5G base stations, since GA aircraft operate at low altitudes more often.	Complete	Acknowledged		
52089	Medium	Jessie Turner The Boeing Company	7	18	Erroneous Radio Altitude affects TAWS which can cause CFIT	"If HMI is presented to the flight crew or the AFGCS, it may lead to incorrect and dangerous flight operations,…." TAWS should also be included in this statement, since erroneous radio altitude could lead to a late (or no) TAWS warning, and therefore, CFIT. (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	"If HMI is presented to the flight crew, the TAWS. or the AFGCS, it may lead to incorrect and dangerous flight operations,…."	Complete	Accepted	Proposal acccepted as-is.	

Id	Category	Name/Orga nization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52090	High	Jessie Turner The Boeing Company	7	36	AC 25.1309-1A is superseded by the Aersenal Version	For Air Transport aircraft, AC 25.1309-1A, which was released on June 21, 1988, is called out, but is no longer used. This AC does not define the hazard classification of "Hazardous/Severe Major" as identified in Table 5-1. AC 25.1309-1A has been replaced by AC/AMJ 25.1309 (Draft Arsenal version) dated June 10, 2002 which does define the "Hazardous" hazard classification. The AC/AMJ 25.1309 (Draft Arsenal version) has been required to be used for Part 25 certification compliance by the FAA & EASA (via FAA Issue Papers (IPs) and EASA Certification Review Items (CRIs)) for the last 15 years. (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	On this page, replace: "AC 25.1309-1A [13] for transport category airplanes" with "AC/AMJ 25.1309 (Draft Arsenal version) for transport category airplanes". The link to [13] on Page 87 should be changed to: "[13] Advisory Circular/Advisory Material Joint AC/AMJ 25.1309, "System Design and Analysis" – Dated June 10, 2002". {Note: An official online copy of AC/AMJ 25.1309 (e.g., posted by the FAA or EASA) could not be found}	Complete	Accepted	Also added AMJ to acronym list.	
51778	Medium	Jean-Luc ROBIN (AIRBUS)	8	8	Classification of operational impact	in the 2nd raw it is indicated: All Phases of Flight - Catastrophic	it is more accurate to allocate the Catastrophic classification as follow: - Catastrophic in landing - Hazardous in approach and take off - Major in cruise Also consider to add a reference to AC 25 .1329-1C	Complete	Accepted with modification	Propose adding a footnote on the word Catastrophic in the table to clarify this. Footnote can include AC reference. Proposal accepted by commenter.	
51779	Editorial	Jean-Luc ROBIN (AIRBUS)	8	4	typo	replace 10-5 by 10-3	The allowable occurrence rate is greater than 1 x 10-3 per flight hour for Minor failure conditions	Complete	Rejected - duplicate comment.	Duplicate comment - see 52091	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51912	Low	Lee Nguyen, FAA	8	43928	Target level of safety; Quantitative probability for Minor failu	The quantitative probability for Minor failure condition is greater than of the order of 1 x 10-5 per flight hour, of the order of 1 x 10-5 per flight hour or less, but greater than of the order of 1 x 10-7 for Major failure conditions, of the order of 1 x 10-7 per flight hour or less, but greater than of the order of 1 x 10-9 for Hazardous/Severe Major failure conditions, and of the order of 1 x 10-9 per flight hour or less for Catastrophic failure conditions.	Change "The allowable occurrence rate is greater than 1 x 10-5 per flight hour for Minor failure conditions, 1 x 10-5 per flight hour or less for Major failure conditions, 1 x 10-7 per flight hour or less for Hazardous/Severe Major failure conditions, and 1 x 10-9 per flight hour or less for Catastrophic failure conditions." to: "The allowable occurrence rate is greater than of the order of 1 x 10-5 per flight hour for Minor failure conditions, of the order of 1 x 10-5 per flight hour or less, but greater than of the order of 1 x 10-7 for Major failure conditions, of the order of 1 x 10-7 per flight hour or less, but greater than of the order of 1 x 10-9 for Hazardous/Severe Major failure conditions, and of the order of 1 x 10-9 per flight hour or less for Catastrophic failure conditions."	Complete	Rejected	Propose to reject: suggested change is technically correct but may be unnecessarily complicated for readers not familiar with the aviation industry. Proposal accepted by commenter.	
52091	Medium	Jessie Turner The Boeing Company	8	4	Minor hazard class failure rate must be ? 1E-03	"The allowable occurrence rate is greater than 1 x 10-5 per flight hour for Minor failure conditions…" A Minor hazard classification requires a failure rate of ? 1 x 10-3 per flight hour. (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	Modify to state: "The allowable occurrence rate is 1 x 10-3 per flight hour or less for Minor failure conditions,…"	Complete	Accepted	Proposal accepted as-is.	

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52092	High	Jessie Turner The Boeing Company	8	8	Undetected loss of PWS is considered a Major hazard level	Table 5-1, 3rd row states that the Undetected loss of PWS is considered to be a Hazardous/Severe Major hazard level. System Requirements Document (SRD) 10.2 “Airborne Short and Long Range Wind Shear Predictive Systems”, which was developed by the FAA and industry, contains specific criteria for PWS System Safety Analyses. Specifically, SRD 10.2 section 4.1.18 states: "The probability of an unannunciated failure shall be 10-5 per flight hour of system operation, or less". (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	Propose that the Severity for this scenario be Major	Complete	Accepted with modification	Proposed change: add a footnote stating that for some aircraft manufacturers, this case may be Major instead of Hazardous. Proposal accepted by commenter.	
52093	High	Jessie Turner The Boeing Company	8	8	Unannunciated NCD is Hazardous class during Cat 2/3 Low Visibili	Table 5-1, 7th row states: "Loss of capability to perform approach and landing in low-visibility conditions (Category II/III approach), leading to unnecessary diversion and jeopardizing safety of surrounding airspace" is classified as a Major severity. This is considered to be a Hazardous/Severe Major failure condition if it occurs at very low altitude (	Propose that the Severity for this scenario be Hazardous/Severe Major	Complete	Accepted with modification	Propose to change to Hazardous, and add a footnote stating that for some aircraft manufacturers this may only be Major depending on the altitude at which it occurs. Proposal accepted by commenter.	
51780	Low	Jean-Luc ROBIN (AIRBUS)	9	4	Proposition to add a reference	add reference to illustrate the statement: "the examples provided are intended…. May be experienced and their severity"	Accident where Undetected Erroneous Altitude of Radio Altimeter have caused unnoticed erroneous AFGCS behaviour has occured in the past [43].	Complete	Rejected	Not sure this fits here. This section gives example operational impacts, but doesn't discuss actual scenarios that have occurred in the past. Propose to make no changes to the text. Proposal accepted by commenter.	

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51777	Medium	Greg Belaus / Uber, greg.belaus @uber.com	12	15-23	47 CFR § 22.925	22.925 does not preclude the use of cellular for airborne applications. It applies to the 800MHz Band 5 Cellular spectrum only. While this might preclude the use of cellular phones on aircraft, as this band is widely used in phones, there are other airborne users of cellular that skip these cellular bands but use others. The FCC recently acknowledged this in the FCC Report on Section 374 of the FAA Reauthorization Act of 2018, p8, "For example, 47 CFR part 22 imposes a prohibition on the airborne use of 800 MHz Cellular service... In addition, several flexible-use bands have restrictions against aeronautical use in the underlying allocation, as reflected in the Non-Federal Table of Allocations. Absent such restrictions, however, current law does not prohibit the use of flexible-use bands for UAS operations."	This paragraph should be rewritten to make it clear that 22.295 only covers some airborne cellular restrictions, particularly line 17 where the question is asked whether "this scenario is even expected to occur". Cellular is indeed likely to be used for airborne use cases, and not just by those ignoring regulation.	Complete	Accepted	Proposed wording: "Although 47 CFR § 22.925 specifically prohibits the use of cellular telephones onboard any aircraft while that aircraft is airborne, this regulation applies in the context of current 800 MHz cellular services and it is not clear how or if it would be extended to 5G operations in the 3.7–3.98 GHz band [18]. Further, studies have shown that not all users will comply with this regulation in all instances, due to either apathy or inattentiveness." Also adding the following footnote text: "The FCC Report and Order [5] establishes the 3.7–3.98 GHz service under 47 CFR § 27—Miscellaneous Wireless Communications Services, and not under 47 CFR § 22—Public Mobile Services." Proposal accepted by commenter, with additional references to the separate 47 CFR sections in the main text.	
51795	Editorial	Garmin	12	20-21	duplicated text	back-to-back instances of "due to either"	Delete one of the instances	Complete	Accepted	Proposal accepted as-is.	
51927	Editorial	Hamza Abduselam, FAA	12	21	Editorial comment	Delete the repeated phrase" due to either due to etiher…"	Delete the repeated phrase	Complete	Rejected - duplicate comment.	Duplicate comment - see 51795.	
51928	Medium	Hamza Abduselam, FAA	13	26	Radar Altimeter Models	The ITU-R M.2059 model is mentioned to provide characteristics for 10 different radar altimeter models but in only three models are specifed in Tables 6-1 and 6-2 (A2, A3. A5). Are the rest of the models covered under the FMCW models?	Clarfity if the rest of the models are covered under the category FMCW models if that is the intent.	Complete	Rejected	Only the worst-case altimeter model for each protection criterion is listed. Thus the protection criteria given will cover all models. Propose to make no changes to the text. Proposal accepted by commenter.	

Id	Category	Name/Orga nization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52094	Medium	Jessie Turner The Boeing Company	13	20	Pulse Altimeters	It states: "Note that the criterion for false altitude reports is only directly applicable to FMCW radar altimeters, and excludes pulsed altimeters". It would be good for readers of the document to understand why this is true. (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	Add a brief description of why pulse altimeters are not subject to false altitude reporting.	Complete	Accepted	Proposed added text: "This does not mean that pulsed altimeters are not susceptible to false altitude reports caused by interference—it is simply a result of the way in which the false altitude criterion is defined, namely in terms of the power contained within a certain assumed resolution bandwidth in the intermediate frequency (IF) stage of the receiver." Proposal accepted by commenter.	
51796	Editorial	Garmin	15	43832	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "applications"	Complete	Accepted	Proposal accepted as-is.	
51797	Editorial	Garmin	15	11	punctuation	Long sentence	Suggest separating this into two sentences, such as “receiver. It can instead”.	Complete	Accepted		
51798	Editorial	Garmin	15	12	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "environment"	Complete	Accepted	Proposal accepted as-is.	
51799	Editorial	Garmin	15	21	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "drawbacks"	Complete	Accepted		
51800	Editorial	Garmin	15	36	missing word	Should the word "source" be followed by "code"?	Add word if appropriate	Complete	Accepted		
51971	Editorial	Andrew Roy Aviation Spectrum Resources, Inc.	15	10	Testing clarification	Further text to clarify why black box testing is sufficient in this case	This approach does not require any specific determination of interference mechanisms in the receiver, and since the radio altimeter only outputs a single parameter (altitude) based on the direct measurement of a transmitted signal’s time of flight, it can instead be based upon the actual behavior observed from the radar altimeters in an interference test environment, at the “black-box” level	Complete	Accepted with modification	Alternate proposed wording: "This approach does not require any specific determination of interference mechanisms in the receiver. Instead, the interference tolerance is be based upon the actual behavior observed from the radar altimeters in an interference test environment at the “black-box” level to give the most direct indication of the expected real-world performance." Proposal accepted by commenter.	
51801	Editorial	Garmin	16	46	punctuation	Long sentence	Suggest separating this into two sentences, such as “general. It must be”.	Complete	Accepted		

Id	Category	Name/Orga nization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51972	Editorial	Andrew Roy Aviation Spectrum Resources, Inc.	16	24	ICAO ref	Clarified ICAO reference summary	The ICAO Handbook on Radio Frequency Spectrum Requirements for Civil Aviation [17] states in paragraph 9.2.23 that an additional safety margin should be considered for interference analysis concerning aeronautical safety systems.	Complete	Accepted		
51802	Medium	Garmin	17	44023	Add supporting evidence	If there is additional supporting evidence which would substantiate the decision to utilize the 6 dB aviation safety margin in scenarios of Hazardous/Severe Major and above failure conditions, it would be good to include here.	Add supporting evidence.	Complete	Rejected	This is based on engineering judgment given the likelihood of our worst-case assumptions occurring simultaneously. Per the guidance from ICAO, the 6 dB safety margin should always be applied unless sufficient analysis can demonstrate, on a case-by-case basis, that it is not necessary. Our judgment in the report identifies that such analysis may be sufficient up to the point of operational scenarios with Major failure conditions, but not with Hazardous or Catastrophic failure conditions.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52016	High	CTIA dhyslop@ctia.org	17	14	Corrections Due to Base Station Beam Steering Error	TWG-3 guidance mistakenly indicated that beam steering was additive to mechanical down tilt. Instead, it is inclusive. For the urban scenario with 10 degrees of mechanical downtilt, typical usage will not exceed 20 degrees of steering from the antenna boresight, and will not create significant grating lobes toward the sky. Additional factors which should be reflected in simulations include: (1) Base stations generally generate multiple simultaneous beams, pointing in different directions and serving different UEs. The power present in any given beam is less than the full EIRP of the site. (2) Close-in UEs, by virtue of their significantly reduced path loss, may be served by the side lobes; extreme beam steering angles are not typically seen. . These factors are not present in the RTCA study, and will reduce the 5G power levels in the direction of the aircraft	P. 17, line 14, section 6.3.3.1.1: The base station simulations must consider additional factors which will reduce the EIRP in a given beam. One factor is that multiple simultaneous beams, pointing in different directions, will share the total EIRP, lessening the power placed into each individual beam. A second factor is that close-in UEs, by virtue of their significantly reduced path loss, may be served by the side lobes; extreme beam steering angles are not typically seen	Complete	Accepted with modification	Base station antenna patterns were computed in accordance with Rec. ITU-R M.2101 using the inputs received from the wireless industry experts in TWG-3. The characterization of worst-case interference conditions in the report is still valid, and if nominal operating conditions produce lower EIRP then this may serve as a mitigation. However, such EIRP reductions are not guaranteed by regulations or industry specifications, and thus the interference analysis for an aeronautical safety service must consider the allowable worst-case conditions. Additional analysis has been conducted and will be presented in the report which considers the AAS scan angles to be inclusive of mechanical down-tilt (see Appendix D). These results make it clear that the fundamental conclusions of the report will not change. No changes will be made to the main body text.	
51781	Editorial	Jean-Luc ROBIN (AIRBUS)	19	6	typo	replace base by based	…output power from the base stations based on the peak power…	Complete	Accepted	Proposal accepted as-is.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52017	High	CTIA dhyslop@ctia.org	19	13	Corrections Due to Base Station Beam Steering Error	TWG-3 guidance mistakenly indicated that beam steering was additive to mechanical down tilt. Instead, it is inclusive. For the urban scenario with 10 degrees of mechanical downtilt, typical usage will not exceed 20 degrees of steering from the antenna boresight, and will not create significant grating lobes toward the sky. Additional factors which should be reflected in simulations include: (1) Base stations generally generate multiple simultaneous beams, pointing in different directions and serving different UEs. The power present in any given beam is less than the full EIRP of the site. (2) Close-in UEs, by virtue of their significantly reduced path loss, may be served by the side lobes; extreme beam steering angles are not typically seen. . These factors are not present in the RTCA study, and will reduce the 5G power levels in the direction of the aircraft	P. 19, footnote 13 change to read: “The vertical scan angle of the AAS array is specified in reference to the local horizon. An urban base station with 10 degrees of mechanical downtilt may scan +10 to -20, which is effectively from horizon to 30 degrees below horizon.”	Complete	Accepted with modification	Refer to Comment 52016.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52018	High	CTIA dhyslop@ctia.org	19	14	Corrections Due to Base Station Beam Steering Error	TWG-3 guidance mistakenly indicated that beam steering was additive to mechanical down tilt. Instead, it is inclusive. For the urban scenario with 10 degrees of mechanical downtilt, typical usage will not exceed 20 degrees of steering from the antenna boresight, and will not create significant grating lobes toward the sky. Additional factors which should be reflected in simulations include: (1) Base stations generally generate multiple simultaneous beams, pointing in different directions and serving different UEs. The power present in any given beam is less than the full EIRP of the site. (2) Close-in UEs, by virtue of their significantly reduced path loss, may be served by the side lobes; extreme beam steering angles are not typically seen. . These factors are not present in the RTCA study, and will reduce the 5G power levels in the direction of the aircraft	P. 19, footnote 14 change to read: “Mechanical down tilt gives the broadside pointing angle of the array below horizon, and allows calculation of the scan angle above and below the broadside direction	Complete	Accepted with modification	Refer to Comment 52016.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51973	High	Andrew Roy Aviation Spectrum Resources, Inc.	20	9	5G basestation spurious emission levels	The use of suggested -20 dBm/MHz spurious limits vs the FCC specified limits of -13 dBm/MHz are conflicting without any reference. The text should comment on the difference, and that the mobile industry is proposing a different limit to those in the rules FCC.	New foot note: The -20 dBm/MHz spurious emission levels proposed by the mobile industry are different than the FCC specified limit of -13 dBm/MHz in the C-Band Report and Order. For such an analysis to remain valid, their should be some formal indication of the -20 dBm/MHz spurious limit being adopted by all operators intending to deploy base stations in the 3.7-3.98 GHz range.	Complete	Accepted with modification	This borders on RTCA issuing recommendations to the FCC and/or mobile wireless industry, which I don't think is appropriate. I would prefer to keep this discussion to a different forum than the report. After further discussion, agreed to add general footnotes indicating that all assumed 5G operational characteristics are not explicitly limited by the FCC Order (with a few exceptions). Also propose to change final paragraph of Section 11.2 to state "minor operational limitations which are not restricted by current regulations". Proposal agreed by commenter.	
51671	Medium	Seth Frick	21	1	Poor Figure Legibility	Many figures throughout the document, beginning with Figure 6-5, have poor legibility due to compression artifacts.	Save document with less figure compression or higher fidelity settings, or provide figures in a separate data package.	In Process	Accepted	Final formatting will be handled by Rebecca.	
51803	Editorial	Garmin	21	10	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "Order"	Complete	Accepted		
51974	Editorial	Andrew Roy Aviation Spectrum Resources, Inc.	21	7	Assessment conditions	Clarify worst case conditions	Although the expectation is that most 5G deployments in the United States in the 3.7–3.98 GHz band will use AAS base stations, the possibility of fixed-beam sectoral antennas, such as those commonly used in fourth-generation Long-Term Evolution (4G LTE) mobile networks, is not precluded by the FCC Order, and thus cannot be ruled out in accounting for all worst case conditions	Complete	Accepted		

51975	High	ASRI	24	1	Use of body loss in table 6-6	Aviation studies have all traditionally ignored body loss under worst case assessments as it is not constant or can be guaranteed, especially for when operated under aircraft as the general public have a habit of taking pictures/videos of low flying aircraft, giving a fully unobstructed propagation path to the aircraft. Suggest removal of body loss for propagation calculations	Remove body loss from calculations.	Complete	Rejected with clarification	Proposed clarifying text: "A body loss term is applied to all UEs as indicated in Table 6 6. Note that for specific operational scenarios considering an aircraft overflying active UEs, it may not be appropriate to include a body loss term in the worst-case analysis—for example, in the case of spectators in a viewing area near the end of a runway who will likely be holding their devices up and away from their bodies to take pictures. However, since the scenario considered here is instead a generic analysis of an aircraft flying over an area inhabited by active UEs distributed in accordance with Rep. ITU-R M.2292, the body loss term is considered to be applicable." Agreed upon text: "A body loss term is applied to all UEs as indicated in Table 6-6. Note that for specific operational scenarios considering an aircraft overflying active UEs, it may not be appropriate to include a body loss term in any additional worst-case analyses—for example, in the case of spectators in a viewing area near the end of a runway who will likely be holding their devices up and away from their bodies to take pictures. However, since the scenario considered here is instead a generic analysis of an aircraft flying over an area inhabited by active UEs distributed in accordance with Rep. ITU-R M.2292, the body loss term is considered to be applicable in this limited example. However, this parameter should be	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
										removed for any specific scenario analyses, especially for UEs which are active near areas in which aircraft operate at low altitudes."	
51804	Editorial	Garmin	26	9	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "band"	Complete	Accepted		
51805	Editorial	Garmin	27	19	punctuation	Add comma after phrase "Once again"	Add comma	Complete	Accepted		
51806	Editorial	Garmin	28	36	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "polarizations"	Complete	Accepted		

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52019	High	CTIA dhyslop@ctia.org	31	Section 7	Corrections Due to Base Station Beam Steering Error	TWG-3 guidance mistakenly indicated that beam steering was additive to mechanical down tilt. Instead, it is inclusive. For the urban scenario with 10 degrees of mechanical downtilt, typical usage will not exceed 20 degrees of steering from the antenna boresight, and will not create significant grating lobes toward the sky. Additional factors which should be reflected in simulations include: (1) Base stations generally generate multiple simultaneous beams, pointing in different directions and serving different UEs. The power present in any given beam is less than the full EIRP of the site. (2) Close-in UEs, by virtue of their significantly reduced path loss, may be served by the side lobes; extreme beam steering angles are not typically seen. . These factors are not present in the RTCA study, and will reduce the 5G power levels in the direction of the aircraft	P. 31, section 7, all: Altimeter test data for all altimeters must be provided to understand the range of performance within each Usage Category. Mitigation approaches are dependent on understanding the breadth of any potential impacts.	Complete	Accepted with modification	Refer to Comment 52016.	
51807	Editorial	Garmin	32	23	clarification	Suggest adding the following words after the word "analysis"	Add the words ", yet remains a valid analysis method, ”	Complete	Accepted with modification	Alternate proposed wording: "Therefore, the aggregation of the interference tolerance thresholds by usage category greatly simplifies such analysis—without compromising the analysis results—by providing a single ITM that is sufficient to ensure that any radar altimeter model which could be used in a given scenario will be protected."	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52022	Medium	Jim McClay/AOPA	32	43961	recognition of radar altimeter equipment specific to general avi	AOPA recognizes and appreciates the consideration given to the size, sophistication, and interference tolerance of radar altimeter equipment used by general aviation aircraft.	AOPA recognizes and appreciates the consideration given to the size, sophistication, and interference tolerance of radar altimeter equipment used by general aviation aircraft.	Complete	Acknowledged		
51808	Medium	Garmin	33	43832	clarification	May not be correct to say this sentence as written. A TSO approval does not grant permission to install an article aboard an aircraft.	Add wording such as "through a combination of the TSO authorization and Type Certification processes" or something similar.	Complete	Rejected	The TSO process does not allow an aircraft operator to install the equipment without the TC process, but a TSO does constitute an approval from the FAA that the equipment can be installed on certified aircraft. The "certified" qualifier implies that the aircraft-level certification process (i.e. TC) also takes place.	
51809	Editorial	Garmin	38	24	punctuation	Remove unnecessary comma separating dependent clause	In footnote 24, remove unnecessary comma after word "altimeters"	Complete	Accepted		
51937	Medium	Edward Hahn Air Line Pilots Association (ALPA)	40	21	Add paragraph about Autoland	Autoland capability, for which proper radar altimeter performance is critical, is one common means of obtaining approval to perform CAT II/III approaches and landings. This linkage is needed to claim the impact on flare modes later in the section. Suggest inserting a paragraph here to explain this.	"In addition, many CAT II/III operations are approved by the FAA on the basis of using the Autoland function in the AFGCS. In these cases, the Autoland function must be engaged during a CAT II or III approach [36]. As described in Section 5.3, the radar altimeter is a critical input to this system, an undetected erroneous altitude from the radar altimeter is considered a Catastrophic hazard."	Complete	Accepted	Added to first paragraph of Section 8.1.1.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51938	High	Edward Hahn Air Line Pilots Association (ALPA)	40	6 (footnote reference)	Update description of CAT II / III in Footnote 25	The latest version (dated 7/2/2018) of AC 120-118 Sec 3-8 (b) eliminates reference to the a, b, c subcategories of CAT III and also changes the RVR values approved for CAT II and III. CAT III a/b/c were also eliminated from 14 CFR 1 definitions. The footnote should be updated to reflect these changes.	"CAT II ILS approaches are associated with a Decision Height (DH) of less than 200 feet (but not less than 100 feet) and a Runway Visual Range (RVR) of less than 1800 feet (but not less than 1000 feet). CAT III approaches are associated with a RVR of less than 1000 feet. Limitations to RVR are generally due to meteorological conditions or nighttime operations. The DH is the altitude at which the pilot must either establish a visual reference along the runway, or abort the landing. CAT III approaches may include an Alert Height (AH) in lieu of a DH, above which a missed approach should be flown if a fault in automation is detected. For CAT II/III approaches, the AH or DH is determined using the radar altimeter output."	Complete	Accepted		
51810	Editorial	Garmin	41	6	clarification	Suggest adding "in Chicago, Illinois." after the word "(ORD)".	Add words	Complete	Accepted		
51811	Medium	Garmin	43	43957	Add explanation	Is there explanation or rationale for why we chose this vertical scan angle?	Suggest providing rationale for why this scan angle was chosen - presumably because it's worst-case?	Complete	Accepted	Added text indicating this is a worst-case assumption.	
51812	Medium	Garmin	45	28-31	Add explanation	Is there explanation or rationale for why we chose these vertical scan angles?	Suggest providing rationale for why these scan angles were chosen - presumably because they're worst-case?	Complete	Accepted	Added text indicating this is a worst-case assumption.	
51813	Medium	Garmin	56	43992	Suggestion	The last few sentences in this paragraph seems like they might be better located in the Findings and Conclusions section	Move if appropriate.	Complete	Rejected	These sentences are considered to be generally applicable to the discussion regarding grating lobes which is necessary for the results analysis given here. Propose to make no changes to the text.	
51814	Editorial	Garmin	56	19	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "coefficient"	Complete	Accepted		
51923	Editorial	Lee Nguyen, FAA	57	3	Clarification	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Complete	Rejected	Proposed text will not fit without reducing font size and degrading legibility. Figure is adequately descriptive given the surrounding context and figure caption.	
51931	Editorial	Lee Nguyen, FAA	62	1	Clarification	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Complete	Rejected	Proposed text will not fit without reducing font size and degrading legibility. Figure is adequately descriptive given the surrounding context and figure caption.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51932	Editorial	Lee Nguyen, FAA	64	3	Clarification	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Complete	Rejected	Proposed text will not fit without reducing font size and degrading legibility. Figure is adequately descriptive given the surrounding context and figure caption.	
51933	Editorial	Lee Nguyen, FAA	69	1	Clarification	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Complete	Rejected	Proposed text will not fit without reducing font size and degrading legibility. Figure is adequately descriptive given the surrounding context and figure caption.	
51815	Editorial	Garmin	71	2	punctuation	To be consistent with other figure titles, a colon should be added after "Figure 10-29"	Change to "Figure 10-29:"	Complete	Accepted		
51934	Editorial	Lee Nguyen, FAA	71	1	Clarification	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Change "Safe Limit" in Y-axis to "Safe Interference Limit".	Complete	Rejected	Proposed text will not fit without reducing font size and degrading legibility. Figure is adequately descriptive given the surrounding context and figure caption.	
51911	Low	Lee Nguyen, FAA	75	12	O'Hare runway 27L CAT II/III approach 5G fundamental interferenc	A signifiant number of aircraft go-arounds during low visibility operations in high volume traffic due to NCD coud cause ATC to stop issuing the approach clearance to that runway during low visibility operations.	Add after "This places additional burden on air traffic controllers to safely manage the airspace": A signifiant number of aircraft go-arounds during low visibility operations in high volume traffic due to NCD coud cause ATC to stop issuing the approach clearance to that runway during low visibility operations.	Complete	Accepted with modification	Alternate proposed text: "In addition, if multiple landing aircraft are impacted by RF interference and must execute missed approaches in low-visibility conditions with high volume air traffic, controllers may need to stop issuing approach clearances to the specific runway or airport that is affected." Proposal accepted by commenter.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52009	High	CTIA dhyslop@ctia.org	82	13-21	Context	UEs cannot attach unless a downlink signal is received with sufficient signal quality, and a UE not connected to the network will not transmit. Also, EIRP for handheld devices is more typically 23 dBm given the need to conserve battery and to meet SAR requirements. The FCC rule of 30 dBm is generally used by desktop modems with access to an electrical power source. Transmit power control will further reduce EIRP in many situations.	Altitude at which interference was observed must be provided.	Complete	Rejected	The analysis of UEs onboard aircraft considers the overall minimum ITM value for each usage category. The altitude at which this minimum occurs can be observed from the ITM plots in Section 9. However, note that the computed worst-case aggregate UE interference will exceed the ITMs for some usage categories at many different altitudes. The FCC Report and Order makes no distinction for the moment regarding the type of UEs when setting the emissions limits. Transmit power control is addressed in the discussion of the results. No change to current wording.	
51816	Medium	Garmin	83	43834	five UE vs one UE	Analysis concludes the exceedance is significant enough that UE Tx control power is not expected to be sufficient to prevent harmful interference for Usage Category 2 & 3 RAs. Would this be true if the analysis were also run for a single UE as was done for section 10.5.2? Section 6.3.3.3 assumes 5 UEs are operated simultaneously, which seems unlikely for small GA airplanes and helicopters that utilize Usage Category 2 & 3 RAs; these aircraft often only have 4 to 6 pax seats including the pilot.	Suggest running single UE analysis as was done for section 10.5.2 and including results.	Complete	Rejected	This would require a change to the bandwidth assumptions for the UEs, which would reduce the radiated PSD, or a determination of the ITM with a different total bandwidth. For the former case, a single UE with 100 MHz transmit bandwidth will result in the computed interference levels shifting downward by 10*log10(5) = 7 dB. Given that the Usage Category 2 and 3 ITMs are exceeded by 33 and 46 dB, respectively, this is an insignificant difference. The point here is to illustrate the worst case, and other cases can be considered as necessary using the material provided in the report.	
51976	Editorial	Andrew Roy Aviation Spectrum Resources, Inc.	84	32	Conclusion Characterization	Added that the results apply to a range of landing scenarios	The results presented in this report reveal a major risk of harmful interference to radar altimeters on all types of civil and commercial aircraft caused by 5G telecommunications systems in the 3.7–3.98 GHz band in a broad range of operational scenarios.	Complete	Accepted		

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52010	Non-Concur	CTIA dhyslop@ctia.org	84	32-42	Context	CTIA does not agree with the results and characterizations presented in this section. The analyses that RTCA relies on for such conclusions have multiple worst-case on worst-case assumptions, as well as multiple margins added. This, along with the shortcomings of the aggregated altimeter performance data, prevents stakeholders from making informed conclusions from these analyses and results in non-consensus regarding the draft report's findings. In any case, mitigation and remediation cannot be properly planned without understanding the depth and variation of performance among the altimeters tested. The draft report also does not offer any potential mitigations and thus doesn't add any clarity or value to efforts to resolve the aviation industry's concern.	CTIA suggests deletion of these conclusions.	Complete	Unresolved	Justification of using worst-case assumptions is now given in Section 3.2 with the following text (see response to Comment 51668): "In accordance with International Civil Aviation Organization (ICAO) standard practices, the analysis conducted in this report will generally consider all variables at their worst-case limits. This provision is outlined in paragraph 9.4.8 of the ICAO Handbook on Radio Frequency Spectrum Requirements for Civil Aviation [17], and has been similarly followed in other assessments of RF interference in aeronautical safety systems caused by telecommunications emissions."	
51817	Low	Garmin	85	4	stronger statement on possible retrofit technical solution	re: suggest using a stronger phrase than "if one exists,"	Suggest replacing with "which to this point remains unexplored and may not even exist,"	Complete	Accepted		

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51818	Low	Garmin	85	43959	improve readability / understandability	The sentence "Therefore, it is critical that the performance of radar altimeters which are currently in service across many thousands of civil aircraft, which is characterized by this report, be fully understood and the risks and operational impacts due to interference be appreciated." is difficult to read and understand. In particular, the phrase "which is characterized by this report" is really relative to the phrase "performance of radar altimeters". This relationship is lost by the intervening phrase "which are currently in service across many thousands of civil aircraft".	Suggest rewriting as two separate sentences.	Complete	Accepted with modification	Alternate proposed wording: "Therefore, it is critical that the performance of radar altimeters which are currently in service across tens of thousands of civil aircraft be understood and the risks and operational impacts due to interference be appreciated based on the characterization provided in this report."	

51924	High	Lee Nguyen, FAA	85	29-32	New radar altimeter designs will be capable of safe operation wi	The sentence "After this point, new radar altimeter designs which seek such approvals from CAAs for use on certified aircraft will be capable of safe operation in the presence of the anticipated RF interference from 5G systems operating in the C-band." indicates that the new radar altimeter designs will solely account for the mitigations. The report states "exceedance of the safe interference limit by expected 5G signals in the 3.7–3.98 GHz band: …. 48 dB for business, regional, and general aviation airplanes (as shown in Figure 10-12), and 34 45 dB for helicopters (as shown in Figure 10-16). Further, the impacts are not only limited to the intentional emissions from 5G systems in the 3.7–3.98 GHz band, but also the spurious emissions from such systems which may land within the protected 4.2–4.4 GHz radar altimeter band directly. In this case, the worst-case exceedance of the safe interference limit is 28 dB for business, regional, and general aviation airplanes (as shown in Figure 10-25), and 12 dB for helicopters (as shown in Figure 10-29). A strong undesired interference signals outside of the altimeter normal receive bandwidth cannot be sufficiently filtered in the receiver to prevent front-end overload or other effects.	Revise the sentence as commented.	Complete	Accepted with modification	Changed "will be capable of safe operation" to "are expected to be capable of safe operation". Proposal accepted by commenter.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
						Also, protection of radar altimeters from the 5G spurious broadband undesired interference signals cannot be achieved by radar altimeter receiver designs (e.g. RF filter). Mitigations might include new radar altimeter designs, potential 5G base stations including antenna limitations, and potential radar altimeter operating limitation, etc. Unless it is certain that “the new radar altimeter designs that seek such approvals from CAAs for use on certified aircraft will be capable of safe operation in the presence of the anticipated RF interference from 5G systems operating in the C-band” (4.2–4.4 GHz), suggest revising this statement to not having the new radar altimeter designs solely account for the mitigations.					

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51929	High	Hamza Abduselam, FAA	85	21-26	Future MOPS Development	The paragraph seems to suggest the new MOPS will be developed " with additional performace requirements for RF interference rejection - are expected..". Are we saying that we would be able to to close the link for the new radar altimeter with the currently proposed power levels of the 5G? In other words, would we be able to design an RA that is robust enough to operate in an environement where the 5G emissions levels are as specified in their current power levels, and with the additional safety margin of 6dB accounted for?	The WG may need to soften the language since we have not assessed the feasibilty of the future RA design.	Complete	Rejected - duplicate comment.	Not an exact duplicate, but refer to Comment 51924. Text has been modified to state that altimeters designed to the new MOPS are "expected to be capable of safe operation" in the presence of 5G interference, not that they "will be capable of safe operation" as in the original text. Proposal accepted by commenter.	
51977	Low	Andrew Roy Aviation Spectrum Resources, Inc.	85	3	Conclusion Characterization	Need to clarify the timelines of potential retrofits.	Even a technical solution which may be viable for retrofit installations, if one exists, will take a decade or more and significant funding to properly validate and deploy across all affected civil aircraft operating in the United States.	Complete	Rejected	If a retrofit is possible (which is currently unknown), it could potentially be implemented for the affected aircraft in less than a decade (but still several years). This depends on the scope of such a retrofit, both in terms of the number and type(s) of affected aircraft, and the extent of the technical solution. Propose no changes to text, keeping timeline open-ended given the limited information currently available on what possible solutions may exist. Proposal accepted by commenter.	
51978	Low	Andrew Roy Aviation Spectrum Resources, Inc.	85	32	Conclusion Characterization	Need to clarify the timelines of current usage.	However, as noted in Section 11.2, radar altimeters exhibiting the performance described in this report will continue to operate on commercial and civil aircraft for the foreseeable future, up to several decades to be replaced as part of a natural lifecycle.	Complete	Accepted with modification	Proposed wording: "However, as noted in Section 11.2, radar altimeters exhibiting the performance described in this report will continue to operate on commercial and civil aircraft for many years into the future." Proposal accepted by commenter.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52011	Non-Concur	CTIA dhyslop@ctia.org	85	43961	Context	CTIA does not agree with the results and characterizations presented in this section. The draft report claims to account for "the performance of radar altimeters which are currently in service," but it does not provide data in any format to determine the performance of any single radar altimeter or even a statement confirming that all altimeters tested are actually in service. Instead, the report relies on aggregated worst-case data for groups of altimeters that prevent stakeholders from being able to evaluate the performance of any single radar altimeter.	CTIA suggests deletion of these conclusions.	Complete	Unresolved	Refer to Comment 52010. No additional changes to current wording.	
52012	Non-Concur	CTIA dhyslop@ctia.org	85	15-18	Context	CTIA does not agree with the results and characterizations presented in this section. While RTCA concludes that that mitigation will likely require significant action to be taken by both the aviation industry and the mobile wireless industry, it does so based on analyses that are overly conservative and that are packed with multiple worst case assumptions and unjustified margins. Further, as noted above, mitigation and remediation cannot be properly planned without understanding the depth and variation of performance among the altimeters tested.	CTIA suggests deletion of these conclusions.	Complete	Unresolved	Refer to Comment 51990 and 52010.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51919	Editorial	Lee Nguyen, FAA	86	44020	Reference website	Change to “Available from EUROCAE eShop at http://www.eurocae.net.”	Change to “Available from EUROCAE eShop at http://www.eurocae.net.”	Complete	Accepted		
51920	Editorial	Lee Nguyen, FAA	86	14	Reference website	Change to “Available from RTCA Store at http:/www.rtca.org.”	Change to “Available from RTCA Store at http:/www.rtca.org.”	Complete	Accepted		
51921	Editorial	Lee Nguyen, FAA	86	41-42	Reference website	“Change to “Available from ARINC Standards Store at https://www.aviation-ia.com/product-categories/arinc.”	“Change to “Available from ARINC Standards Store at https://www.aviation-ia.com/product-categories/arinc.”	Complete	Accepted		
51820	Editorial	Garmin	90	24	missing blank line	The prior major section headings all have a blank line before them	Insert blank line	In Process	...	Final formatting will be handled by Rebecca.	
51916	Editorial	Lee Nguyen, FAA	90	25	Put in upper case letter	Put "t(he)" in upper case letter "T(he)" for "the percentage of time ….".	Put "t(he)" in upper case letter "T(he)" for "the percentage of time ….".	Complete	Accepted		
51917	Editorial	Lee Nguyen, FAA	90	41	Put in upper case letter	Put "t(he)" in upper case letter "T(he)" for "the ability of ….".	Put "t(he)" in upper case letter "T(he)" for "the ability of ….".	Complete	Accepted		
51930	Editorial	Lee Nguyen, FAA	90	18-19	Reference website	Change to “Available from RTCA Store at http:/www.rtca.org.”	“Change to “Available from ARINC Standards Store at https://www.aviation-ia.com/product-categories/arinc.”	Complete	Accepted		
51918	Editorial	Lee Nguyen, FAA	91	16	Put in upper case letter	Put "t(he)" in upper case letter "T(he)" for "the measure of ….".	Put "t(he)" in upper case letter "T(he)" for "the measure of ….".	Complete	Accepted		
51939	High	Edward Hahn Air Line Pilots Association (ALPA)	91	32	Update definitions of CAT II/III	The latest version (dated 7/2/2018) of AC 120-118 Sec 3-8 (b) eliminates reference to the a, b, c subcategories of CAT III and also changes the RVR values approved for CAT II and III.	For Category II, update text: "?runway visual range not less than 300m (1000ft). (FAA AC 120-118)" For Category III, update text: "?runway visual range less than 300m (1000 ft). (FAA AC-120-118)"	Complete	Accepted		
51782	Editorial	Jean-Luc ROBIN (AIRBUS)	92	44	Accronym	AAS= Active Antenna System or Advanced Antenna System	AAS Active (or Advanced) Antenna System	Complete	Accepted		
51821	Editorial	Garmin	92	40	missing blank line	The prior major section headings all have a blank line before them	Insert blank line	In Process	...	Final formatting will be handled by Rebecca.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51913	Editorial	Lee Nguyen, FAA	92	13	Put in upper case letter	Put "a" in upper case letter "A" for "a set of Interference ….".	Put "a" in upper case letter "A" for "a set of Interference ….".	Complete	Accepted		
51914	Editorial	Lee Nguyen, FAA	92	18	Put in upper case letter	Put "t(he)" in upper case letter "T(he)" for "the maximum allowable level ….".	Put "t(he)" in upper case letter "T(he)" for "the maximum allowable level ….".	Complete	Accepted		
51915	Editorial	Lee Nguyen, FAA	92	6	CAT II/III precision approach and landing	Change "For precision instrument CAT II/III approach and landing, ..." to "For CAT II/III precision approach and landing, ..."	Change "For precision instrument CAT II/III approach and landing, ..." to "For CAT II/III precision approach and landing, ..."	Complete	Accepted		
51822	Editorial	Garmin	99	15	abbreviation	re: "NASA"	Change to "National Aeronautics and Space Administration (NASA)" since this is the first (and only) instance of NASA used anywhere in the text other than the abbreviations list	Complete	Accepted		
51823	Editorial	Garmin	99	26	Word choice	Replace word "are" with "were" for correct tense	Correct tense of word	Complete	Accepted		
51824	Editorial	Garmin	99	32	Word choice	Suggest adding word "mechanisms" after "signal processing"	Add word if appropriate	Complete	Accepted with modification	Added "algorithms" instead of "mechanisms".	
51825	Medium	Garmin	100	2	Update diagram	Block diagram needs to be updated to show all correct altitudes used in testing and to add notch filter used in testing.	Update block diagram	Complete	Accepted	Dave Redman will need to be contacted to provide an updated block diagram.	
51826	Editorial	Garmin	100	12	Word choice	Suggest deleting "with high reliability" and saying "without operationally significant interference" instead.	Update if appropriate	Complete	Accepted		
51827	Editorial	Garmin	100	14	abbreviation	re: "AUT"	Add to abbreviations list	Complete	Accepted		
51828	Editorial	Garmin	101	1	abbreviation	re: "Tx"	Add to abbreviations list	Complete	Accepted		
51829	Editorial	Garmin	101	4	abbreviation	re: "Rx"	Add to abbreviations list	Complete	Accepted		
51830	Editorial	Garmin	101	6	abbreviation	re: "USB"	First use in document. Spell out and add to abbreviations list	Complete	Accepted		
51831	Editorial	Garmin	101	7	abbreviation	re: "VAC"	First use in document. Spell out and add to abbreviations list	Complete	Accepted		
51832	Editorial	Garmin	101	7	abbreviation	re: "Hz"	First use in document. Spell out and add to abbreviations list	Complete	Accepted		
51833	Editorial	Garmin	101	7	abbreviation	re: "VDC"	First use in document. Spell out and add to abbreviations list	Complete	Accepted		

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51834	Editorial	Garmin	101	13	misused word	Seems like "equivalent" should be "equivalence"	Change to "equivalence"	Complete	Rejected - resolved by other comment.	Instead of changing the word, deleted preceding phrase "required for" based on Comment 51835.	
51835	Editorial	Garmin	101	13	Word choice	Suggest deleting the two words "required for"	Delete words	Complete	Accepted		
51836	Editorial	Garmin	101	15	unclear language	It isn't clear whether "These" is referring to only the Type 8 voltage / discrete signals or also to the Type 6, 7, and 9 ARINC 429 output bus described earlier in the paragraph.	Clarify text	Complete	Accepted	Changed to "The precision analog altitude and discrete output signals from the Type 8 altimeter".	
51837	Medium	Garmin	101	21-22	Cross coupling	Suggest that the sentence beginning with "The test equipment" be deleted, since the 76s2 setup did not simulate antenna cross-coupling.	Delete sentence	Complete	Accepted		
51838	Editorial	Garmin	101	46	keep with next	A.2.4 section header should be on same page as its first paragraph	Adjust formatting	Complete	Accepted	Final formatting will be handled by Rebecca.	
51670	Editorial	Seth Frick	102	30	Broken Table Reference	Table reference given in text is inaccurate ("Table 5 1"), with no cross-reference.	Change text to include correct cross-reference to Table 5-1.	Complete	Accepted		
51839	Editorial	Garmin	102	13	abbreviation	re: "DC"	First use in document. Spell out and add to abbreviations list	Complete	Accepted		
51840	Editorial	Garmin	102	15	Word choice	Suggest add the words "or less" after "160 MHz"	Add words if appropriate	Complete	Accepted		
51841	Editorial	Garmin	102	23	verb tense	re: "is attenuated". Other paragraphs in this appendix describe what "was" done.	Change "is" to "was"	Complete	Accepted		
51842	Editorial	Garmin	102	30	incorrect cross-reference	re: "Table 5 1"	Should be "Table 5-1" (missing hyphen)	Complete	Rejected - duplicate comment.	Duplicate comment - see 51670.	
51843	Editorial	Garmin	102	31	punctuation	Long sentence	Suggest splitting in two and say "catastrophic. This situation is coupled"	Complete	Accepted with modification	Split sentences, but instead began second sentence with "This situation is exacerbated by".	
51844	Editorial	Garmin	102	39	unclear language	It isn't clear what "these" refers to in "these consideration". Additionally, it seems like "consideration" should be plural.	Change to "these aerodrome considerations"	Complete	Accepted		

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51672	Low	Seth Frick	103	2	Clarify Landing Aircraft Altitude in WCLS	Text does not explain circumstances of 200 ft aircraft altitude in WCLS.	Add clarifying text stating that the landing aircraft need not cross the runway threshold at exactly 200 ft AGL, but that the aircraft is assumed to be at 200 ft AGL as it is in-line with the first aggressor aircraft on the taxiway and apron. This could occur in circumstances other than a 200 ft threshold crossing, depending on the specific aerodrome geometry.	Complete	Accepted	Proposal accepted as-is.	
51845	Editorial	Garmin	103	9	abbreviation	re: "IPL"	First use in document. Spell out and add to abbreviations list	Complete	Accepted	Spelled out acronym. Only one usage, so not added to acronym list.	

51846	Medium	Garmin	104	1	Figure A-2(b)	There are legitimate situations where an airplane could cross 200 feet above the runway threshold (e.g., purposefully landing long to use an exit taxiway further down a long runway, or a steep approach where it is not possible to follow the glideslope directly to landing, or when executing a missed approach). However, the Figure A-2 (b) depiction of the aircraft being on the 3 degree glideslope (GS) is inconsistent with a normal 3 degree GS that would place the aircraft about 50 feet above the runway threshold. While there are some situations where a steep GS angle raises the threshold crossing height (TCH), e.g., SBGP (Embraer Unidade Gavião Peixoto, Brazil) ILS Y RW20 which has a 5.50 degree GS and a TCH of 99 feet, even this situation is not typical when examining the latest cycle ARINC 424 navigation data. For example: - The well-known steep approaches at EGLC (London City, UK) have TCH of 34 and 35 feet respectively on the ILS RW09 and RW27 approaches - The LSZA (Lugano, Switzerland) IGS RW01 approach has the maximum GS angle of 6.65 degree, but its TCH is only 48 feet - In theory the GS antenna could be moved down the runway ~4000 feet instead	Adjust figure to show appropriate position of airplane relative to the glideslope	Complete	Accepted	Suggest removing the glide slope from the figure completely, since this is not relevant to the WCLS. Dave Redman will need to make the change and provide a new figure.	

Id	Category	Name/Orga nization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
						of the typical ~1000 feet to obtain a 200 ft TCH using a 3 degree GS. However, there is no evidence such an approach exists. - The maximum TCH at any airport is 99 feet but there is only a single instance of any approach with a 99 foot TCH (the previously mentioned SBGP ILS Y RW20) - Most steep approach TCH are					
51847	Editorial	Garmin	104	1	unclear language	Seems like a word is missing between "is" and "for" in the phrase "victim RA is for aircraft". Also, seems like "is" should be "was" to be consistent with prior language.	Clarify text	Complete	Accepted	Proposed text: "The worst-case aggregate FMCW interference power at the victim RA is for determined assuming that the aircraft on the ground in the WCLS geometry are equipped with RAs that transmit at one watt average power and for with each aircraft having a triplex RA installation."	
51848	Editorial	Garmin	105	23	keep with next	A.2.7 section header should be on same page as its first paragraph	Adjust formatting	Complete	Accepted	Final formatting will be handled by Rebecca.	
51849	Editorial	Garmin	106	4	abbreviation	re: "R&S"	Add to abbreviations list	Complete	Accepted	Spelled out acronym in all instances, so not added to acronym list.	
51850	Editorial	Garmin	106	12	punctuation	missing comma after "7.5.1"	Add comma	Complete	Accepted		
51851	Editorial	Garmin	106	12	abbreviation	re: "NR-FR1-TM1.1 "	Add to abbreviations list	Complete	Accepted		

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51852	Editorial	Garmin	106	17	incorrect document reference	re: "FCC Report & Order" should be "FCC Report and Order" to be consistent with reference "[5]". Additionally, it seems like the "[5]" should be included to be consistent with other references.	Change to "FCC Report and Order [5]"	Complete	Accepted		
51853	Editorial	Garmin	106	20	abbreviation	Seems like "TM1.1" should be "NR-FR1-TM1.1" to be consistent with the abbreviation used earlier in this paragraph	Change to "NR-FR1-TM1.1"	Complete	Accepted		
51854	Editorial	Garmin	106	22	unclear language	It isn't clear what "this" refers to in "The intent of this testing".	Change to "The intent of the 5G fundamental emissions testing"	Complete	Accepted with modification	Alternate proposed wording: "the 5G interference tolerance testing".	
51855	Low	Garmin	106	30-34	Notch filter	As stated in Section A.3.1, it seems that the necessary compensation for the notch filter was determined by measuring the insertion loss of the filter over the proper frequency range on a network analyzer. Was this method actually used instead?	Clarify which method was used to determine loss compensation for notch filter.	Complete	Accepted with modification	Insertion loss compensation for the 5G fundamental waveform was determined using the 100 MHz channel power measurement as described. The network analyzer characterization of the filter frequency response was used to determine the worst-case VSG spurious output during fundamental emissions tests based on the minimum observed filter rejection across the 4.2-4.4 GHz band. Changed one sentence prior to Figure A-5 to clarify that the filter response measured on the network analyzer was not used directly in determining the loss compensation values for the 5G fundamental emissions tests. Sentence now states: "The band-stop filter was also characterized using a network analyzer to evaluate the stopband attenuation."	
51856	Editorial	Garmin	107	13	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "control"	Complete	Accepted	Also added the word "instead" after "but".	

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51857	Editorial	Garmin	107	29-30	abbreviation	Seems like "TM 1.1" should be "NR-FR1-TM1.1" to be consistent with the abbreviation used in A.2.7.1	Change to "NR-FR1-TM1.1"	Complete	Accepted		
51858	Editorial	Garmin	107	31	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "input"	Complete	Accepted		
51859	Editorial	Garmin	107	35	unclear language	It isn't clear what "this" refers to in "This is shown in Figure A-3."	Change to "This measurement is shown in Figure A-3."	Complete	Accepted		
51860	Editorial	Garmin	108	5	unclear language	It isn't clear what "this" refers to in "This occurred with"	Change to "The channel power reached 1 dB above the spectrum analyzer noise floor with"	Complete	Accepted with modification	Proposed alternate wording: "…until the measured channel power rose to 1 dB above the spectrum analyzer noise floor".	
51861	Editorial	Garmin	109	10	verb tense	re: "is continuously recorded". Other paragraphs in this appendix describe what "was" done.	Change "is" to "was"	Complete	Accepted		
51862	Editorial	Garmin	109	18	punctuation	"post processed" is missing a hyphen	Change to "post-processed"	Complete	Accepted		
51863	Editorial	Garmin	109	18	missing cross-reference	re: "as described above"	Change "above" to the appropriate section cross-reference (maybe section A.2.8?)	Complete	Accepted	Added cross-ref to Section A.2.8.	
51864	Editorial	Garmin	110	43832	punctuation	"ARINC 707 defined" is missing a hyphen	Change to "ARINC 707-defined"	Complete	Accepted with modification	Changed to "defined in ARINC 707" at the end of the sentence.	
51865	Editorial	Garmin	110	5	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "(NCD)"	Complete	Accepted		
51866	Medium	Garmin	110	44182	unclear logic	re: "Longer interference power on dwell times were thus implemented". It isn't clear why the preceding statement about 429 bus samples of 30 / second and resolution of 1 foot would "thus" require longer interference power on dwell times.	Clarify text	Complete	Accepted with modification	Alternate proposal: delete this entire paragraph. It seems like a complete non-sequitur.	
51867	Editorial	Garmin	110	21	abbreviation	Seems like "TM 1.1" should be "NR-FR1-TM1.1" to be consistent with the abbreviation used in A.2.7.1	Change to "NR-FR1-TM1.1"	Complete	Accepted		
51868	Editorial	Garmin	110	25	missing cross-reference	re: "as described above"	Change "above" to the appropriate section cross-reference	Complete	Accepted	Added cross-ref to Section A.2.7.1.	

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51869	Editorial	Garmin	111	4	missing cross-reference	re: "as described above"	Change "above" to the appropriate section cross-reference	Complete	Accepted	Added cross-ref to Section A.2.7.2.	
51870	Editorial	Garmin	111	7	verb tense	re: "becomes unacceptable". Other paragraphs in this appendix describe what "was" done.	Change to "became unacceptable"	Complete	Accepted		
51871	Editorial	Garmin	111	17	missing document reference	re: "specified by ARINC 707" is missing the document reference number.	Change to "specified by ARINC 707 [47]"	Complete	Accepted		
52013	High	CTIA kgraves@ctia.org	113	Appendix B	Context	CTIA suggests that Appendix B be reformatted to show the iterative nature of the TWG-3 information exchange, including dates and additional submissions	Provide dates for when questions on both sides (wireless and aviation) were asked and, likewise, provide dates for when the answers were provided	Complete	Accepted		

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52014	High	CTIA kgraves@ctia.org	113	Appendix B	Context	CTIA suggests that Appendix B be reformatted to show questions that were asked but which did not receive responses.	Add a paragraph in Appendix B as follows. [Please note that we are reviewing the materials and will flag for RTCA during the adjudication process any other questions that did not receive responses]. On June 16 "What is the frequency dependent rejection of each altimeter model outside of the altimeter operating band of 4200-4400 MHz." We received a response on July 1 indicating that aviation "anticipate[d] being able to provide the frequency-dependent rejection data for the altimeter receivers no later than July 15th" and that "some of the data may be provided as a total combined system, accounting for both the antenna frequency response and the altimeter receiver frequency-dependent rejection." On July 13, we received a graph showing "Envelope of Radar Altimeter Receiver FDR for Various Commercial Altimeters." On July 20, we again requested more than the envelope that was procided. We stated, "Specifically, we are seeking real world data relative to each sensor represented in ITU-R Recommendation M.2059-0 Tables 1 &2, in order to accurately estimate the impact on the radio-altimeters operating within the 4200-4400 MHz band. As noted in ITU-R M.2059, different types of altimeters have a wide range of operating parameters and performance. The generic envelope of frequency domain rejection provided on July 13 does not provide enough information to perform analyses for the various altimeter types. To avoid a worst case of one altimeter being used with a worst case of a different altimeter, creating a situation that would not exist in the real world, we are requesting the underlying FDR data for each of the altimeter models. To that effect, we ask that the aviation community provide the underlying data overlaid with ITU-R Recommendation M.2059-0 Annex 3 of Table 3, for each individual sensor that went into the creation of the envelope. In addition, when providing the data set, please indicate which representative altimeter in ITU-R Recommendation M.2059-0 Tables 1 &2 the data corresponds to, in order for us to properly match it with the receiver sensitivity thresholds." On August 5, we received a response indicating that "This data would be considered proprietary by the individual altimeter manufacturers, and there is no mechanism to obtain or distribute it through AVSI or RTCA." The information was thus not provided within TWG-3.	Complete	Accepted with modification	Appendix B contains the complete and exact wording used in the written technical information exchange that took place in TWG-3. With the addition of dates on each item to address Comment 52013, this comment will be addressed without the need for additional formatting changes. Also, the proposed solution in this comment editorializes the TWG-3 information exchange process, which SC-239 will not do.	

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52015	High	CTIA kgraves@ctia.org	113	Appendix B	Context	Appendix B should be updated to include the context in which the information was exchanged within TWG-3	Add the following sentences, consistent with the language in CTIA's July 1 response. In the interests of advancing the discussion within Working Group #3—5G/Aeronautical Coexistence, the wireless and aviation industries agreed to exchange questions and provide information regarding the general operating parameters for 5G networks to be deployed in the 3.7 GHz Service and altimeter and other aeronautical operations in the 4.2-4.4 GHz band, respectively. The information that the wireless industry provides here is in response to questions from RTCA on behalf of the aeronautical industry. This information is provided solely for the purposes of the work of Working Group #3 in response to Federal Communications Commission GN Docket No. 18-122, and reflects the unique environment and network characteristics within the United States. Neither the information nor studies or analyses thereof may be used for any other purposes or made available in any other fora. By making this information available, the wireless industry does not endorse or support any analyses or studies that the aeronautical industry may perform.	Complete	Accepted with modification	This wording will be added to Appendix B, but an additional disclaimer from CTIA explicitly allowing the use of the responses provided in the TWG-3 information exchange by RTCA will also be needed.	Disclaimer provided by CTIA, to be included in Appendix B: "CTIA does not object to RTCA publication of the information into the public domain, but CTIA disputes the report's analysis and conclusions."
51669	High	Seth Frick	115	43866	Update Appendix B	Appendix B has been removed for public comment release version.	Update Appendix B to include full TWG-3 technical information exchange if material is approved for publication. If not, update Appendix B to include TWG-3 questions and responses from aviation stakeholders only.	Complete	Rejected - duplicate comment.	Duplicate comment - see 52013.	
51872	Editorial	Garmin	116	4	misspelled word	re: "fhe"	Change to "the"	Complete	Accepted		
52005	Non-Concur	CTIA kgraves@ctia.org	43894	41-43, 1-2	Context	This sentence incorrectly states that the RTCA Report is the deliverable from TWG-3.	Replace these lines with the following: The primary role of the TWG-3 has been to facilitate the exchange of technical information between subject matter experts in the aviation and wireless industries. Specifically, the aviation stakeholders and 3.7 GHz Service stakeholders exchanged information regarding the 5G operating environment and altimeter technical characteristics. The TWG-3 members, including RTCA, agreed that use of any information exchanged would not reflect any judgments or support with respect to the findings in any analysis utilizing such information and that all reports developed based on the exchanged information would be presented to TWG-3. No reports developed in whole or in part from the information exchanged within TWG-3 can be appropriately characterized as consensus documents or work product of TWG-3 or the C-Band MSG.	Complete	Unresolved	Refer to Comment 52003.	

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52007	High	CTIA kgraves@ctia.org	43957	34-35, 1-2	Context	The reference to Appendix B should make clear the parameters of the TWG-3 information exchange.	Replace the sentence starting at page 5, line 34 with the following. Appendix B contains the correspondence between the aviation industry and wireless industry conducted within TWG-3 for the exchange of technical characteristics that would successfully define a 5G environment in the U.S. and altimeter technical characteristics. The information was exchanged under the context of the Report and Order, which found there to be no likelihood of harmful interference from 3.7 GHz Service operations to aeronautical operations above 4.2 GHz. The TWG-3 members, including RTCA, agreed that use of any information exchanged would not reflect any judgments or support with respect to the findings in any analysis utilizing such information.	Complete	Rejected	This section reflects only the organization of the document. No changes to current text. See the other comments directly on Appendix B.	
51819	Editorial	Garmin	86-90	all of Section 13	justification	Unlike the rest of the document, the paragraphs in Section 13 are not justified	Adjust formatting	Complete	Rejected	The reference formatting gets very messy when attempting to use justified margins. Leaving as-is.	
51786	Editorial	Garmin	i	4	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "licenses"	Complete	Accepted		
51787	Editorial	Garmin	i	9	punctuation	Remove unnecessary comma separating dependent clause	Remove unnecessary comma after word "worldwide"	Complete	Accepted		
51788	Editorial	Garmin	i	14	clarification	Add clarifying word	Add word "expected" before "5G"	Complete	Rejected - duplicate comment.	Duplicate comment - see 51946 ("future" 5G networks instead of "expected").	
51789	Editorial	Garmin	i	20	clarification	Add clarifying words	Change "This includes" to "This process included"	Complete	Accepted		
51790	Medium	Garmin	i	25	expected vs actual	re: "the presence of the 5G interference will result" implies that the interference exists today	Suggest changing to "the presence of the expected 5G interference will result"	Complete	Accepted		
51791	Editorial	Garmin	i	25	new paragraph	Suggest starting a new paragraph after the word "safety" so the subject of the next sentences are more apparent to readers.	Begin new paragraph after the word "safety" and before the following word "The".	Complete	Accepted	Began new paragraph at proposed sentence and merged with the following paragraph (which also discusses the analysis results).	
51792	Editorial	Garmin	i	44-45	grammar	re: "aviation systems will be continue to be" has two instances of "be"	Suggest changing to "aviation systems will continue to be"	Complete	Rejected - duplicate comment.	Duplicate comment - see 51925.	
51922	Editorial	Lee Nguyen, FAA	i	9	Clarification	Change to "…., and support several critical safety-of-life aircraft functions throughout multiple phases of flight."	Change to "…., and support several critical safety-of-life aircraft functions throughout multiple phases of flight."	Complete	Accepted		

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51925	Editorial	Hamza Abduselam, FAA	i	45	Typo	delete "be" between "wll" and "continue"	Correct the typoe	Complete	Accepted		
51935	Editorial	Executive Summary	i	30	Same Words used multiple times	The phrase "catastrophic failures leading to multiple fatalities" is basically the same as the phrase used on line 12	Suggest shortening sentence on Line 30 to end : "?for broad impacts to aviation operations in the United States."	Complete	Rejected	Propose to reject - executive summary is meant primarily for non-aviation audiences who may not have the same appreciation for "catastrophic failures" without additional context. Proposal accepted by commenter. Comment will be rejected and no change made to the text.	
51944	Editorial	ASRI	i	5	Exec Summary Characterization	Corrected/simplified text in sentence	The frequency spectrum from 3.7–3.98 GHz has been reallocated for flexible use licenses, and will be auctioned to mobile network operators beginning in December 2020.	Complete	Accepted		
51945	Editorial	ASRI	i	8	Exec Summary Characterization	Corrected/simplified text in sentence	The aviation industry noted in the FCC rulemaking process that deployment of 5G networks in this frequency band may introduce harmful radio frequency (RF) interference to radar altimeters currently operating in the globally-allocated 4.2–4.4 GHz aeronautical band	Complete	Accepted		
51946	Editorial	ASRI	i	13	Exec Summary Characterization	Corrected/simplified text in sentence	The aviation industry has explained to the FCC that further study is needed to adequately characterize the performance of currently fielded radar altimeters operating in the presence of RF interference from future 5G networks in the 3.7–3.98 GHz band, as well as the risk of harmful interference and associated impacts to safe aviation operations, such that appropriate mitigations could be developed and employed before flexible use operations are deployed.	Complete	Accepted	Minor wording change: "before such 5G networks begin operation" instead of "before flexible use operations are deployed."	
51947	Editorial	ASRI	i	16	Exec Summary Characterization	Corrected/simplified text in sentence	RTCA Special Committee 239 (SC-239) formed a 5G Task Force open to interested public participation in Apr 2020 specifically to lead this study effort as a multi-stakeholder group.	Complete	Accepted	Minor wording change: "RTCA Special Committee 239 (SC-239) formed a 5G Task Force in April 2020 specifically to lead this study effort as a multi-stakeholder group with open participation from the interested public."	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51948	Editorial	ASRI	i	18	Exec Summary Characterization	Corrected/simplified text in sentence	Using information supplied by the commercial mobile industry as well as radar altimeter manufacturers, this report provides a quantitative evaluation of radar altimeter performance in the face of RF interference from expected 5G telecommunication emissions in the 3.7–3.98 GHz band, as well as a thorough assessment of the risk of such interference occurring and impacting aviation safety	Complete	Accepted with modification	Alternate proposed wording: "Using technical information supplied by the mobile wireless industry and radar altimeter manufacturers, this report provides a quantitative evaluation of radar altimeter performance regarding RF interference from expected 5G emissions in the 3.7–3.98 GHz band, as well as a thorough assessment of the resulting risk of such interference occurring and impacting aviation safety." Proposal accepted by commenter.	
51949	Editorial	ASRI	i	20	Exec Summary Characterization	Corrected/simplified text in sentence	The report is based on the testing of many representative radar altimeter models to empirically determine their tolerance to expected 5G interference signals; the development of interference models and assumptions to predict the received interference levels across a wide range of operational scenarios, such that they may be compared to the empirical tolerance limits; and a thorough study of multiple real-world operational scenarios for civil aircraft in which the presence of the 5G interference will result in a direct impact to aviation safety	Complete	Rejected - duplicate comment.	Duplicate comment - see 51789.	
51950	Editorial	ASRI	i	25	Exec Summary Characterization	Spilt out into new para and corrected/simplified text in sentence	The results presented in this report reveal a major risk of harmful interference caused by 5G telecommunications systems in the 3.7–3.98 GHz band to radar altimeters on all types of civil aircraft—including commercial transport airplanes; business, regional, and general aviation airplanes; and both transport and general aviation helicopters	Complete	Accepted		
51951	Editorial	ASRI	i	29	Exec Summary Characterization	Corrected/simplified text in sentence	The report provides a clear indication that the risk will be widespread and has the potential for broad impacts to aviation operations in the United States, including the possibility of catastrophic failures leading to multiple fatalities, in the absence of appropriate mitigations	Complete	Accepted		
51952	Editorial	ASRI	i	32	Exec Summary Characterization	Corrected/simplified text in sentence	The extent of the RF interference is summarized by the worst-case exceedance of the safe interference limit of radar altimeters by expected 5G signals in the 3.7–3.98 GHz band	Complete	Accepted		
51953	Editorial	ASRI	i	37	Exec Summary Characterization	Corrected/simplified text in sentence	In this latter case, the worst-case exceedance of the safe interference limit is 28 dB for business, regional, and general aviation airplanes (as shown in Figure 10?25), and 12 dB for helicopters (as shown in Figure 10?29).	Complete	Accepted		

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51954	Editorial	ASRI	i	41	Exec Summary Characterization	Corrected/simplified text in sentence	As such, it is envisioned that this report will be useful to those in the aviation industry, the wireless telecommunications industry, and both aviation and spectrum regulators to fully understand and take appropriate steps in a timely fashion to mitigate this risk	Complete	Accepted		
51979	Editorial	ASRI	i	2	Summary Characterization	Corrected/simplified text in sentence	The Federal Communications Commission (FCC) has taken recent action in the United States to reallocate a portion of the 3.7–4.2 GHz frequency band historically used by the Fixed Satellite Service to flexible mobile and fixed services, including 5G applications (which flexible use services will be referred to as "5G services" for convenience).	Complete	Accepted with modification	Alternate proposed wording: "The Federal Communications Commission (FCC) has recently taken action to reallocate a portion of the 3.7–4.2 GHz frequency band, making the frequency spectrum from 3.7–3.98 GHz available for flexible use including 5G applications. This spectrum will be auctioned to new licensees beginning in December 2020." Proposal accepted by commenter.	
51991	High	CTIA kgraves@ctia.org	i	43959	Context	This section fails to recognize the FCC findings and thus omits important context. The FCC expressly said that the spectral separation and technical rules were sufficient to prevent against interference, let alone harmful interference. This section should acknowledge that the FCC determined that no interference would occur and should make clear that the FCC considered the submissions by AVSI, along with other technical filings, in making its determination	Insert a new sentence after the sentence at lines 5-8 as follows. Based on the record before it, the FCC found that interference was not likely to occur, stating: "We find the limits we set for the 3.7 GHz Service are sufficient to protect aeronautical services in the 4.2-4.4 GHz band. Specifically, the technical rules on power and emission limits we set for the 3.7 GHz Service and the spectral separation of 220 megahertz should offer all due protection to services in the 4.2-4.4 GHz band."	Complete	Rejected	In the executive summary, no change based on this finding. Please see how further comments in the body of the report are addressed regarding references to the FCC Report and Order. Note that RTCA will not attempt to characterize the actions and statements of the FCC - the Report and Order is only incorporated by reference to explain the new spectrum allocation and associated operating restrictions necessary for the analysis.	
51992	Non-Concur	CTIA dhyslop@ctia.org	i	18-20	Context	For reasons noted herein, CTIA does not agree that this report is "a thorough assessment of the resulting risk of such interference occurring and impacting aviation safety."	CTIA suggests removal of this statement.	Complete	Unresolved	Please review updated executive summary which has accounted for this comment, among others. The statement will not be completely removed as suggested. Please provide a technical reference in support of any further suggested changes.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51993	Non-Concur	CTIA dhyslop@ctia.org	i	24-25	Context	For reasons noted herein, CTIA does not agree with the characterization of analysis conducted by RTCA as "a thorough study of multiple real-world operational scenarios for civil aircraft in which the presence of 5G interference will result in a direct impact to aviation safety."	CTIA suggests removal of this statement.	Complete	Unresolved	Please review updated executive summary which has accounted for this comment, among others. The statement will not be completely removed as suggested. Please provide a technical reference in support of any further suggested changes.	
51994	Non-Concur	CTIA dhyslop@ctia.org	i	25-29	Context	CTIA does not agree that the data and analysis presented in the RTCA Report "reveal a major risk of harmful interference to radar altimeters on all types of civil aircraft . . . which could be caused by 5G telecommunications systems in the 3.7-3.98 GHz band."	CTIA suggests deletion of this conclusion.	Complete	Unresolved	CTIA's disagreement with the technical conclusions outlined in the report does not provide a sufficient basis for the deletion of these conclusions. No change to current wording. SC-239 would consider a technical reference which disputes our conclusion.	
51995	Non-Concur	CTIA dhyslop@ctia.org	i	29-31	Context	CTIA does not agree with the conclusion presented in the RTCA Report that "[t]his risk is widespread and has the potential for broad impacts to aviation operations in the United States, including the possibility of catastrophic failures leading to multiple fatalities."	CTIA suggests deletion of this conclusion.	Complete	Unresolved	CTIA's disagreement with the technical conclusions outlined in the report does not provide a sufficient basis for the deletion of these conclusions. No change to current wording. SC-239 would consider a technical reference which disputes our conclusion.	
51996	Non-Concur	CTIA dhyslop@ctia.org	i	32-39	Context	CTIA does not agree that the data and analysis presented in the RTCA Report correctly demonstrate "exceedance of the safe interference limit by expected 5G signals."	CTIA suggests deletion of this conclusion.	Complete	Unresolved	CTIA's disagreement with the technical conclusions outlined in the report does not provide a sufficient basis for the deletion of these conclusions. No change to current wording. SC-239 would consider a technical reference which disputes our conclusion.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
51997	Non-Concur	CTIA dhyslop@ctia.org	i	40-41	Context	CTIA does not agree that "[t]he risk of harmful interference to radar altimeters and its associated impact to aviation safety cannot be adequately mitigated by the aviation industry acting alone." The FCC made clear that its technical rules and the spectral separation between 3.7 GHz Service operations and aeronautical operations above 4.2 GHz were sufficient to prevent against interference, let alone harmful interference.	CTIA suggests deletion of this conclusion.	Complete	Unresolved	The final paragraph of the executive summary has been modified accounting for this comment, among others, including providing the technical basis for this conclusion. The conclusion will not be deleted as suggested.	
51998	Non-Concur	CTIA dhyslop@ctia.org	i	43	Context	As further explained herein, aggregated altimeter performance data as provided in the RTCA Report does not permit stakeholders to "fully understand" the coexistence environment. Aggregated altimeter performance data based only on the envelope of the worst performing altimeter for the various use categories shrouds the performance of specific radar altimeters in specific scenarios, and prevents stakeholders from performing realistic analyses or making informed assessments about the extent of any impact and whether mitigation measures might be necessary or beneficial.	Test data for all altimeters is essential to understand the range of performance and potential mitigation approaches.	Complete	Unresolved	Refer to Comment 51990.	

Id	Category	Name/Organization	Page	Line	Subject	Comment	Proposal	Status	Resolution	Details of Committee Disposition	Commentor's Final Rebuttal (as needed)
52084	Medium	Jessie Turner/The Boeing Company	i	40	Mitigation Responsibility	It states: "The risk of harmful interference to radar altimeters and its associated impact to aviation safety cannot be adequately mitigated by the aviation industry acting alone. As such, it is envisioned that this report will be useful to those in the aviation industry, the wireless telecommunications industry, and both aviation and spectrum regulators to fully understand and appropriately account for this risk". The wireless telecommunications industry and spectrum regulators will likely state that the issue should be mitigated by the aviation industry alone. (Boeing Comment: Jessie Turner, jessie.turner@boeing.com)	It is highly recommended that objective evidence or rationale within the report (e.g., from sections 10 and 11) be referenced (after the first sentence) in order to substantiate this statement.	Complete	Accepted with modification	Added reference to results summary in previous paragraph. Proposed wording: "Given the extent to which the safe interference limits are exceeded and the breadth of the impacts to aviation safety, the risk of harmful interference to radar altimeters cannot be adequately mitigated by the aviation industry acting alone." Proposed wording accepted by commenter.	
51943	Editorial	Andrew Roy Aviation Spectrum Resources, Inc.	Throughout		Language Clarification	Need to be specific when referring to external entities	The wireless industry should be called the mobile industry	Complete	Accepted	Used "mobile wireless industry"	
51980	Editorial	ASRI	Throughout document		Band terminology	Technically both S- and C-band are in the range considered. So all C-band references should say S- and C-band. May also need the title to be changed to 3.7-3.98 GHz to be specific.	portions of the S-band and C-band	Complete	Accepted	Did not change title, or references to C-band MSG or FCC proceedings. Added "or upper S-band" in parenthesis elsewhere.	
51942	Low	Rebecca Morrison RTCA, Inc.			Modification of Appendix B	CTIA requests that we reformat the appendix to show the iterative nature of the exchange including dates and additional submissions.	Reformat.	Complete	Rejected - duplicate comment.	Duplicate comment - see 52013.	

Appendix D ADDITIONAL ANALYSIS RESULTS TO ADDRESS PUBLIC COMMENTS

D.1 Introduction

During the public commenting process (see Appendix C), CTIA submitted four comments on September 25, 2020 (52016, 52017, 52018, and 52019) asserting that some of the technical information provided by the mobile wireless industry in the TWG-3 information exchange regarding AAS base station vertical scan angles (see Appendix B) was incorrect for typical usage. According to these comments, the AAS vertical scan angles are not additive with the base station downtilt angle as stated by the mobile wireless industry in the TWG-3 information exchange, but are instead inclusive of the base station downtilt angle. That is, the vertical scan angle ranges provided should be referenced to the local horizon, and not to the AAS array broadside direction.

For example, for an Urban AAS base station with a downtilt of 10 degrees (see Table 6-3 and Table 6-4), the vertical scan angle range of -30 degrees to 0 degrees relative to the horizon would be accomplished by electronic steering of the main beam through a range of -20 degrees to +10 degrees. This is slightly different from the assumptions made in the main body of the report based on the information previously provided by the mobile wireless industry, in which case the range of -30 degrees to 0 degrees is taken to be the extent of the electronic beam steering, resulting in the main beam being directed between -40 degrees and -10 degrees relative to the local horizon.

In discussions held between members of SC-239 and CTIA related to the public comments received on this issue, SC-239 members determined that although the assumptions made regarding scan angles in the original analysis (listed in Section 6.3.3.1.1) may not represent typical operating conditions for expected 5G AAS base stations, such operating conditions are still allowable given current FCC regulations and mobile wireless industry standards. For example, the downtilt angles actually implemented may differ from those listed in Table 6-3 and Table 6-4, potentially allowing for AAS vertical scan angles relative to the horizon equivalent to those considered in the original analysis in the main body of the report. Therefore, the original analysis is still valid considering worst-case operating conditions. Nevertheless, the analysis cases which are impacted by this scan angle assumption were reevaluated to determine if any results will change significantly.

The following sections show the results of the additional analysis performed with the AAS vertical scan angle assumption modified in accordance with the comments received from CTIA. Instead of changing the definition of the vertical scan angle given in Section 6.3.3.1.1 to be relative to the local horizon, the scan angle ranges are adjusted to yield equivalent results. That is, for the Urban AAS base station configurations the vertical scan angle range is modified to -20 to +10 degrees, for the Suburban AAS base station configurations the vertical scan angle range is modified to -4 to +6 degrees, and for the Rural AAS base station configurations the vertical scan angle range is modified to -7 to +3 degrees. This produces effective scan angle ranges relative to the horizon of -30 to 0 degrees for the Urban AAS base stations, and -10 to 0 degrees for the Suburban and Rural AAS base stations. All other analysis assumptions and parameters remain the same.

Analysis cases which are not dependent on vertical scan angle, namely those considering non-AAS sectoral base station configurations and the cases of 5G spurious emissions in the 4.2–4.4 GHz band from all base station configurations (including AAS configurations), were not reevaluated.

D.2 Analysis Results

D.2.1 Parametric Analysis: 5G Fundamental Emissions in the 3.7–3.98 GHz Band

D.2.1.1 Usage Category 1: Commercial Air Transport Aircraft

In the main body of the report, the worst cases identified in the 5G fundamental emissions parametric analysis for Usage Category 1 were at the minimum AAS vertical scan angles, which resulted in a grating lobe directing significant RF energy well above the horizon. In the additional analysis conducted, these cases no longer exist. However, the additional analysis now includes the possibility of the AAS main beam being directed straight out at the horizon, which introduces a new worst case. As in the original analysis, the 16 x 16 AAS BS configurations produce more significant interference than the 8 x 8 AAS BS configurations. Further, the Urban, Suburban, and Rural 16 x 16 AAS BS configurations all yield similar results. To illustrate the interference impacts, Figure D-1 shows the case of the Rural 16 x 16 AAS BS with a vertical scan angle of +3 degrees, and no aircraft pitch or roll.

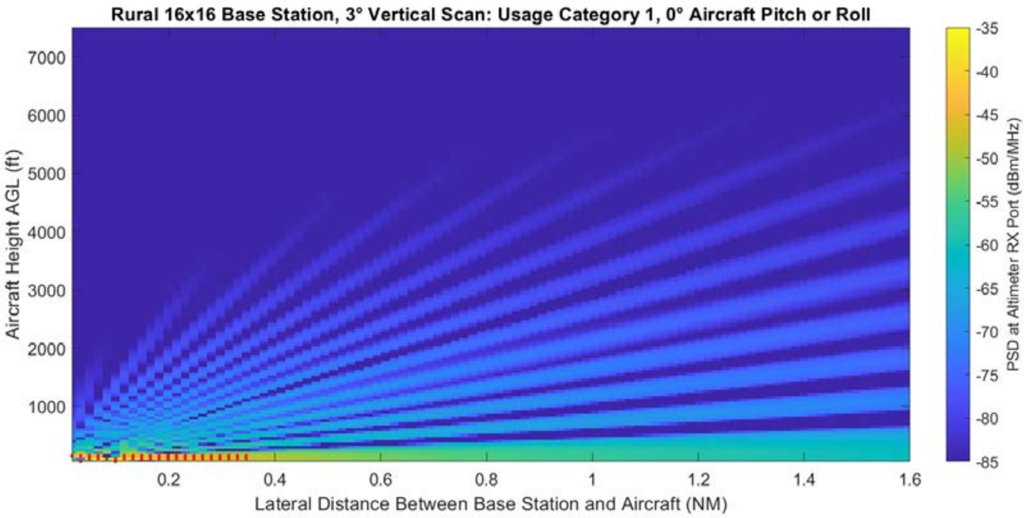

Figure D-1: Rural 16 x 16 AAS BS at +3° Vertical Scan, Usage Category 1

Unlike the original analysis, the worst case for Usage Category 1 is now dependent on the aircraft pitch or roll angle. Figure D-2 shows the case of the same Rural 16 x 16 AAS BS configuration with a vertical scan angle of +3 degrees, with an aircraft pitch or roll angle of 20 degrees. In this case, the interference exceeds the safe limit while the aircraft is more than 0.9 nautical miles away from the base station.

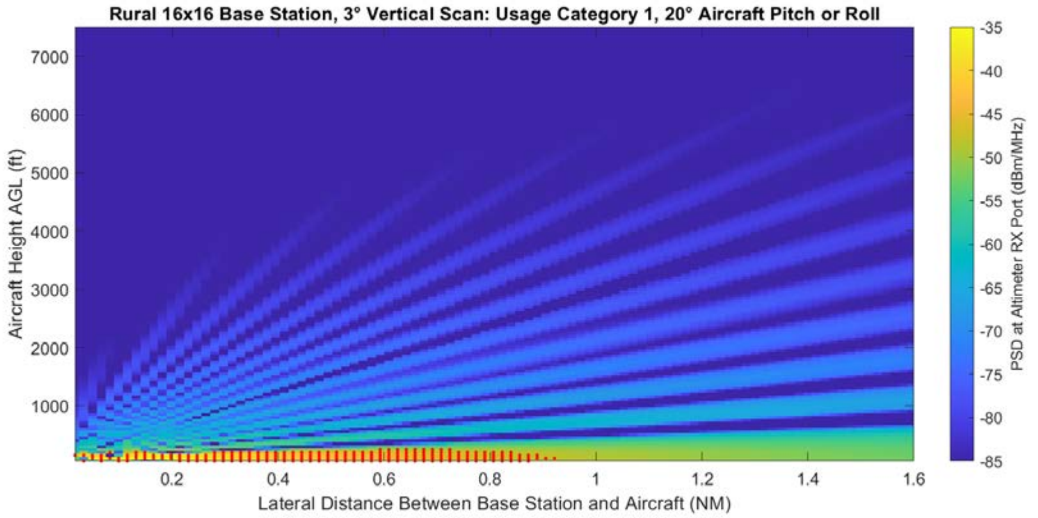

Figure D-2: Rural 16 x 16 AAS BS at +3° Vertical Scan, Usage Category 1 at 20° Pitch/Roll

Although most operations of Usage Category 1 aircraft at low altitudes will not involve significant pitch or roll angles, these scenarios cannot be ruled out entirely. Many takeoff and landing scenarios require low altitude turns (with roll angles of up to 20 degrees) in order to navigate around buildings, terrain, or restricted airspace. One example of this is the approach into runway 19 at Reagan National Airport just outside of Washington, D.C. This approach requires a late turn maneuver just prior to landing in order to avoid Prohibited Area 56 surrounding the White House and the National Mall. The turn maneuver will typically involve a roll angle of up to 15-20 degrees and conclude with the aircraft at an altitude of about 250 feet AGL.

Figure D-3 provides an updated version of Figure 10-3 for the additional analysis with the modified AAS vertical scan angle assumptions. Figure D-4 then provides an updated version of Figure 10-4 for the additional analysis. Note that in the additional analysis, only the AAS BS configurations produce different results.

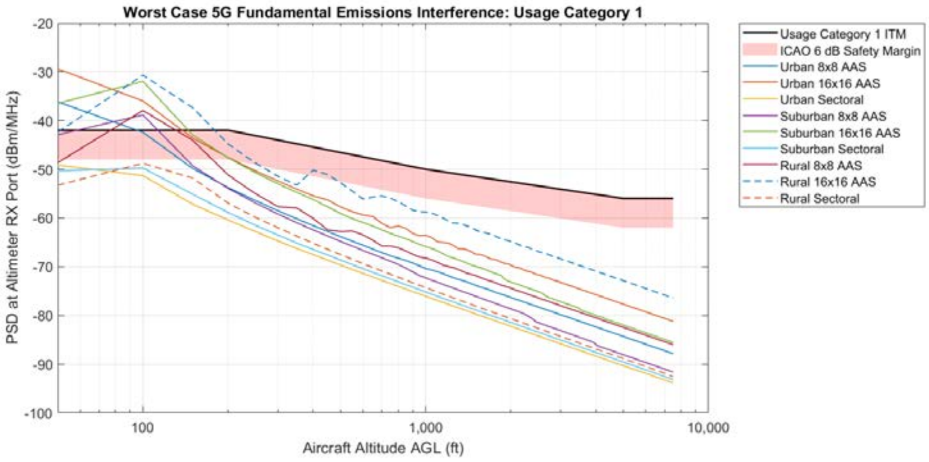

Figure D-3: Maximum 5G Fundamental Emissions Levels, Usage Category 1

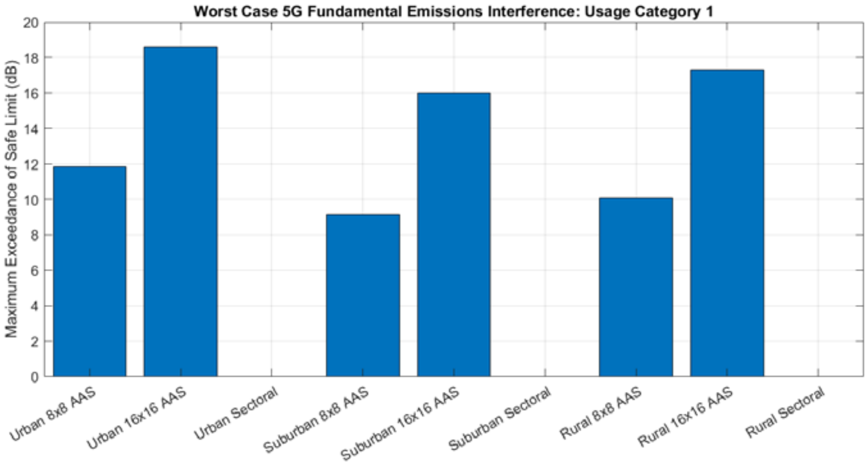

Figure D-4: 5G Fundamental Emissions Exceedance of Safe Interference Limit, Usage Category 1

D.2.1.2 Usage Category 2: Regional, Business Aviation, and General Aviation Aircraft

Given the extent of the interference impacts observed for Usage Category 2 in the original analysis, there was little improvement observed in the additional analysis. In fact, the fact that the modified AAS vertical scan angle ranges now allow for the main beam to be steered up to the horizon results in even more widespread impacts in some cases. To illustrate this, plots of the same example cases presented in Section 10.1.1.2 will be shown here for comparison.

Figure D-5 provides an updated version of Figure 10-5 for the additional analysis with the modified AAS vertical scan angle assumptions, showing the minimum vertical scan angle for the Rural 8 x 8 AAS BS configuration (now -7 degrees instead of -10 degrees). Likewise, Figure D-6 provides an updated version of Figure 10-6, showing the maximum vertical scan angle for the Rural 8 x 8 AAS BS configuration (now +3 degrees instead of 0 degrees). Figure D-7 provides an updated version of Figure 10-7, and Figure D-8 provides an updated version of Figure 10-8, showing the minimum and maximum vertical scan angles for the Urban 16 x 16 AAS BS configuration, respectively (now -20 degrees and +10 degrees, instead of -30 degrees and 0 degrees).

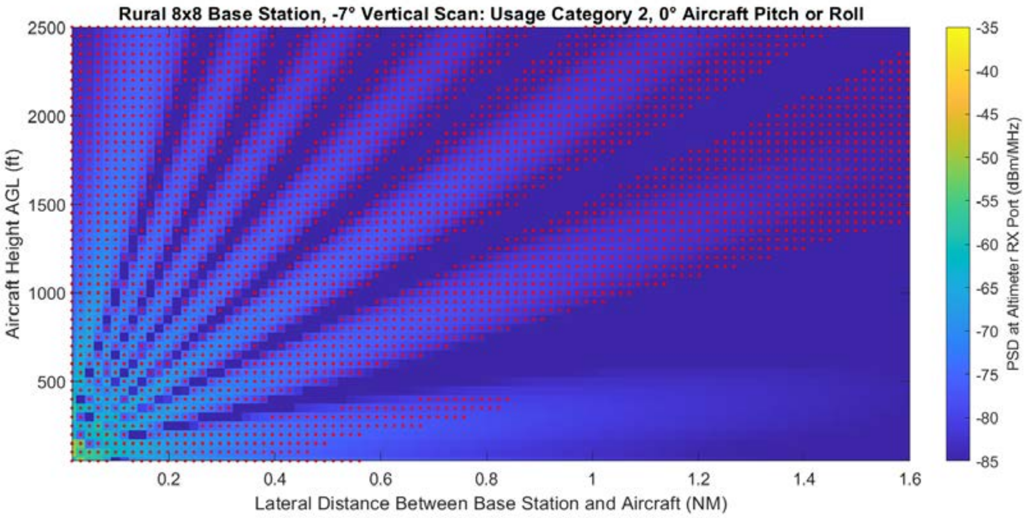

Figure D-5: Rural 8 x 8 AAS BS at -7° Vertical Scan, Usage Category 2

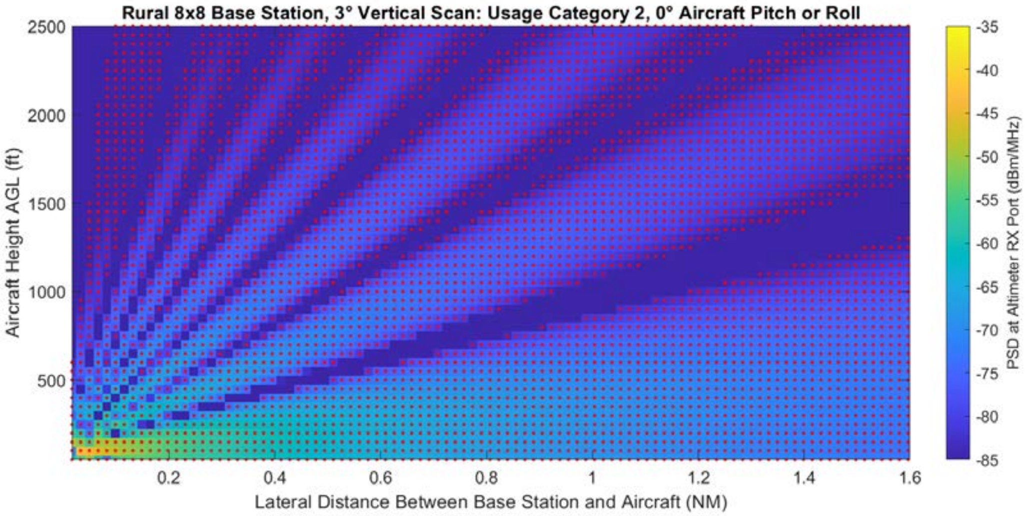

Figure D-6: Rural 8 x 8 AAS BS at +3° Vertical Scan, Usage Category 2

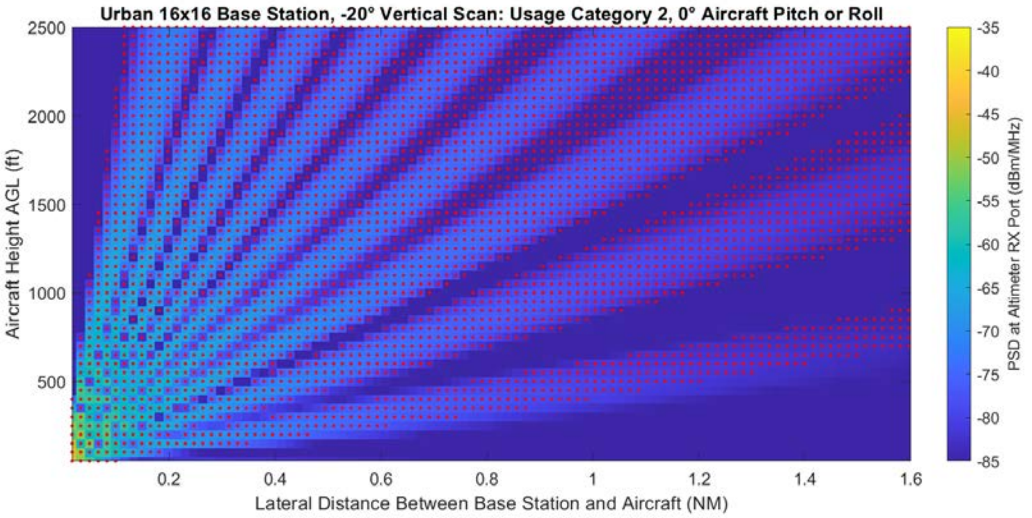

Figure D-7: Urban 16 x 16 AAS BS at -20° Vertical Scan, Usage Category 2

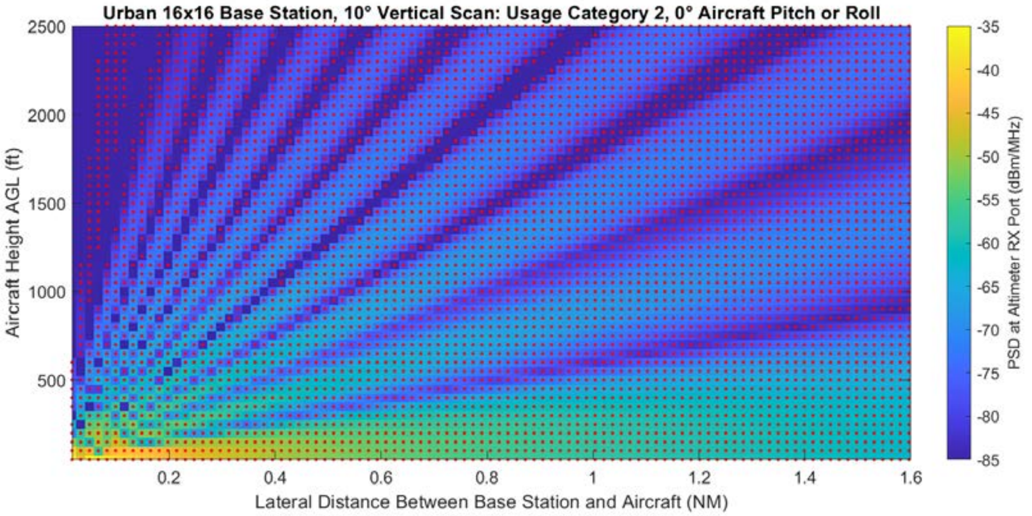

Figure D-8: Urban 16 x 16 AAS BS at +10° Vertical Scan, Usage Category 2

Figure D-9 provides an updated version of Figure 10-11 for the additional analysis with the modified AAS vertical scan angle assumptions. Figure D-10 then provides an updated version of Figure 10-12 for the additional analysis. Note that in the additional analysis, only the AAS BS configurations produce different results.

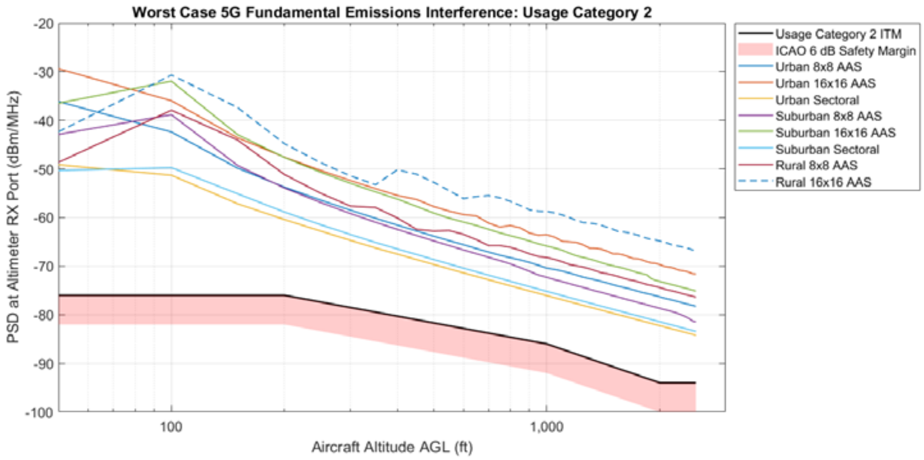

Figure D-9: Maximum 5G Fundamental Emissions Levels, Usage Category 2

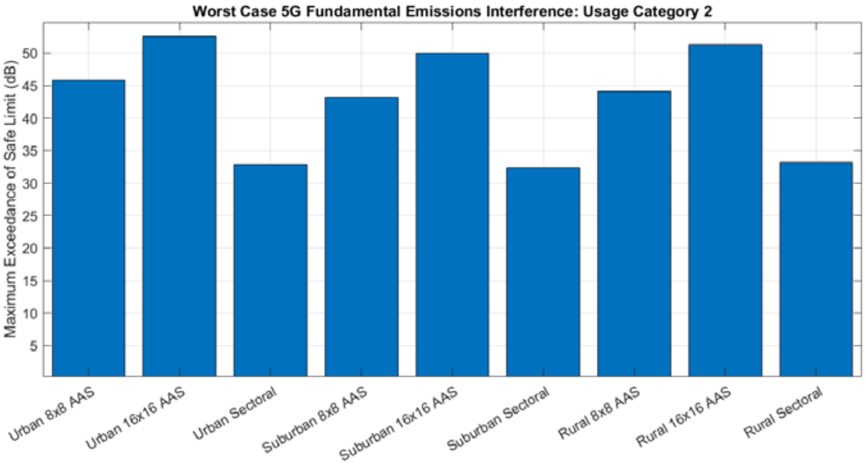

Figure D-10: 5G Fundamental Emissions Exceedance of Safe Interference Limit, Usage Category 2

D.2.1.3 Usage Category 3: Helicopters

As seen for Usage Category 2, there was little difference in interference impacts observed in the additional analysis for Usage Category 3. To illustrate this, plots of the same example cases presented in Section 10.1.1.3 will be shown here for comparison. Figure D-11 provides an updated version of Figure 10-13, and Figure D-12 provides an updated version of Figure 10-14, showing the minimum and maximum vertical scan angles for the Urban 16 x 16 AAS BS configuration, respectively (now -20 degrees and +10 degrees, instead of -30 degrees and 0 degrees).

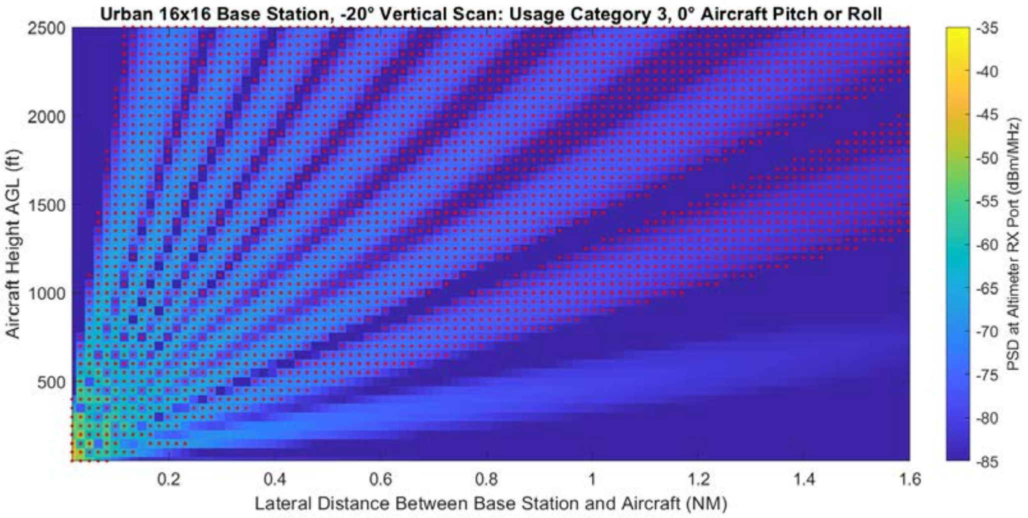

Figure D-11: Urban 16 x 16 AAS BS at -20° Vertical Scan, Usage Category 3

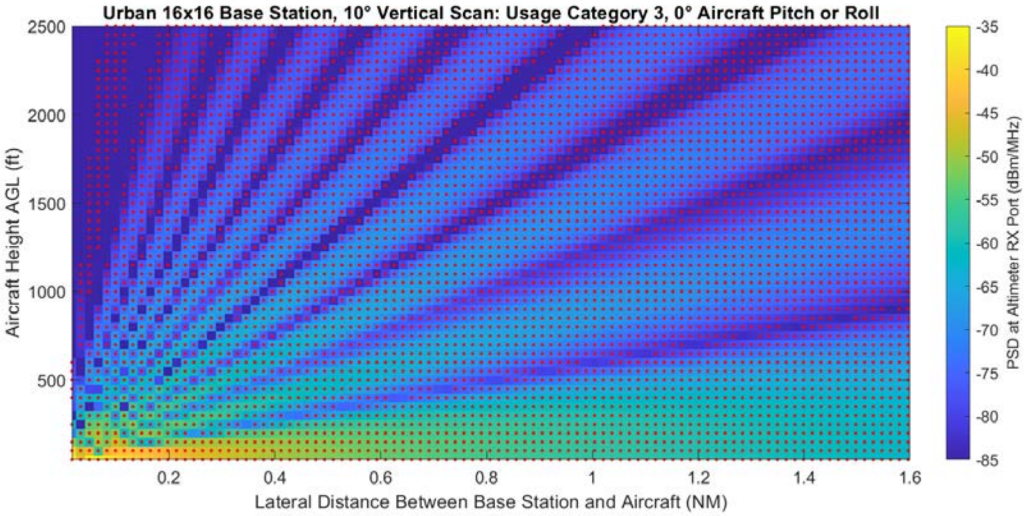

Figure D-12: Urban 16 x 16 AAS BS at +10° Vertical Scan, Usage Category 3

Figure D-13 provides an updated version of Figure 10-15 for the additional analysis with the modified AAS vertical scan angle assumptions. Figure D-14 then provides an updated version of Figure 10-16 for the additional analysis. Note that in the additional analysis, only the AAS BS configurations produce different results.

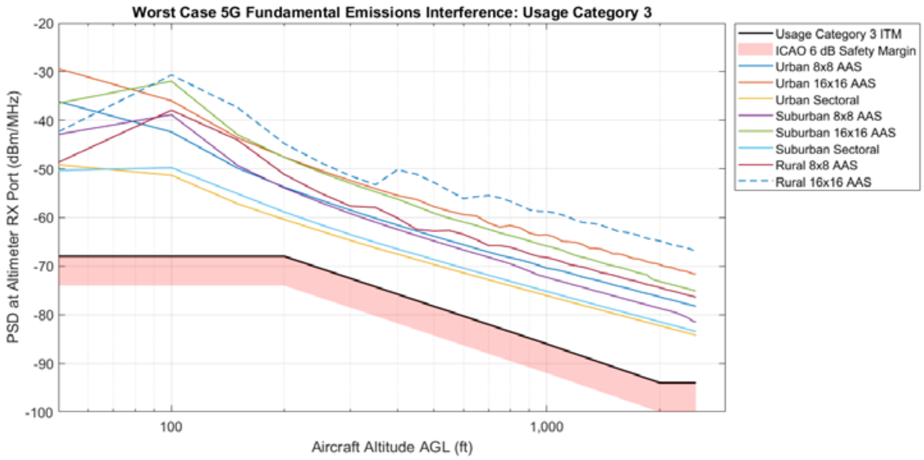

Figure D-13: Maximum 5G Fundamental Emissions Levels, Usage Category 3

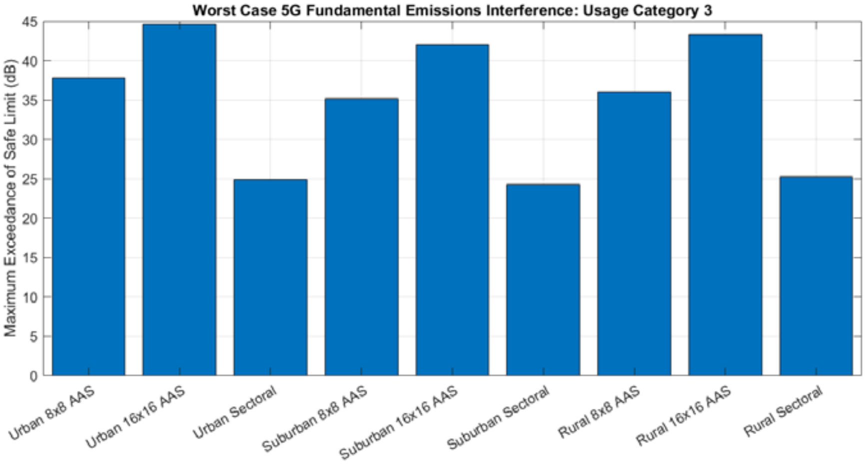

Figure D-14: 5G Fundamental Emissions Exceedance of Safe Interference Limit, Usage Category 3

D.2.2 Instrument Approach Procedure Scenario: 5G Fundamental Emissions

The original analysis of the CAT II/III ILS approach into O’Hare runway 27L considered each BS to be of the Urban 16 x 16 AAS configuration, with a vertical scan angle of -30 degrees. This scan angle is not considered applicable for the additional analysis with updated scan angle assumptions. Therefore, the additional analysis considered both the minimum and maximum vertical scan angles for the Urban 16 x 16 AAS BS configuration of -20 degrees and +10 degrees. In each case, all five base stations are assumed to have the same scan angle. Figure D-15 shows the results with a vertical scan angle of -20 degrees, and Figure D-16 shows the results with a vertical scan angle of +10 degrees.

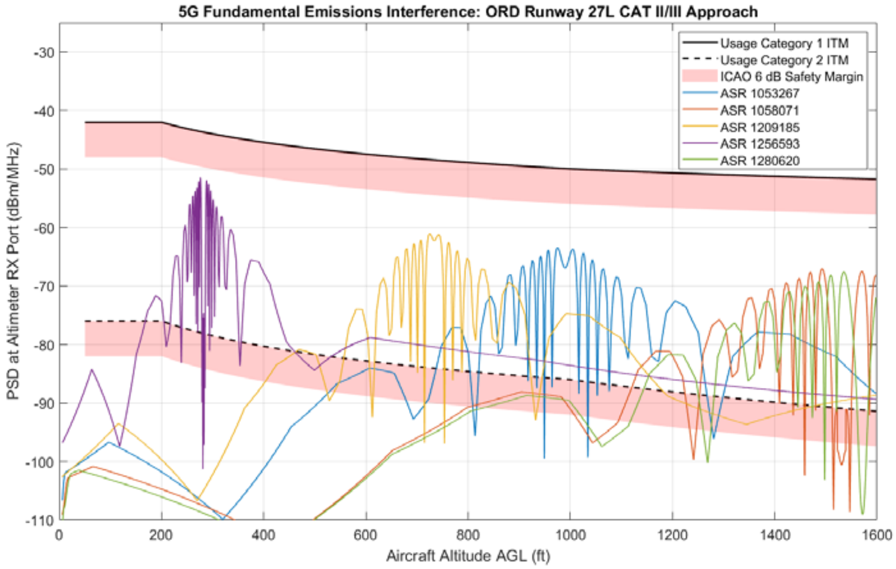

Figure D-15: CAT II/III Approach Scenario Results for 5G Fundamental Emissions with -20° AAS Vertical Scan Angle

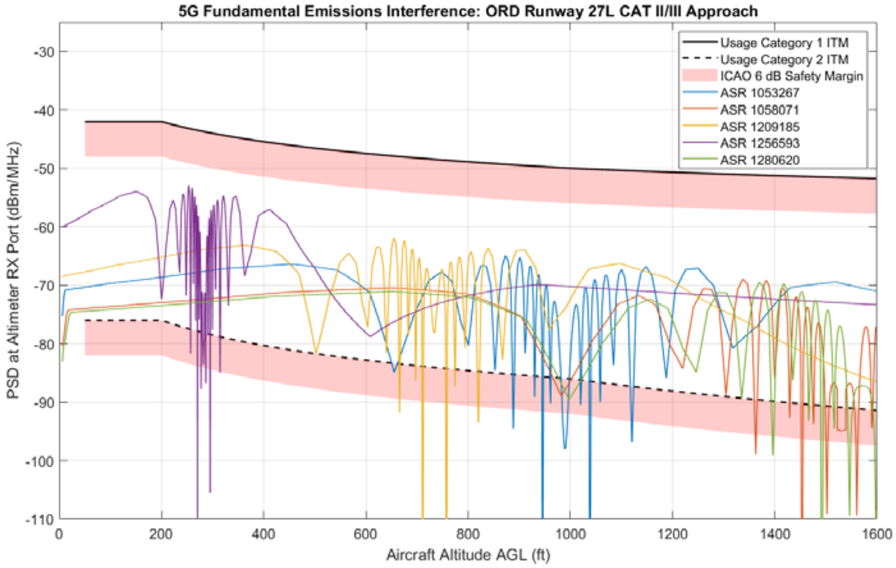

Figure D-16: CAT II/III Approach Scenario Results for 5G Fundamental Emissions with +10° AAS Vertical Scan Angle

Unlike the original analysis, the safe interference limit for Usage Category 1 is not exceeded anywhere along the approach. However, this is expected given the changes observed in the parametric analysis—the worst-case interference no longer occurs at various altitudes while the aircraft is very close to the base station, but instead only at low altitudes at various distances from the base station, especially with some amount of aircraft pitch or roll. These worst-case geometries are not encountered on the O’Hare runway 27L approach, although they may be seen in other approach scenarios as discussed in Section D.2.1.1.

For Usage Category 2, the observed interference levels greatly exceed the safe limits throughout the entirety of the approach, as seen in the original analysis.

D.2.3 Helicopter Air Ambulance Landing Scenario: 5G Fundamental Emissions

As with the CAT II/III ILS approach scenario, the original analysis of the HAA landing scenarios included assumptions of a -30 degree vertical scan angle for Urban 16 x 16 AAS base stations. Therefore, the additional analysis considered both the minimum and maximum vertical scan angles for the Urban 16 x 16 AAS BS configuration of -20 degrees and +10 degrees. In each case, both base stations are assumed to have the same scan angle.

The results with the -20 degree scan angle are shown in Figure D-17 for the Memorial Hermann heliport, Figure D-18 for the Houston Methodist Hospital heliport, Figure D-19 for the Baylor St. Luke's Medical Center heliport, and Figure D-20 for the Texas Children's Hospital heliport.

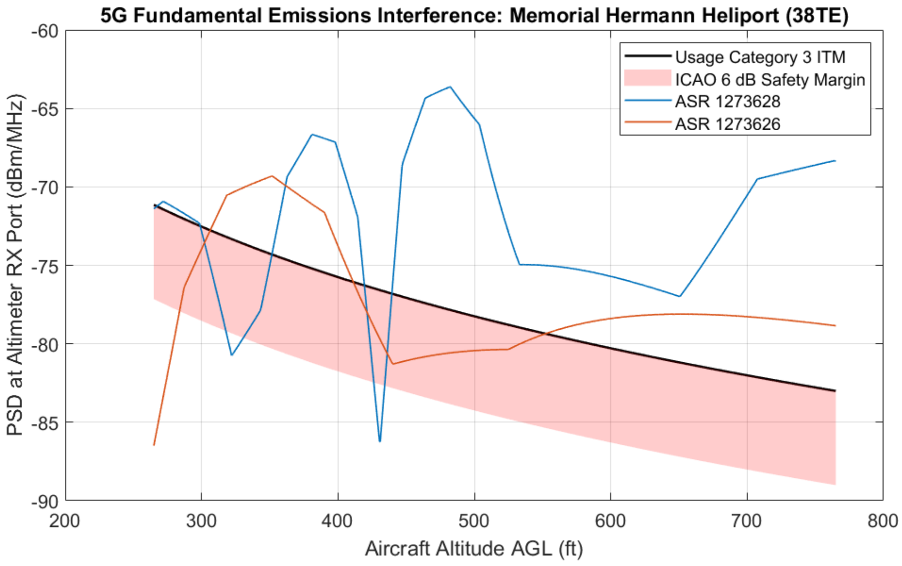

Figure D-17: HAA Scenario Results for 5G Fundamental Emissions, Heliport 38TE with -20° AAS Vertical Scan Angle

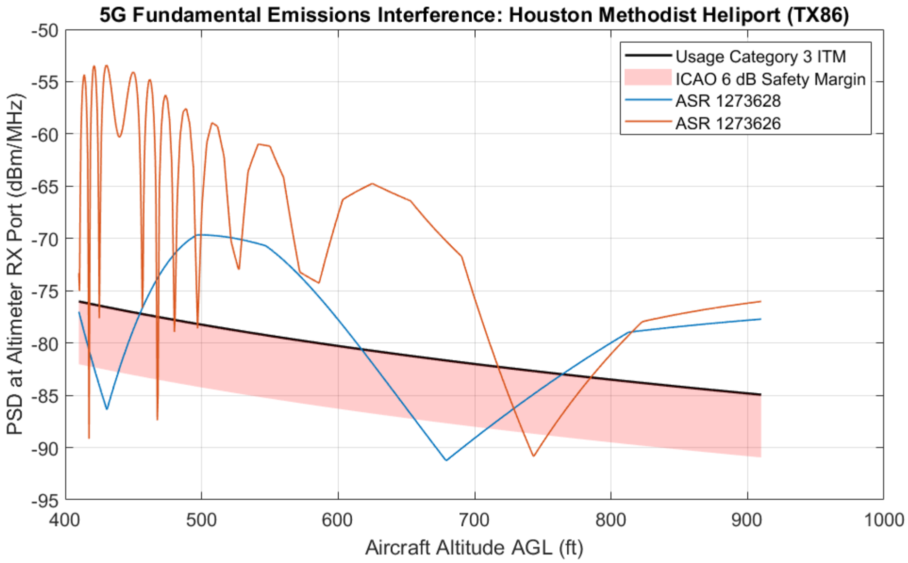

Figure D-18: HAA Scenario Results for 5G Fundamental Emissions, Heliport TX86 with -20° AAS Vertical Scan Angle

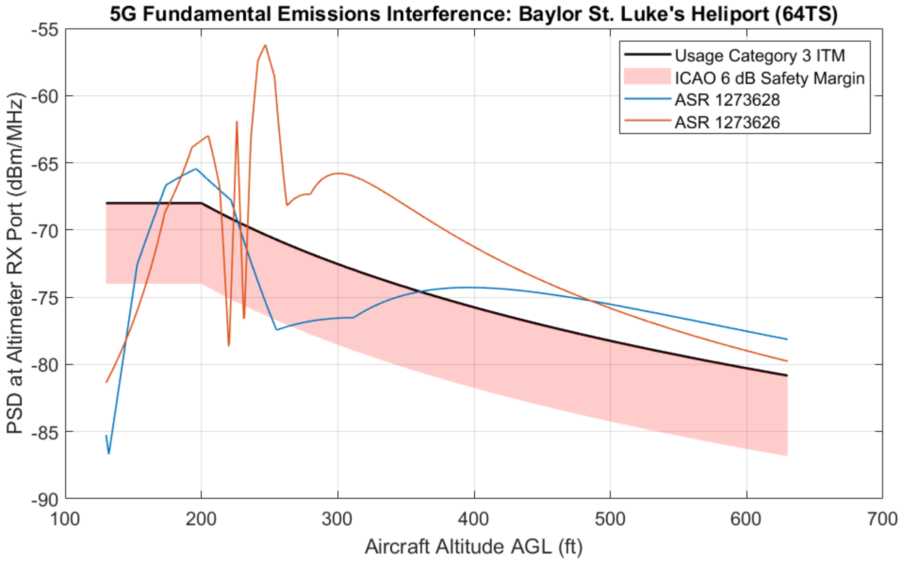

Figure D-19: HAA Scenario Results for 5G Fundamental Emissions, Heliport 64TS with -20° AAS Vertical Scan Angle

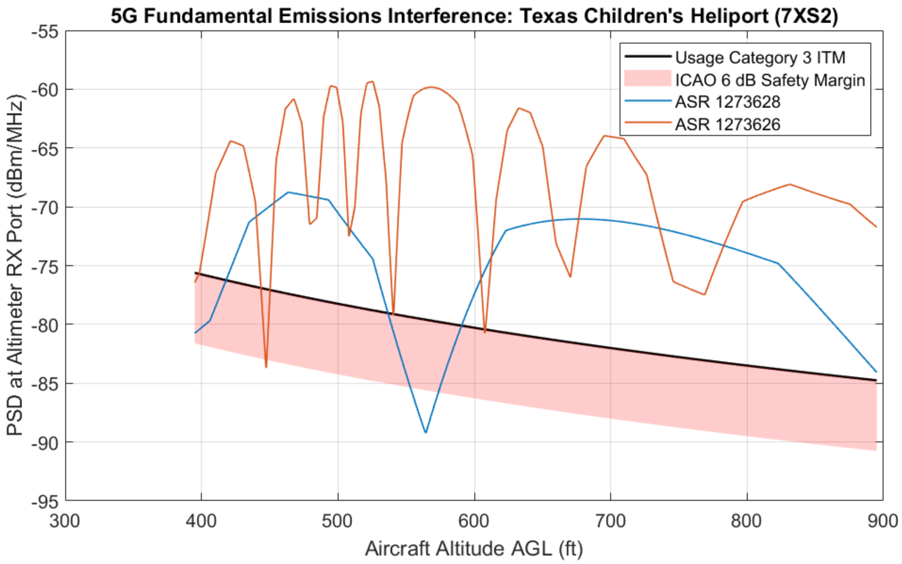

Figure D-20: HAA Scenario Results for 5G Fundamental Emissions, Heliport 7XS2 with -20° AAS Vertical Scan Angle

The results with the +10 degree scan angle are shown in Figure D-21 for the Memorial Hermann heliport, Figure D-22 for the Houston Methodist Hospital heliport, Figure D-23 for the Baylor St. Luke's Medical Center heliport, and Figure D-24 for the Texas Children's Hospital heliport.

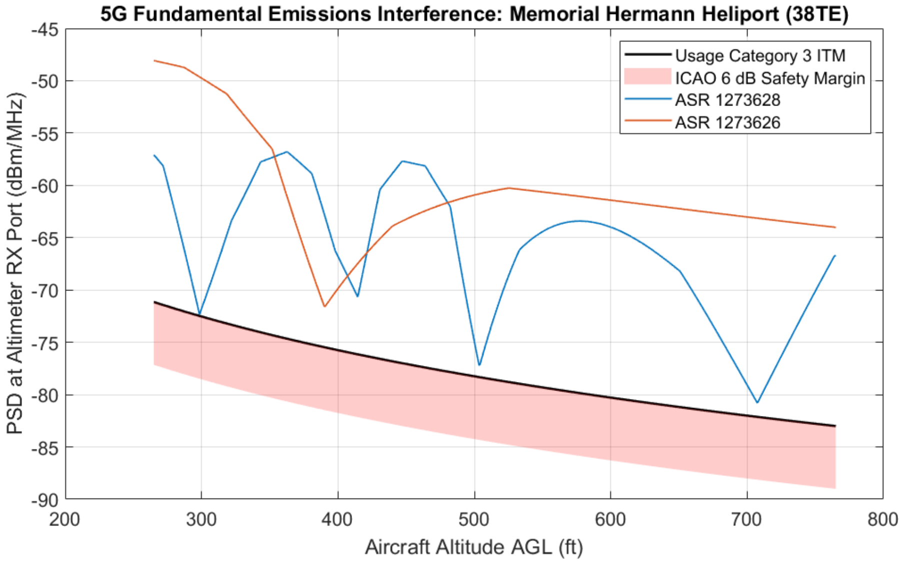

Figure D-21: HAA Scenario Results for 5G Fundamental Emissions, Heliport 38TE with +10° AAS Vertical Scan Angle

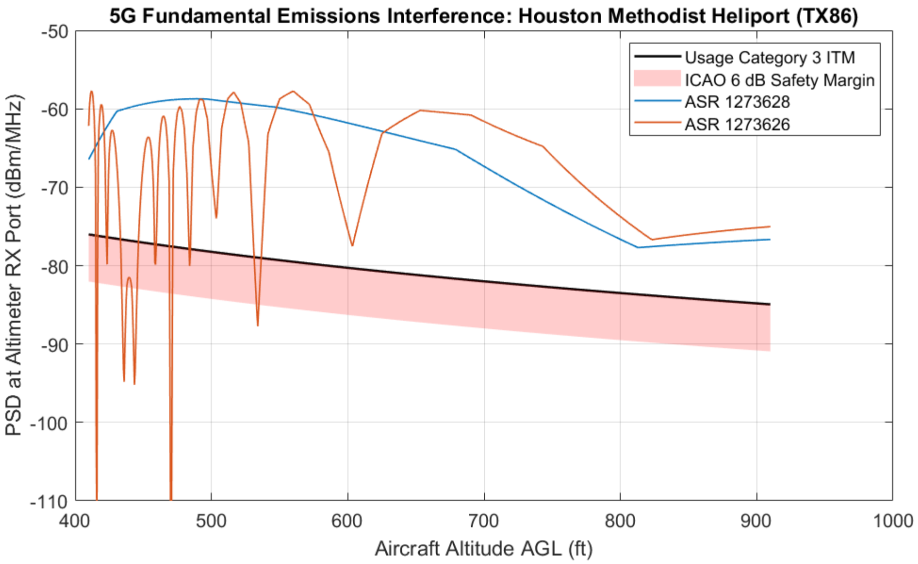

Figure D-22: HAA Scenario Results for 5G Fundamental Emissions, Heliport TX86 with +10° AAS Vertical Scan Angle

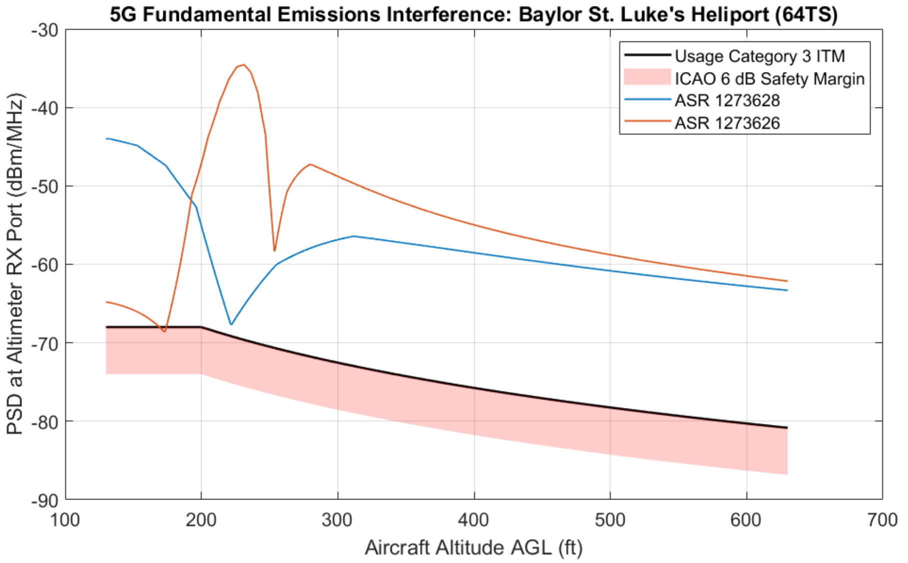

Figure D-23: HAA Scenario Results for 5G Fundamental Emissions, Heliport 64TS with +10° AAS Vertical Scan Angle

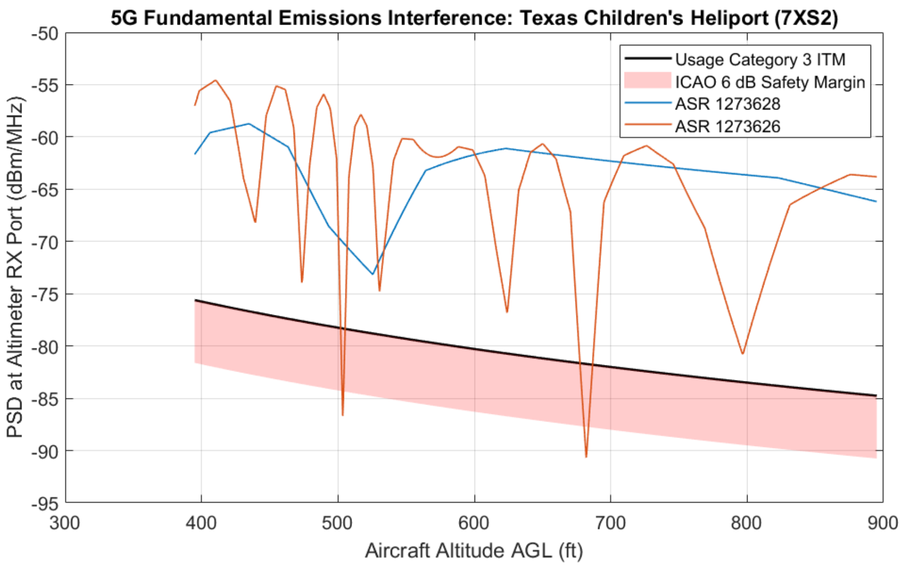

Figure D-24: HAA Scenario Results for 5G Fundamental Emissions, Heliport 7XS2 with +10° AAS Vertical Scan Angle

With the -20 degree AAS vertical scan angle, the results of the additional analysis are largely similar to those of the original analysis, with some small reductions in the received interference levels in most cases. However, with the +10 degree vertical scan angle, the additional analysis shows substantial increases in the received interference levels for the Memorial Hermann and Baylor St. Luke's heliports. In all cases, the interference levels are well above the safe limits throughout the entirety of all four approaches.

D.3 Summary

D.4 Overall, the additional analysis results show only minor differences from the original analysis in terms of operational impacts, and the fundamental conclusions drawn from the original analysis are unchanged. Further, the maximum exceedance of the safe interference limit actually increased by about 5 dB for Usage Category 1 and Usage Category 2. For Usage Category 3 the maximum exceedance changed by less than 1 dB, but the interference impacts remain widespread, and as seen in the HAA landing scenario analysis there is a potential for even greater interference levels in certain real-world scenarios.

For Usage Category 1, the parametric analysis shows a different range of impacted operating conditions than seen in the original analysis. However, as previously stated this does not change the overall conclusions of the original analysis. Instead, this change would only alter the specific operating conditions and scenarios which must be targeted for appropriate mitigation of interference risks. For Usage Category 2 and Usage Category 3, the interference impacts remain just as widespread as in the original analysis, if not more so.