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Minimum Operational Performance Standards (MOPS) for Air-to-Air Radar for Traffic Surveillance

RTCA DO-366
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Prepared by: SC-228

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FOREWORD

This document was prepared by RTCA Special Committee 228 (SC-228). This document was approved by the RTCA Program Management Committee (PMC) on May 31, 2017.

RTCA, Incorporated is a not-for-profit corporation formed to advance the art and science of aviation and aviation electronic systems for the benefit of the public. The organization functions as a Federal Advisory Committee and develops consensus-based recommendations on contemporary aviation issues. RTCA's objectives include, but are not limited to:

- 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 (MOPS) 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 (ICAO) and the International Telecommunication Union (ITU) and other appropriate international organizations can be based.

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Revision History

Rev Level	Description	Date	Effective Sections
-	Draft for RTCA/Program Management Committee Review	12/21/16	All

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EXECUTIVE SUMMARY

This document contains Phase 1 Minimum Operational Performance Standards (MOPS) for the air-to-air radar for traffic surveillance. The intended application is supporting Detect and Avoid (DAA) operations for aircraft transitioning to and from Class A or special use airspace, traversing Class D, E, and G airspace in the National Airspace System (NAS). It does not apply to small Unmanned Aircraft Systems (sUAS) operating in low-level environments (below 500') or other segmented areas. These standards specify the radar system characteristics that should be useful for designers, manufacturers, installers and users of the equipment.

The intended function of the radar is to detect and generate tracks for all airborne traffic within the radar detection volume. The onboard radar complements other airborne surveillance sensors by providing detection of non-cooperative traffic. The track should be established at sufficient range and with sufficient accuracy to enable the system to plan and execute a maneuver to keep the UAS well clear of other traffic and avoid collisions.

This document has the detailed performance and environmental requirements of the radar along with their verification methods. Verification includes bench tests, flight tests and environmental tests. Recommendations and flight tests for installed performance are also provided.

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1 PURPOSE AND SCOPE

1.1 Introduction

This document contains Phase 1 Minimum Operational Performance Standards (MOPS) for air-to-air radar for traffic surveillance implemented in Unmanned Aircraft (UA) transitioning to and from Class A or special use airspace, traversing Class D, E, and G airspace in the National Airspace System (NAS). It does not apply to small Unmanned Aircraft Systems (sUAS) operating in low-level environments (below 500') or other segmented areas. Likewise, it does not apply to operations in the Visual Flight Rules (VFR) traffic pattern of an airport. These standards specify the radar system characteristics that should be useful for designers, manufacturers, installers and users of the equipment.

Compliance with these standards is recommended as one means of assuring that the equipment will perform its intended function(s) satisfactorily under the conditions specified herein. Any regulatory application of this document is the sole responsibility of appropriate governmental agencies.

Section 1 of this document provides information needed to understand the rationale for the equipment characteristics and requirements in Section 2. It describes typical equipment operations and operational goals as envisioned by the members of RTCA Inc. Special Committee (SC)-228, and establishes the basis for the standards stated herein. Definitions and assumptions essential to proper understanding of this document are also provided in this section.

Section 2 contains the requirements for the equipment. These standards specify the required performance under standard environmental conditions. Also included are recommended bench test procedures necessary to demonstrate equipment compliance with the stated minimum requirements.

Section 3 describes the performance required of installed equipment. Tests for the installed equipment are included when performance cannot be adequately determined through bench testing.

Section 4 contains aircraft operational performance characteristics.

Section 5 contains an informative listing of SC-228 committee members who contributed to these MOPS.

Appendix A contains information on the proposed frequency bands for the radar, and their regulatory status.

Appendix B contains analysis and simulations that derive the required maximum range for the radar for different categories of intruders and different encounter geometries between the ownship and intruders.

Appendix C analyzes the frequency of the cases where an intruder enters the radar Field of Regard (FOR) within the Radar Declaration Range (RDR).

Appendix D provides validation of RDR against Detect and Avoid (DAA) alerting requirements.

Appendix E provides results of simulations to estimate the Radar Cross-Section (RCS) of different kinds of aircraft as guidance for radar design against expected intruders.

Appendix F provides a list of acronyms and abbreviations used in this document.

This document sets performance standards for air-to-air radar for traffic surveillance as part of a DAA system. Separate MOPS were developed for the DAA system.[1] The RTCA MOPS for DAA Systems (hereafter referred to as the “DAA MOPS”) refer to these MOPS (hereafter referred to as the “DAA Radar MOPS” or “these MOPS”) to satisfy surveillance requirements for non-cooperative intruders. The radar basic functions, e.g., power ON/OFF, transmit power ON/OFF, are controlled by the Pilot-in-Command (PIC) in the Control Station (CS). Similarly, the radar provides its status to the CS during operation. The CS sends commands to the radar and receives status from it. Tracks generated by the radar are sent to the DAA system for further processing.

1.2 DAA System Overview

DAA systems are designed to provide Unmanned Aircraft (UA) the ability to remain well clear of and avoid collisions with other aircraft. Two types of surveillance equipment are identified for such a system: cooperative sensors such as Mode S active surveillance and Automatic Dependent Surveillance-Broadcast (ADS-B), which rely on having compatible equipment in the intruder aircraft, and non-cooperative sensors, which detect intruders without any equipage assumptions. The air-to-air radar is the primary sensor for non-cooperative intruders. Paragraphs 1.2.1 and 1.2.2 give an outline of the UA elements and the CS elements of a DAA system.

The Federal Aviation Administration’s (FAA’s) UAS Operational Concept document includes assumptions, constraints, requirements, and high-level operational considerations for UAS, and is intended to provide the foundation for the DAA MOPS and DAA Radar MOPS.[2] However, the scope and functionality of these Phase 1 DAA MOPS and DAA Radar MOPS may require specific restrictions, operating limitations and/or supplemental operational controls or provisions to achieve an acceptable level of collision risk mitigation for use in the NAS. Operating limitations for radar equipment compliant with these MOPS are documented in Paragraph 1.2.4.

These MOPS define the minimum functional and performance requirements, test procedures, limitations, and installation considerations for DAA radar equipment to be used in an operational environment where the UA is transitioning to and from Class A or Special Use Airspace (SUA), or traversing Class D, E, or G airspace.

1.2.1 DAA System Description – Unmanned Aircraft

Figure 1-1 shows one possible implementation of a DAA system onboard the aircraft, as depicted in the Phase 1 DAA MOPS. The radar interacts mainly with the UA DAA processor as a surveillance sensor. The radar sends the radar-generated tracks to the DAA processor, which will create unified tracks that will combine information from all sensors.

[1] Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems, RTCA Paper No. 261-15/PMC-1400

[2] United States (U.S.) Department of Transportation (DoT) Joint Planning and Development Office (JPDO) Unmanned Aircraft Systems (UAS) Comprehensive Plan, September 2013

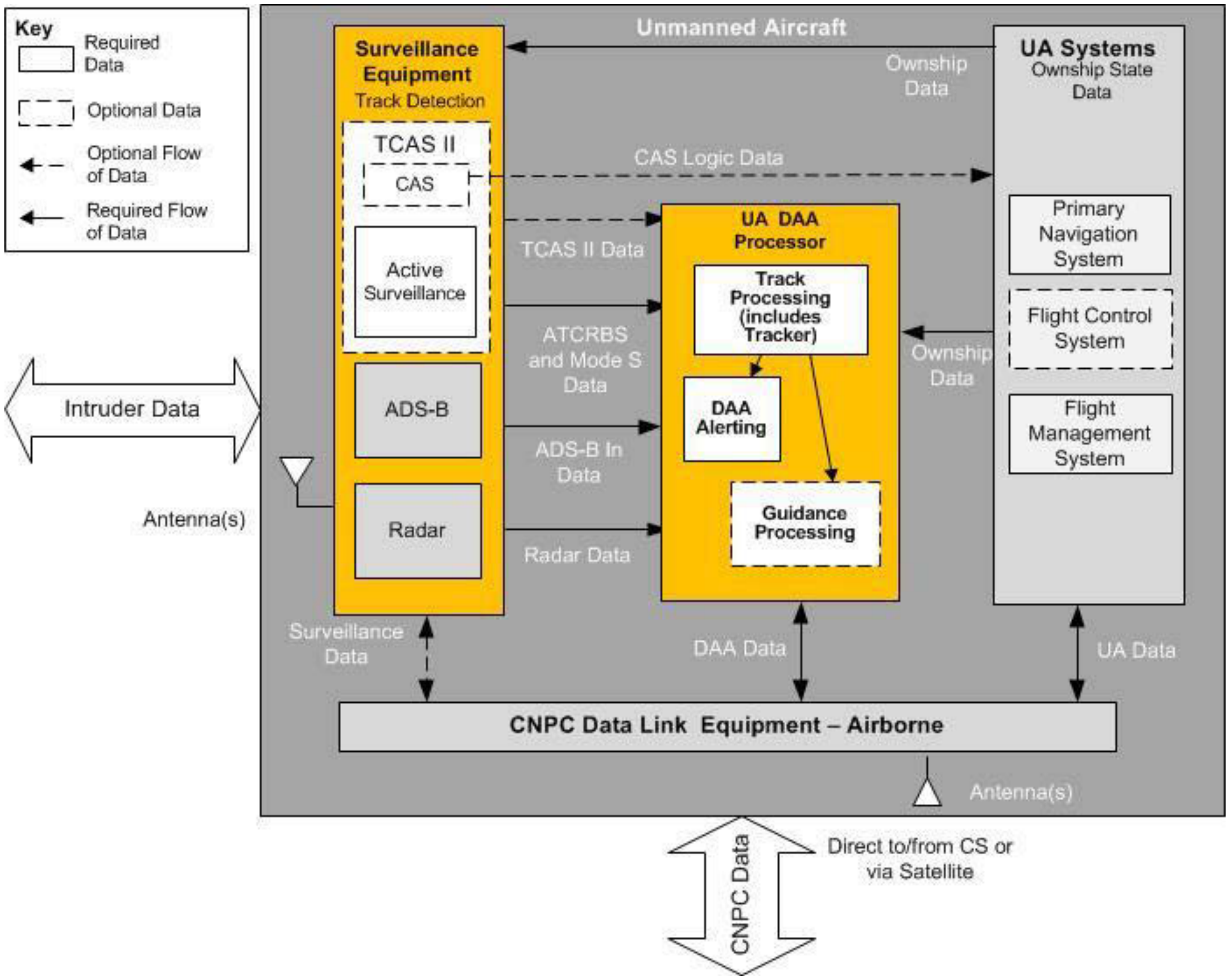

Figure 1-1 **Major Elements of the DAA System Onboard the Aircraft**

1.2.2 DAA System Description – Control Station

Figure 1-2 shows the control segment as depicted in the DAA MOPS. From the radar perspective, the PIC will have control over the radar functionality, and receive radar status and health information through the CS surveillance control panel.

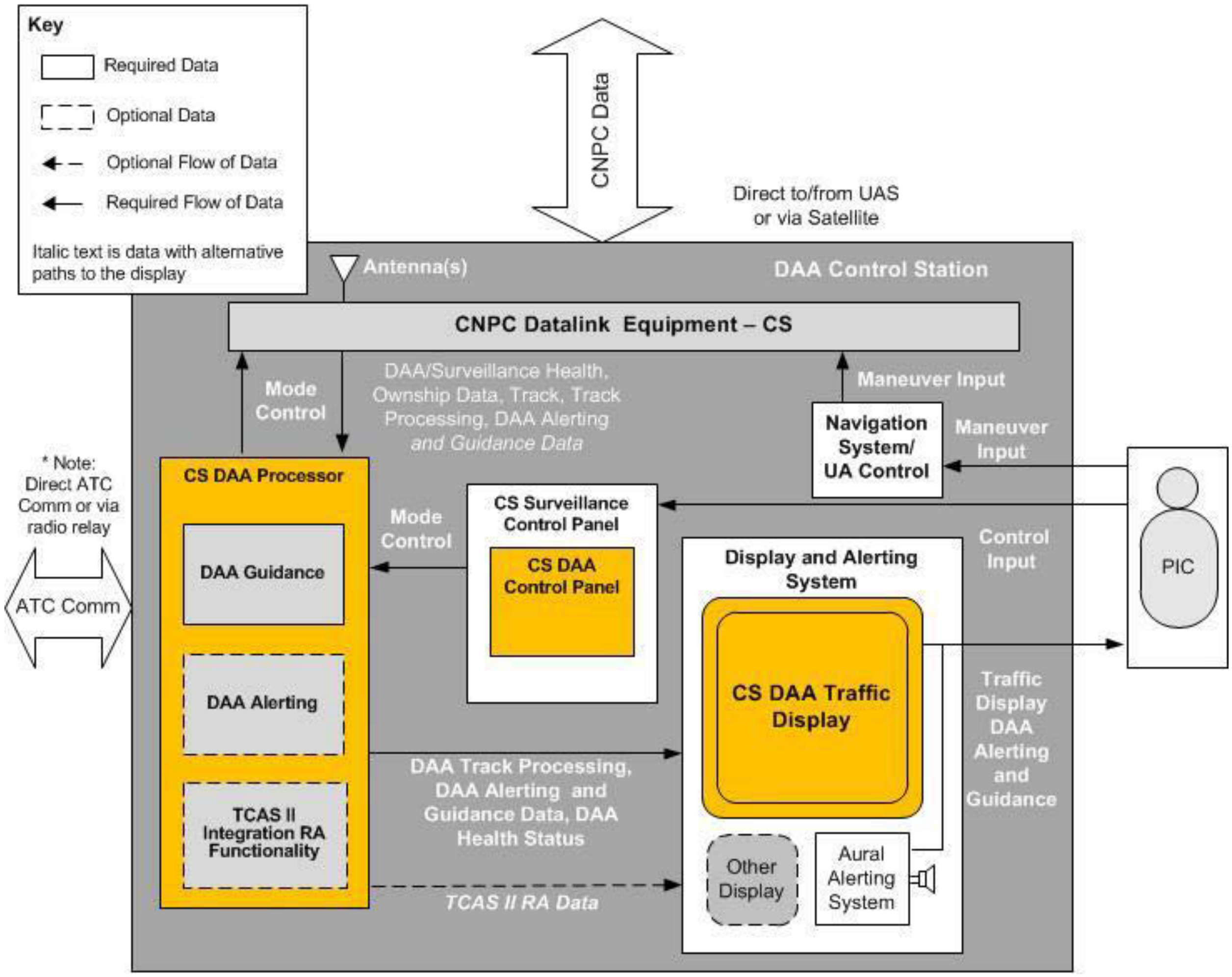

Figure 1-2 **Major Elements of the DAA System in the Control Segment**

1.2.3 DAA Radar Overview

Figure 1-3 shows the major elements of DAA radar. It will have one or more antenna elements carefully placed in the UA to cover the FOR. The radar electronics provide all transmit, receive, control, status and tracking functions for the radar. The radar receives commands and navigation data and sends out status and track data. Optionally, the radar may also receive cueing information from the DAA system. The radar electronics maybe co-located with the antenna or placed close by.

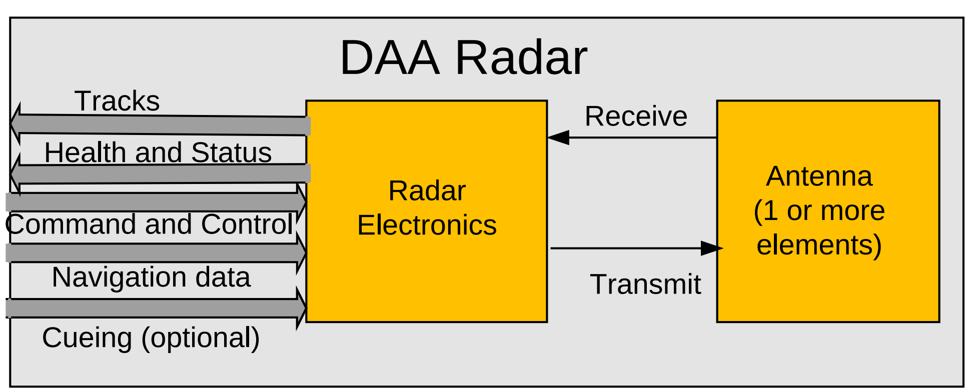

Figure 1-3 **DAA Radar Block Diagram**

1.2.4 System Limitations

Installed DAA radar meeting these MOPS **does not**:

- Detect and track intruders that have no reflection in the radar frequency band. It is assumed that at a minimum the intruder would have an RCS of a human.
- Detect and track objects while conducting taxi operations or flying at low altitudes below the minimum altitude recommended in Subparagraph 2.2.7–21.
- Detect and track every stationary or hovering target; detection of such targets will depend on their RCS, their location with respect to the ownship, and the level of ground clutter.

1.2.5 Document Hierarchy

Radar operational performance requirements at the aircraft level and associated recommendations are derived from the DAA MOPS. However, for all radar requirements, this document supersedes any other document.

1.3 Intended Function

The intended function of the radar is to detect and generate tracks for all airborne traffic within the radar detection volume. The onboard radar complements other airborne surveillance sensors by providing detection of non-cooperative traffic. This equipment will support some traffic avoidance systems, including Detect and Avoid Systems.

1.4 Operational Goals

The radar is the surveillance source for non-cooperative intruders in a DAA system. This allows UAs to conduct flight operations on an Instrument Flight Rules (IFR) flight plan between the terminal area and Class A airspace while transitioning through Class D, E, or G airspace. The radar will provide intruder track information to the DAA system that will enable a decision to be made whether a maneuver is necessary to maintain DAA Well Clear (DWC) and avoid collisions. The track should be established at sufficient range and with sufficient accuracy to enable the system to plan and execute a maneuver to keep the UAS well clear of other traffic and avoid collisions. The DAA system may use the radar data to validate other sensors.

1.5 Assumptions

1.5.1 Operational Assumptions

1. The DAA radar will mainly operate in the environment defined in the Operational Services and Environment Description in Appendix A of the DAA MOPS. The limitations to this operation are outlined in Paragraph 1.2.4 above. If needed, the DAA system will have other means to provide the functions expected of the radar under the limitations imposed in Paragraph 1.2.4, above.
2. The radar will be the non-cooperative sensor for intruders below 10,000’ Above Ground Level (AGL), where non-cooperative intruder aircraft fly at speeds up to 170 Knots True Airspeed (KTAS).
3. Below 10,000’ AGL, where ownship UA aircraft fly at speeds up to 200 KTAS.
4. The radar will be qualified for 4 millimeters per hour (mm/hr) of rain. Operation at higher rates of rain is possible, but performance may be affected, especially at the higher frequency bands.

1.5.2 Radome Assumptions

In most cases, the radar antenna will be covered with a radome supplied by the UAS manufacturer. The radar performance will be evaluated with the radome, so radar manufacturers will need to work with the UAS manufacturer to ensure that radar will perform as specified when used with the radome.

1.5.3 Ownship State Data Assumptions

Table 1-1 defines the ownship state data that needs to be supplied to the radar from the ownship or the DAA processor. Where available, the quality indicators will also be supplied. The update rate needs to be a minimum of 1 Hertz (Hz).

Since the radar measures the intruder azimuth and elevation angle from a body frame, it will be sensitive to any aircraft heading, roll and pitch errors. In addition, any error in the Time of Applicability of the ownship data will add to this error. It is recommended that these errors are at least an order of magnitude lower than those of the radar since they will be stacked on top of radar errors. For example, if the radar has an azimuth angle error of 1 degree (deg) (1 sigma), the heading error should be <0.1 deg (1 sigma). Lower accuracy navigation data may be used if the radar error budget allows for it.

Table 1-1 Ownship State Data (Note 1)

Description	Notes
Time of Applicability of Ownship Data	None
Velocity North	None
Velocity East	None
Velocity Down	None
Roll Angle	None
Pitch Angle	None
True Heading	None
Latitude	Note 2, 3
Longitude	Note 2, 3
Geometric Altitude (Height Above Ellipsoid)	None
Roll Rate	Note 4
Pitch Rate	Note 4
Heading Rate	Note 4
Angle of Attack (If Available)	None
Global Positioning System (GPS) Timing Reference (Optional)	Note 5
Height Above Ground (If Available)	None

Note:

1. *These may be received from the ownship directly or from the DAA processor.*
2. *Horizontal Position is based on reference to World Geodetic System – 1984 (WGS-84) latitude/longitude from the ownship position sources.*
3. *This is not a minimum requirement, but may be useful for the radar to predict ownship and intruder ground level.*
4. *This is not a minimum requirement, as it can be derived from the Roll, Pitch and heading data if sent at a higher update rate.*

5. *A timing reference is not needed for the radar operation. However, verification of the radar accuracy will depend on flight tests where the radar intruder location estimates are compared to intruder truth based on a GPS unit. Any timing misalignment between the radar and intruder GPS will cause additional errors. This error should be kept below 30 milliseconds (ms) or corrected during test data processing to maintain accuracy.*

1.6 Test Procedures

The test procedures specified in this document are intended to be used as one means of demonstrating compliance with the performance requirements defined in Subsection 2.2. Although specific test procedures are cited, it is recognized that other methods may be preferred. These alternate procedures may be used if they provide at least equivalent information. In such cases, the procedures cited herein should be used as one criterion in evaluating the acceptability of the alternate procedures. Users of this document should not use the test procedures as a method of deriving the performance requirement.

The order of tests specified suggests that the equipment be subjected to a succession of tests as it moves from design to design qualification to operational use. For example, compliance with the requirements of Subsection 2.2 would have been demonstrated as a precondition to completion of the installed system tests of Subsection 3.3.

1. Environmental Tests

    a. Environmental test requirements are specified in Subsection 2.3. The procedures and their associated limits are intended to provide a laboratory means of determining the electrical and mechanical performance of the equipment under environmental conditions expected to be encountered in actual operations.

    b. Unless otherwise specified, the environmental conditions and test procedures contained in RTCA Document (DO)-160G, Environmental Conditions and Test Procedures for Airborne Equipment, will be used to demonstrate equipment compliance.

2. Bench Tests

    a. Bench test procedures are specified in Subsection 2.4. These tests provide a laboratory means of demonstrating compliance with the requirements of Subsection 2.2. Test results may be used by equipment manufacturers as design guidance for monitoring manufacturing compliance, and, in certain cases, for obtaining formal approval of equipment design. In these MOPS, flights are suggested as one means of verifying the requirements in Subsection 2.2. These tests may be conducted on a surrogate aircraft, and are covered in Paragraph 2.4.2.

3. Installed Equipment Considerations

    a. Tests for installed equipment are included when performance cannot be adequately determined through bench testing.

    b. Test procedures and associated limits for installed equipment are specified in Subsection 3.3. Although bench and environmental test procedures are not included in the installed equipment test, their successful completion is a precondition to completion of the installed test. In certain instances, however, an installed equipment test may be used in lieu of bench test simulation of such factors as power supply characteristics, interference from or with other equipment installed on the aircraft, etc. Installed tests are normally performed under two conditions:

i. With the aircraft on the ground using simulated or operational system inputs

ii. With the aircraft in flight using operational system inputs appropriate to the equipment under test.

c. Test results may be used to demonstrate functional performance in the intended operational environment.

1.7 Definition of Terms and Acronyms

DAA Well Clear (DWC) or Well Clear refers to the DAA Well Clear definition in Appendix B and Appendix C of the RTCA MOPS for DAA Systems, referenced herein as the DAA MOPS.

A list of acronyms and abbreviations used in this document can be found in Appendix F.

1.7.1 Range (R) Definitions

The radar performance requirements will be evaluated between a maximum range, called the Radar Declaration Range (RDR), and a minimum range called the Radar Closest Performance Range (RCPR).

The RDR is defined as the minimum value for the maximum range at which the track accuracy requirements for a radar-generated intruder need to be met. The RDR is dependent on intruder category/speed, ownship speed and intruder bearing angle.

From a DAA perspective, the RDR is the point in the encounter timeline at which the generated radar tracks would be used by the PIC to make a decision as to whether there is a need to maneuver and plan the maneuver (corrective alerting in the DAA MOPS). The RDR values were derived in Appendix B for three different intruder category/speeds and different intruder bearing angles. The ownship speed was varied and the longest range was selected as the RDR. The calculation takes into account the Well Clear boundary, the delay of Air Traffic Control (ATC) interaction, and pilot response time. The RDR may be affected if the ownship is maneuvering at the start of encounter, however the impact is expected to be small. For the RDR derivation, the UA is assumed to be non-maneuvering at the start of encounter, which helps calculate an average number.

In Appendix D, the RDR values calculated in Appendix B are validated against the alerting requirements in the DAA MOPS. This was accomplished by evaluating the Loss of Well Clear (LoWC) when the alerting occurs at the RDR for 25,000 uncorrelated encounters.

Note, in many cases, alerting will not be required at RDR, since the encounter may not be the worst case encounter used to derive the RDR. In such cases, the radar will use its prioritization scheme to focus its efforts on the higher priority intruders, and will need to meet its accuracy requirements for those that are within the corrective alert zone (see Subparagraph 2.2.4.3.4.3 of the DAA MOPS).

RCPR is defined as the maximum value for the minimum range at which the intruder track accuracy requirements are met for a radar-generated track. In general, the radar will continue to track the intruder closer than RCPR.

1.7.2 Track Definitions

A high priority track is defined as one in which the intruder is in the corrective alert zone and hence the DAA system needs a track that meets accuracy requirements. The DAA MOPS has defined an average alerting time of 85 seconds. This will be used as the minimum radar alerting time. The radar system will also maintain a minimum of two high-priority tracks, irrespective of their calculated alerting priority.

A track is continuous if it maintains the same track identification (ID) between RDR and RCPR. A track has a discontinuity if the ID changes sometime between the RDR and RCPR. The discontinuity time is the time between disappearance of the first ID and appearance of the second ID.

A track is a split track if two tracks represent one intruder, identified by having both tracks close to each other within the 95% accuracies defined in Table 2-5.

A false track is defined as a track that is established by the radar for which there is no true intruder. The following notes describe special cases:

1. Moving intruders on the ground (e.g., cars) detected by the radar require special consideration. These are not considered false tracks. The radar manufacturer should reduce their detections so as not to create a nuisance for the PIC, and ensure that true intruders continue to be tracked.
2. The UA may encounter birds; estimated bird encounter rates are dynamic and depend on location, altitude, season, and time of day. In general terms, bird encounters may occur on the rough order of magnitude of at least once per hour. The DAA system should treat them no different than any other track.[1]
3. Rain and other weather conditions may create radar detections based on reflections in the used frequency. The radar should handle these detections so as not to create tracks that are sent to the DAA processor. These are considered false tracks.

1.7.3 Intruder Categories

Intruders are classified into three categories based on their speeds and sizes as defined below. Paragraph 1.7.4 contains the evaluation of their RCS.

1. Small, which includes gliders, balloons, etc., with a representative true airspeed up to 100 knots
2. Medium, which includes single-engine aircraft with a representative true airspeed up to 130 knots
3. Large, which includes dual-engine and larger aircraft with a representative true airspeed up to 170 knots.

1.7.4 Radar Cross-Section (RCS)

In this paragraph, guidelines are given to radar manufacturers regarding the RCS of the non-cooperative intruders that will be encountered. If the manufacturer uses the RCS value to perform analysis to verify requirements, more justification for the values used would be needed.

Appendix E provides information for RCS guidance for the C, X and Ku bands. Subsection E.4 points to seven references for RCS measurements. Subsection E.2 and E.3 provide results from two separate studies that used three-dimensional (3D) microwave simulation techniques to estimate the RCS for aircraft from the three categories defined

[1] US Wildlife Strikes to Civil Aircraft in the United States, 1990–2014, Federal Aviation Administration, National Wildlife Strike Database, Serial Report No. 21, Report of the Associate Administrator of Airports, Office of Safety and Standards, Airport Safety and Certification, Washington, DC, July 2015

above at different frequencies, azimuth angles, and elevation angles. A summary is presented below.

- Significant variations were observed between aircraft of the same category, depending on their size and design. No studies could be found in the literature on the frequency of encounters with each intruder category as non-cooperative intruders.
- There is a large variation in the aircraft RCS depending on the pose angle of the intruder, as explained in Subsection E.1. Typically, the nose and the side views show larger RCS, while poses in the middle can show significantly lower RCS. For radar design, the manufacturer will need to weigh factors such as closure rate and antenna gain in different directions, in addition to the RCS.
- The RCS for the medium and large intruders seems to show little variation across the C, X and Ku frequency bands.
- For a small intruder, the RCS of a human should be assumed at a minimum.
  - References 4 and 5 in Subsection E.4 provide some results for a human RCS.
  - Subparagraph E.2.2.1 provides the simulation results for a glider, which show an average RCS of 0.9 to 4 decibels per square meter (dBsm), depending on frequency.
- For a medium intruder, large variations were observed between studies.
  - The first study showed an average RCS of 5.1 dBsm for a helicopter intruder in the vertical plane. The second study showed means of 0.2 and -0.1, and medians of -0.3 and -0.4 for the C and Ku bands respectively, for single-engine aircraft (Piper Cherokee and Cessna 172).
  - Reference 6 includes a table for median RCS distribution for three aircraft at 2.8 Gigahertz (GHz) for a 3-dBsm RCS, showing 79% for a Piper Cherokee 140, 39% for Cessna 150, and 85% for a Piper Super Cub.
  - Reference 3 shows mean and probability density for Cherokee 140, Cessna 177 and Cessna 172 aircraft, showing mean values between 1.3-8.9 square meters ($m^{2)}$, depending on pose angle.
  - Data in Reference 7 shows RCS measurements for a Cessna 172R. No median or average is given, but it seems to show a higher average than other measurements.
- For a large intruder
  - The first study used a Cessna Citation and it showed a mean RCS of 9.1-11.9 dBsm, depending on frequency.
  - Study 2 included six aircraft: a Gulfstream G1, a Beech Baron 58, a King Air 200, a Citation X, a C29 and a Learjet 36. In the C band the models had a mean RCS of 3.9 and median of 3.4 dBsm. In the Ku band the models had a mean of 4 dBsm and a median of 3.8 dBsm.

1.8 Aircraft Equipment Information Vulnerabilities

Aircraft equipment information vulnerabilities (such as cybersecurity risks) have been present for digital systems since the development of the Personal Computer (PC) in the late 70s and even longer for Radio Frequency (RF) systems, and the advent of internet connectivity has substantially increased those risks. Internet and Wireless Fidelity (Wi-Fi) connectivity have become popular as a means for aircraft or equipment manufacturers to update installed avionics software, to update databases, or provide an alternate means of communicating with the flight crew or cabin (e.g., in-flight entertainment, weather, etc.).

In most countries, the State provides oversight of safety-of-flight systems (sometimes referred to as "authorized services"), which provide information to aircraft, such as an Instrument Landing System (ILS), VHF Omnidirectional Range Radar (VOR), Global Navigation Satellite System (GNSS), and Distance Measuring Equipment (DME), to name a few. However, the State typically does not provide oversight on "non-trusted"[1] connectivity such as the internet, Wi-Fi, or manufacturer-supplied equipment interfaces, which permit input of externally supplied data into aircraft systems. A manufacturer may expose aircraft information vulnerability through equipment design, or become vulnerable as a result of being connected to a common interface. Therefore, it is important that manufacturers consider aircraft information security risk mitigation strategies in their equipment design, particularly when the equipment is responsible for an interface between the aircraft and aircraft external systems.

Apart from any specific aircraft performance requirements related to information security that are contained in these MOPS, it is recommended that manufacturers look at a layered approach to aircraft information security risk mitigation that includes both technical (e.g., software, signal filtering) and physical strategies. From a technical perspective, for example, this could include signal spoofing detection capabilities or more stringent, multi-factored authentication techniques such as passwords, personal identification numbers, and digital certificates. From a physical perspective, for example, such as in an in-flight entertainment system in the cabin, a manufacturer could consider connectors that require special tools to remove to prevent passenger tampering. And finally, but just as important, manufacturers should consider supply chain risk management; for example, if a manufacturer is outsourcing software code development, is the contractor and its staff properly vetted?

Civil aviation authorities have a regulatory interest when an applicant's design makes use of a non-trusted connectivity where the installation can potentially introduce aircraft information security vulnerability. This requires the applicant to address not only the information security vulnerabilities and mitigation techniques for the new installation, but to also consider how vulnerability could propagate to existing downstream systems. Therefore, it is recommended that manufacturers reference their equipment aircraft information security review and mitigation strategies in the equipment's installation manual so that the applicant can consider them in meeting the regulatory requirements for installation.

[1] A "non-trusted" connectivity (sometimes referred to as third-party system) is any frequency or service where an Air Navigation Service Provider is not providing direct monitoring/protection.

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2 EQUIPMENT PERFORMANCE REQUIREMENTS AND TEST PROCEDURES

2.1 General Requirements

2.1.1 Airworthiness

In the design and manufacture of the equipment, the manufacturer **shall (001)** provide for installation so as not to impair the airworthiness of the aircraft.

2.1.2 Intended Function

The equipment **shall (002)** perform its intended function(s), as defined by the manufacturer, and its proper use **shall (003)** not create a hazard to other users of the NAS.

2.1.3 Federal Communications Commission (FCC) Rules

All equipment **shall (004)** comply with the applicable rules of the Federal Communication Commission.

2.1.4 Fire Protection

All materials used **shall (005)** be self-extinguishing except for small parts (such as knobs, fasteners, seals, grommets and small electrical parts) that would not contribute significantly to the propagation of a fire.

2.1.5 Operation of Controls

The equipment **shall (006)** be designed so that controls intended for use during flight cannot be operated in any position, combination or sequence that would result in a condition detrimental to the reliability of the equipment or operation of the aircraft.

2.1.6 Accessibility of Controls

Controls that do not require adjustment during flight **shall (007)** not be readily accessible to the PIC.

2.1.7 Effects of Test

The equipment **shall (008)** be designed so that the application of specified test procedures **shall (009)** not be detrimental to equipment performance following the application of the tests, except as specifically allowed.

2.1.8 Design Assurance

Design Assurance Levels (DAL) should be adequate to mitigate the failure classification appropriate to the contribution of the equipment to the aircraft-level failure in the aircraft in which it is to be installed. The DAL appropriate for a given hazard classification is not the same for all aircraft types, and the contribution of the equipment to an aircraft-level failure may vary depending on the aircraft and other installed equipment.

2.1.9 Harmful Interference

1. Frequencies transmitted by the radar system **shall (010)** not cause harmful interference to aviation systems on the UAS or other aircraft.
2. The radar **shall (011)** not degrade the performance of other DAA radars outside the RCPR of the system as defined in Subparagraph 2.2.7–15.

2.2 Equipment Performance – Standard Conditions

2.2.1 Introduction

The requirements in this paragraph address the needs of a non-cooperative surveillance sensor for a DAA system. In most aspects, the radar is a standalone system and its compliance with this standard can be verified without being interfaced to a DAA system.

The requirements in this paragraph are mostly performance-based, and do not dictate a design. The manufacturer has several degrees of freedom in the design to meet these requirements. While the expected performance has assumptions on the UAS capabilities as outlined in Paragraph 1.5.1, a similar approach can be used to derive requirements for a less or more capable UAS.

2.2.2 DAA Radar Input/Output Requirements

2.2.2.1 Ownship State Data

The radar **shall (012)** be capable of receiving the ownship state data as given in Paragraph 1.5.3.

2.2.2.2 Radar States and Control

1. The radar **shall (013)** have three states: Off, Standby and Transmit.
2. The radar **shall (014)** be in the off state when no power is applied to it.
3. The radar **shall (015)** be in standby mode when initially powered up.
4. The radar **shall (016)** provide the ability to be externally controlled to enable or disable the transmitter, and thus put the radar in transmit and standby modes, respectively.

2.2.2.3 Radar Output Data to the DAA Processor

1. The radar **shall (017)** provide a radar track report that includes a unique track ID, an estimate of an intruder aircraft's range, range rate, azimuth and elevation angles, their error estimates, and the time of the track measurement or estimate, as shown in Table 2-1, below.

Note: *The radar may output additional data such as intruder azimuth angle rates and elevation angle rates or velocity.*

Table 2-1 Track Output Data

Radar Intruder Data	Notes
Time of Applicability	Time of the track measurement or estimate
Track ID	None
Slant Range	None
Slant Range Accuracy	None
Range Rate	None
Range Rate Accuracy	None
Elevation Angle	None
Elevation Angle Accuracy	None
Azimuth Angle	None
Azimuth Angle Accuracy	None
Track Priority Number	Based on the prioritization as described in Subparagraph 2.2.7–3

Radar Intruder Data	Notes
Measured/Estimated Flag	Indicates whether there was a radar measurement of the track since the last update
End of Track Coasting Flag	This flag is set when the radar is ready to terminate a track after coasting for some time. No reports on the same track are expected after this.

2. The radar **shall (018)** generate and output track reports at an average rate of 1 Hertz (Hz) ±20% for all existing tracks that are between the RDR and RCPR.

Note:

1. *The track output may be based on a measurement done since the last update, or based an estimate based on time extrapolation.*

2. *In order to meet the latency requirement in Paragraph 2.2.7–16, the track report for each individual track will need to be sent as soon as it is ready, without bundling all the tracks into one report.*

2.2.2.4 Radar Status

1. When operational, the radar **shall (019)** report its status as ready or faulted at intervals of 1 second or less. A ready status is an indication the radar is working normally. A faulted status is an indication the radar is not operational.

   Note: *Faulted status may occur when the radar is in standby or transmit modes. If in transmit mode and faulted, the radar should attempt to turn off transmission irrespective of the status of the transmitter control input from the DAA system.*

2. The radar **shall (020)** provide status that indicates whether or not the transmitter is enabled.

2.2.3 Radar Frequency Bands

The radar **shall (021)** use one of the frequency ranges in Table 2-2, below. The first six are in the Aeronautical Radio Navigation Spectrum (ARNS) allocations for primary airborne surveillance radars as specified in ITU Radiocommunications Sector (ITU-R) report ITU-R M.2204, dated November 2010. The last two are allocated by the ITU for general radio navigation, which includes aeronautical, maritime, and land applications. Further details can be found in Appendix A.

Table 2-2 Radar Frequency Bands

Band	Frequency Range
C	4,200-4,400 Megahertz (MHz)
C	5,350 – 5,470 MHz
X	8,750 – 8,850 MHz
X	9,300 – 9,500 MHz
Ku	13,250 – 13,400 MHz
Ku	15.40 – 15.70 GHz
K	24.45 – 24.65 GHz
Ka	32.3 – 33.4 GHz

Note: *The 4,200 – 4,400 (MHz band is not recommended, as the user will need to show non-interference with airborne altimeters in the band. An FCC license will be required for all frequency utilizations. Use of frequencies outside the above will need additional pre-coordination with the FCC.*

2.2.4 Radar Frequency Channels

The radar **shall (022)** be capable of switching automatically between a minimum of three frequency channels within the utilized band based on interference in the channel.

The manufacturer may also allow manual frequency channel control by the PIC.

Note:

1. *The number of frequency channels is limited by FCC frequency bandwidth allocation, which allows 100-200 MHz in every band. The manufacturer has the freedom to select the channel bandwidth for the waveform, which allows a tradeoff between performance and interference.*

2. *The potential for interference between UA systems will remain significantly low, helped by the following facts:*

    a. *The radar operates over the FOR of ±110º azimuth and ±15º elevation, while the instantaneous antenna bandwidth is significantly smaller, which implies that the radar will be pointed at any particular location for a short period only, so any interference will be short-lived.*

    b. *A false detection of an interfering UAS will not cause a false track to be generated. A false track will require consistent detections with repeatable parameters.*

2.2.5 Operation in Rain and Instrument Meteorological Conditions (IMC)

1. The radar **shall (023)** meet its range performance requirement in at least four millimeters of rain per hour (mm/hr).
2. Radar **shall (024)** perform its intended function during day and night.
3. The radar **shall (025)** be qualified to operate under the same conditions that the UAS is qualified for, as a minimum.

Note:

1. *The rain rate of 4 mm/hr was chosen as it is widely acknowledged as the maximum value for rain when flying against the radar's primary targets, VFR traffic. For example, see "I. Gultepe, J. A. Milbrandt, Probabilistic Parameterizations of Visibility Using Observations of Rain Precipitation Rate, Relative Humidity, and Visibility," Journal of Applied Meteorology and Climatology, Volume 49, January 2010, pages 36-46.*

2. *In verifying this requirement during flight test in clear conditions the manufacturer will use Table 2-3, below, to calculate the rain-adjusted RDR value for a particular flight test that will be carried out. Table 2-3 has attenuation values for the C, X, and Ku bands. Manufacturers using K and Ka will need to propose attenuation values and justify them. First, use Equation 2.2.5.1 to calculate the Attenuation Factor, then use Equation 2.2.5.2 to calculate the rain-adjusted RDR. Equation 2.2.5.1 may be modified if the test is carried out in actual rain. Also,*

Equation 2.2.5.2 assumes that RDR is affected by the range raised to the fourth power (R^4), which is an approximation for this case.

2.2.5.1 Attenuation Factor Equation

Attenuation Factor =

RDR(4 mm/hr rain attenuation – clear air attenuation)*Likelihood,*

Where Likelihood =50%, which denotes the percentage of area within the FOR where rain exists.

2.2.5.2 Rain-Adjusted RDR Equation

*Rain-Adjusted RDR = RDR *2^(Attenuation Factor/12)*

As an example, for an RDR of 6 Nautical Miles (NM) in the Ku band, use the following:

Attenuation Factor = 6(0.44-0.053)*0.5= 1.16 Decibels (dB)*

*Rain-Adjusted RDR = 6*2^(1.16/12)= 6.4 NM.*

Table 2-3 Rain Attenuation for Different Frequency Bands

	Environment	C Band	X Band	Ku Band
Two-way Attenuation (dB/NM)	**Clear Air**	0.021	0.032	0.053
	1 mm/hr	0.007	0.031	0.083
	4 mm/hr	0.037	0.190	0.440

Note: *The values in Table 2-3 were derived using the equations and software provided by Range Equations for Modern Radar,[1] assuming 4,000' elevation, zero elevation angle and vertical polarization.*

2.2.6 Radar Field of Regard (FOR)

1. The horizontal FOR of the radar **shall (026)** be a minimum of ±110° with respect to the longitudinal axis of the UAS.
2. The vertical FOR of the radar **shall (027)** be a minimum of ±15° vertically referenced to the flight path of the UA (UA body frame corrected by the aircraft angle of attack), limited to intruders above 1,000' AGL.
3. The radar **shall (028)** correct for a UA Angle of Attack (AOA) up to ±5°.

Note: *If no AOA measurement is available, use an estimate of the aircraft pitch.*

2.2.7 Radar Tracks

1. The radar **shall (029)** provide a unique ID for each established radar track.
2. The radar **shall (030)** provide a track capacity of up to 20 intruders within its FOR.

[1] Range Equations for Modern Radar, David K. Barton, Artech House, 2012

Note:

1. *The interpretation of this requirement is that the radar needs to be able to detect up to 20 intruders, and can meet its performance requirements for the high priority intruders that meet alerting thresholds as defined in Subparagraph 2.2.7–4.*

2. *The maximum number of 20 intruders was derived from The Lower Altitude Airspace Density Model for the Traffic Alert and Collision Avoidance System (TCAS) (DO-185B, Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II) Change 2, §2.2.1.2.1,) and resulted in 38 aircraft within the radar surveillance range of 8 NM. Accounting for the limited azimuth FOR requirement reduces the number of aircraft to 23. Further reduction can be made for the limited elevation FOR. This is conservatively accounted for, such that the requirement is 20 aircraft. For TCAS, lower altitude airspace is defined as being below 10,000' AGL (DO-185B, §2.2.1.3.1).*

3. The radar **shall (031)** prioritize all intruder tracks based on their modified Tau (τ_{mod}) and range in the order defined below:

   $\tau_{mod} = \frac{-(r^2 - DMOD^2)}{r\dot{r}}$ for closing geometries and $r > DMOD$.

   $\tau_{mod} = 0$ for $r \leq DMOD$, intruders will be prioritized by range, with higher priority given to intruders at shorter range.

   $\tau_{mod} = inf$ for non-closing geometries where $r > DMOD$.

   Where:

   $r = Intruder\ range$

   $\dot{r} = Range\ rate$

   $DMOD =$ Distance Modification of Modified Tau, $0.66\ NM$.

Note:

1. *For closing targets, the range rate will be negative and τ_{mod} will be positive, thus the highest priority will be given to the lowest τ_{mod}.*

2. *For radars receiving optional cueing information from the DAA system, the cued information can be used to override the radar internal prioritization.*

3. *For radars that have the capability of calculating the horizontal and vertical miss distances as defined in Subparagraph 2.2.4.3 of the DAA MOPS, Alerting Requirements, those parameters can be used for a more accurate prioritization scheme.*

4. The radar **shall (032)** be capable of supporting a minimum of 5 high priority tracks simultaneously.

5. The two highest priority targets **shall (033)** always be high priority irrespective of their priority values.

6. The radar **shall (034)** establish a track for greater than 95% of all high priority intruders within the FOR starting at the RDR.

7. For high priority intruders, the radar **shall (035)** establish an intruder aircraft track that meets the track performance requirements in Paragraph 2.2.8 between the RDR and the RCPR 90% of the time.

Note: *For verification purposes, a pool of tracks can be generated, whether in simulation or flight test, and the error statistics for each accuracy parameter in Paragraph 2.2.8 between RDR and RCPR can be calculated for each track.*

8. The radar **shall (036)** establish an intruder aircraft track before the RCPR more than 99% of the time for intruders entering the FOR at or before the RDR.
9. For high-priority tracks, the radar **shall (037)** maintain track continuity for 95% of the time between the RDR and RCPR. A track is considered not continuous for the time that the track is lost until it appears under a different ID.
10. For high-priority tracks, the radar **shall (038)** stay free of split tracks for 90% of the time between the RDR and RCPR.
11. For an ownship UA capable of a standard rate turn of 3 degrees/second, the RDR in clear air for a small intruder in the head-on direction **shall (039)** be a minimum of 5.4 NM.
12. For an ownship UA capable of a standard rate turn of 3 degrees/second, the RDR in clear air for a medium intruder in the head-on direction **shall (040)** be a minimum of 6 NM.
13. For an ownship UA capable of a standard rate turn of 3 degrees/second, the RDR in clear air for a large intruder in the head-on direction **shall (041)** be a minimum of 6.7 NM.

Note:

1. *The derivation of RDR values for intruder categories and bearing angles can be found in Appendix B.*
2. *For an ownship UA incapable of a standard rate turn, a different RDR value will need to be calculated. For example, for a UA capable of a 1.5-degree turn, the RDR values are 5.9, 6.4, and 7.2 NM for small, medium and large intruders, respectively. The correction factors for non-head-on cases will remain unchanged for this case.*

14. The RDR for non-head-on intruders **shall (042)** be scaled by the factors shown in Table 2-4 below. Note the factors are relative to the RDR values in Subparagraphs 11, 12 and 13 above.

Table 2-4 RDR Corrections per Intruder Bearing Angle

Intruder Bearing Angle	RDR Correction Factor		
	Small	Medium	Large
|angle| < 30	1	1	1
30 ≤ |angle| < 60	0.67	0.78	0.84
60 ≤ |angle| < 90	0.45	0.52	0.6
|angle| ≥ 90	0.35	0.43	0.55

15. The RCPR **shall (043)** be 4,000’ for all intruder categories and angles.

16. The radar latency in reporting an update on an established track **shall (044)** be below 0.5 second. The latency is the difference in the time of applicability given in the track report and the time the report was sent to the DAA processor.
17. The radar **shall (045)** maintain the intruder track if the intruder is performing a horizontal maneuver with horizontal acceleration up to 1.5 times the acceleration of gravity (1.5xg).
18. The radar **shall (046)** maintain the intruder track if the intruder is performing a vertical maneuver up to a rate of ±5,000'/minute.
19. The radar **shall (047)** maintain the intruder track if the ownship is performing a horizontal maneuver up to a heading rate of ± 6 degrees/second or maximum rate that can be performed by the ownship.
20. The radar **shall (048)** maintain the intruder track if the ownship is performing a vertical maneuver at the maximum rate that can be performed by the ownship.
21. The minimum altitude for radar operation **shall (049)** be defined by the manufacturer.

Note: *The recommended minimum altitude is 1,000' AGL for the intended environment of operation. This will facilitate UAS operation without the extra measures listed in Appendix A of the DAA MOPS.*

22. For cases where the intruder enters the FOR within the RDR (cases dominated by ownship maneuvers) the radar **shall (050)** take no more than 15 seconds 90% of the time to establish a track that meets the accuracy requirements in Paragraph 2.2.8, evaluated 15 seconds from the time the intruder enters the FOR until RCPR or the intruder exits the FOR.

Note: *It is shown in Appendix C that the probability of an intruder entering the FOR within the RDR is low, and these cases are mainly in two classes; those with the ownship maneuvering, which are covered by this requirement, and those with the intruder overtaking the ownship, . When the ownship is being overtaken by an intruder the responsibility for "See and Avoid" falls on the pilot of the intruder aircraft since the ownship is in the intruder pilot's field of view.*

23. The radar **shall (051)** be able to resolve two intruder aircraft separated vertically or horizontally by a minimum of 2000' at a range of the lesser of RDR or 4.8 NM with at least 90% probability.

2.2.8 Radar Track Accuracy

Note: *All the accuracies defined in this paragraph apply to high-priority intruders.*

1. The error of the radar track range within the FOR and between the RDR and the RCPR **shall (052)** have a mean not to exceed 50' and a standard deviation not to exceed 70'.
2. The error of the track range rate within the FOR and between the RDR and the RCPR **shall (053)** have a mean not to exceed 8'/second (sec) and a standard deviation not to exceed 10'/sec.
3. The radar track angular error in azimuth within the FOR and between the RDR and the RCPR **shall (054)** have a mean not to exceed 0.5 degrees and a standard deviation not to exceed the maximum of 100' or 1 degree referenced from the platform's body frame of reference.

4. The radar track angular error in elevation within the FOR and between the RDR and the RCPR **shall (055)** have a mean not exceed 0.5 degrees and a standard deviation not to exceed the maximum of 100’ or 1 degree referenced from the platform’s body frame of reference.

Note: *The manufacturer may replace accuracy estimation using mean and standard deviation with Root Mean Square Error (RMSE) or 95% containment. Table 2-5 below gives the conversion between the three sets of units. These assume a Gaussian distribution. The manufacturer may use a different conversion if a different statistical distribution can be shown.*

Table 2-5 Parameter Conversion

Parameter	Mean	Standard Deviation	95% Containment	RMSE
Range Error (feet (ft))	50	70	±166	86
Range Rate Error (ft/sec)	8	10	±24.5	12.8
Azimuth Angle Error (Degrees)	0.5	1	±2.2	1.1
Elevation Angle Error (Degrees)	0.5	1	±2.2	1.1

5. The accuracy numbers for range, range rate, azimuth and elevation angles in Table 2-1 **shall (056)** be given a numeric index that provides a bound on the error in that parameter relative to the accuracy given in Subparagraphs 2.2.8–1-4, as shown in Table 2-6.
6. The error bound in Subparagraph 2.2.8-5 **shall (057)** be correct for 80% of all track updates of a high priority track.
7. The error bound for a high priority track **shall (058)** be Accuracy Index 4 or lower for 80% of the updates.

Table 2-6 Allowed Error for Accuracy Parameter

Accuracy	Accuracy Index
Accuracy within 0.25 of 95% containment in Table 2-5	1
Accuracy within 0.5 of 95% containment in Table 2-5	2
Accuracy within 0.75 of 95% containment in Table 2-5	3
Accuracy within 1X of 95% containment in Table 2-5	4
Accuracy within 1.25X of 95% containment in Table 2-5	5
Accuracy within 1.5X of 95% containment in Table 2-5	6
Accuracy within 2X of 95% containment in Table 2-5	7
Accuracy unbounded	8

2.2.9 Radar False and Ground Tracks

1. The radar **shall (059)** have a probability of false tracks of less than 1 false track per hour for a track with a modified Tau of less than 110 seconds as defined in Subsection 1.7.
2. Ground moving targets **shall (060)** not be prioritized such that there are no high-priority slots left for airborne targets.

3. When operating at the minimum altitude, the radar **shall (061)** output no more than four tracks related to ground moving targets at any one time, so as to limit nuisance tracks on the pilot display.

Note:

1. *There is concern that having any Ground Moving Tracks (GMT) on the pilot display may create nuisance and diversion to the pilot. GMT should be filtered from the pilot's display to the extent possible. GMT during operations should be considered in studies regarding pilot and display safety analysis. Phase 1 MOPS operations are intended for flight altitude transitions at lower altitudes rather than continuous operations at the minimum altitude. GMT are likely to be more prevalent, harder to filter, and have greater impact to UA operations when operating at lower altitudes over ground traffic.*

2. *For verification of Subparagraph 2.2.9-2 and 2.2.9-3, the radar will be flown at the minimum defined altitude over a busy highway, and the instrumented target will be tracked as a high priority target, with no more than four high priority ground moving targets at any one time.*

2.2.10 Radar Health Monitoring

1. At power up, the radar **shall (062)** perform a comprehensive set of tests to check hardware, software, and firmware, to evaluate that the components of the radar are functioning normally and report status as mentioned in Subparagraph 2.2.2.4.
2. The radar **shall (063)** perform a health monitoring function run in the background of its run-time environment, which provides continuous health status updates for its status update report as mentioned in Subparagraph 2.2.2.4.

2.3 Equipment Performance – Environmental Conditions

The environmental tests and performance requirements described in this subsection are intended to provide a laboratory means of determining the overall performance characteristics of the equipment under conditions representative of those that may be encountered in actual aeronautical operations.

The specified performance tests cover the radar for DAA systems. Additional tests may need to be performed in order to determine performance of particular design requirements that are not specified in this document. It is the responsibility of the manufacturer to determine appropriate tests for these functions.

Unless otherwise specified, the environmental conditions and test procedures contained in RTCA DO-160G, *Environmental Conditions and Test Procedures for Airborne Equipment,* will be used to demonstrate equipment compliance.

2.3.1 Use of Special Purpose Software

It is acceptable but not necessary to use FAA-approved production software during the environment tests. Special purpose test software is acceptable and may be a more appropriate way to ensure that the hardware and interfaces are comprehensively exercised during environmental excursions. When using this approach, the applicant will show by inspection or analysis that the hardware functions necessary to meet all applicable requirements of Subsection 2.2 are thoroughly exercised, and will establish appropriate pass/fail criteria consistent with the performance requirements and test procedures of

Subsection 2.4. In addition, configuration of the special purpose software will be controlled.

2.3.2 DAA Airborne Equipment – Environmental Conditions

RTCA DO-160G contains environmental test categories for each environmental condition to be tested. Many of the environmental conditions offer multiple categories of exposure, which vary in severity. The equipment manufacturer is allowed to choose the environmental category to which the article is to be qualified and should select a category that best represents the most severe environment the equipment is expected to be regularly exposed to during its service life. System components designed to be located in different parts of the aircraft may be tested separately using the appropriate categories for each component.

Table 2-7 lists all of the environmental conditions, performance requirements and test procedures documented in RTCA DO-160G. It identifies the performance tests to be run subject to the various procedures in RTCA DO-160G. The manufacturer should follow the performance test procedures of Subsection 2.4. If an entry is blank, then performance testing is left to the manufacturer to determine applicable performance criteria for that environmental test.

Tests identified by the phrase, “when required,” apply when the manufacturer wishes to qualify the equipment to additional environmental conditions such as may be required by contractual obligations or environments applicable only to specific aircraft. Tests identified by the phrase “if applicable,” apply to equipment that is expected to be exposed to that environment during its service life. For example, Lightning Direct Effects testing is only applicable to externally mounted equipment.

Some of the performance requirements in Subsection 2.2 are not tested by the test procedures herein. Moreover, not all tests are required to be conducted in each of the environmental conditions in RTCA DO-160G. Judgment and experience have indicated that these particular performance parameters are not susceptible to certain environmental conditions and that the level of performance specified in Subsection 2.2 will not be measurably degraded by exposure to these particular environmental conditions.

Additional tests may have to be performed to determine performance of particular design requirements that are not specified in this document. It is the responsibility of the manufacturer to determine appropriate tests for these functions.

Table 2-7 DAA Airborne Equipment Environmental Test Requirements

Environmental Test					
Function	**DO-160G Paragraph**	**2.2.2.3 (Requirement) 2.4.3.3 (Test)[5] Radar Output Data to the DAA Processor**	**2.2.2.4 (Requirement) 2.4.3.4 (Test)[6] Radar Status**	**2.2.7. (Requirement) 2.4.3.9. 1(Test)[8]Radar Track Unique ID**	**Remarks**
Temperature/Altitude	4.0				Heading Only
Ground Survival Low-Temperature Test and Short-Time Operating Low-Temperature Test	4.5.1	X	X	X	None
Operating Low-Temperature Test	4.5.2	X	X	X	None
Ground Survival High-Temperature Test and Short-Time Operating High-Temperature Test	4.5.3	X	X	X	None
Operating High-Temperature Test	4.5.4	X	X	X	None
In-Flight Loss of Cooling Test	4.5.5	X	X	X	(7); If Applicable
Altitude Test	4.6.1	X	X	X	None
Decompression Test	4.6.2	X	X	X	When Required
Overpressure	4.6.3	X	X	X	When Required
Temperature Variation	5.0	X	X	X	None
Humidity	6.0	X	X	X	None
Shock	7.0				Heading Only
Operational Shock	7.2	X	X	X	(1)
Crash Safety Shocks	7.3	X	X	X	(1)
Vibration	8.0	X	X	X	None
Explosive Atmosphere	9.0	X	X	X	When Required
Waterproofness	10.0				Heading Only
Condensing Water Drip Proof Test	10.3.1	X	X	X	When Required
Drip Proof Test	10.3.2	X	X	X	When Required
Spray Proof Test	10.3.3	X	X	X	When Required
Continuous Stream Proof Test	10.3.4	X	X	X	When Required

Environmental Test					
Function	**DO-160G Paragraph**	**2.2.2.3 (Requirement) 2.4.3.3 (Test)[5] Radar Output Data to the DAA Processor**	**2.2.2.4 (Requirement) 2.4.3.4 (Test)[6] Radar Status**	**2.2.7. (Requirement) 2.4.3.9. 1(Test)[8] Radar Track Unique ID**	**Remarks**
Fluids Susceptibility	11.0				Heading Only
Spray Test	11.4.1	X	X	X	When Required
Immersion Test	11.4.2	X	X	X	When Required
Sand and Dust	12.0	X	X	X	When Required
Fungus Resistance	13.0	X	X	X	When Required
Salt Fog	14.0	X	X	X	When Required
Magnetic Effect	15.0	X	X	X	(2)
Power Input	16.0				Heading Only
Normal Operating Conditions	16.5.1 16.6.1	X	X	X	None
Abnormal Operating Conditions	16.5.2 16.6.2	X	X	X	None
Voltage Spike	17.0	X	X	X	None
Audio Frequency Conducted Susceptibility	18.0	X	X	X	None
Induced Signal Susceptibility	19.0	X	X	X	None
RF Susceptibility	20.0				Heading Only
Conducted	20.4	X	X	X	None
Radiated	20.5	X	X	X	None
Radiated (Alternate Procedure)	20.6	X	X	X	None
Emission of RF Energy	21.0				Heading Only
Conducted	21.4	X	X	X	(2)
Radiated	21.5	X	X	X	(2)
Radiated (Alternate Procedure)	21.6	X	X	X	(2)
Lightning Induced Transient Susceptibility	22.0	X	X	X	When Required

Environmental Test					
Function	**DO-160G Paragraph**	**2.2.2.3 (Requirement) 2.4.3.3 (Test)[5] Radar Output Data to the DAA Processor**	**2.2.2.4 (Requirement) 2.4.3.4 (Test)[6] Radar Status**	**2.2.7. (Requirement) 2.4.3.9. 1(Test)[8]Radar Track Unique ID**	**Remarks**
Lightning Direct Effects	23.0				(3); If Applicable
Icing	24.0				If Applicable
Electrostatic Discharge	25.0	X	X	X	None
Fire/Flammability	26.0				(2) (4)

Note:

1. *The application of this test may result in damage to the equipment. It may, therefore, be conducted after the other tests. Furthermore, Paragraph 2.1.7 of this document, Effects of Test, does not apply following crash safety shocks.*

2. *Equipment performance requirements for this function of the equipment under test are defined within DO-160G.*

3. *Lightning direct effects applies to the externally mounted equipment.*

4. *The fire/flammability test is to ensure the equipment doesn't support flame propagation. There are no performance requirements.*

5. *This test is carried out where a radar test is called out during the DO-160 test.*

6. *This test is carried out where a radar test is called out after the DO-160 test.*

7. *In-flight loss of cooling testing is only applicable if the airborne equipment requires cooling air to be provided.*

2.4 Equipment Test Procedures

The test procedures and associated limits specified in this document are intended as recommended means of proving compliance with the minimum acceptable performance parameters. Although specific test procedures are listed, it is recognized that other methods may be preferred the testing authority. These alternate procedures may be used if they provide at least equivalent information. In such cases, the procedures cited herein should be used as one criterion in evaluating the acceptability of the alternate procedures.

The two types of DAA radar test procedures are described below: ground test and flight test.

The recommended ground test procedure is conducted in an anechoic chamber and described in Subparagraph 2.4.2.1 (refer to Figure 2-1 for initial setup diagram).

The ground or bench test procedures in an anechoic chamber provide a means to show equipment performance in a non-operational environment. Test results may be used by equipment manufacturers as design guidance, monitoring manufacturing compliance and, in certain cases, for obtaining formal approval of equipment design and manufacture. Bench test procedures may also be used after corrective maintenance has been performed or for checking flight crew reports on performance.

The recommended flight test procedures and post-flight analysis methodology are described below in Subparagraph 2.4.2.2 (refer to Figure 2-2 for a setup diagram). A set of encounters for the flight scenarios are described in Subparagraph 2.4.2.2, Table 2-8 and Table 2-9. These test procedures are intended as one means of design verification and ensuring that the equipment is working properly and can be used for its intended function.

2.4.1 Definitions of Terms and Conditions of Test

The following are definitions of terms and the conditions under which the tests described in this paragraph should be conducted.

1. Power Input Voltage – Unless otherwise specified, all tests must be conducted with calibrated equipment capable of measuring the voltage to design requirements. The input voltage must be measured at the input terminals of the equipment under test.
2. Power Input Frequency
    a. In the case of equipment designed for operation from an Alternating Current (AC) source of essentially constant frequency (e.g., 400 Hz); the input frequency must be adjusted to design frequency.
    b. In the case of equipment designed for operation from an AC source of variable frequency (e.g., 300 to 1,000 Hz), unless otherwise specified, tests must be conducted with the input frequency adjusted to a selected frequency and within the range for which the equipment is designed.
    c. Adjustment of Equipment – The circuits of the equipment under test must be properly aligned and otherwise adjusted in accordance with the manufacturer's recommended practices prior to application of the specified tests.
    d. Test Equipment – All equipment used in the performance of the tests should be identified by make, model and serial number where appropriate, and its latest calibration date. When appropriate, all test equipment calibration standards should be traceable to national and/or international standards.
    e. Test Instrument Precautions – Adequate precautions must be taken during the test to prevent the introduction of errors resulting from the connection of voltmeters, oscilloscopes and other test instruments across the input and output impedances of the equipment under test.
    f. Ambient Conditions – Unless otherwise specified, all lab tests must be made within the following ambient conditions:
        i. Temperature: +15 to +35 degrees Celsius (C)
(+59 to +95 degrees Fahrenheit)
        ii. Relative Humidity: Not greater than 85%
        iii. Ambient Pressure: 84 to 1-7 Kilopascals (equivalent to +5,000' to -1,500') (+1,525' to –460 meters).

3. Connected Loads – Unless otherwise specified, all tests must be performed with the equipment connected to loads having the impedance values for which it is designed.
4. Warm-up Period – All tests must be conducted after an appropriate warm-up time as specified by the manufacturer.

***Note**: The organization performing these tests should take necessary precautions to prevent exposure of personnel to hazardous microwave radiation.*

5. The radome should meet the requirements of RTCA DO-213A, Minimum Operational Performance Standards for Nose-Mounted Radomes.

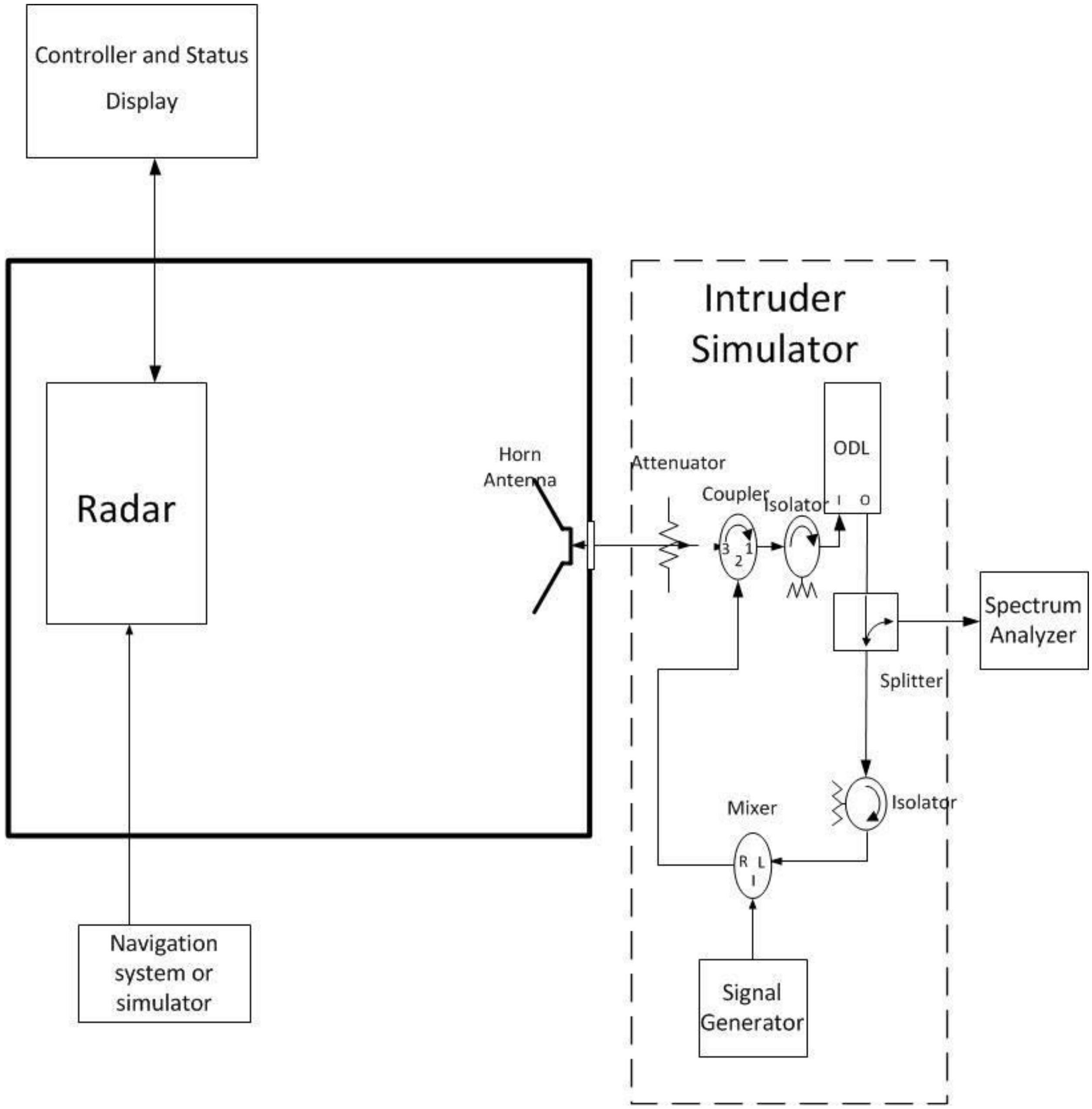
2.4.2 Required Test Equipment

2.4.2.1 Ground Test Setup (Anechoic Chamber)

The Radar Under Test (RUT) is placed in the anechoic chamber and connected to the following as shown in Figure 2-1:

- A controller unit that can send commands to the radar
- A radar status display
- A display that shows the tracks created by the radar
- A navigation system that provides an input similar to navigation input from the UA or an equivalent simulator for the navigation system.

The receiving horn antenna is placed in the anechoic chamber as well and connected to the intruder simulator. The intruder simulator will simulate path attenuation, propagation delay and create intruder Doppler shift. The recommended test equipment consists of cabling of a measured length and attenuation, an attenuator, a coupler, two isolators, an Optical Delay Line (ODL), a splitter, a mixer, a spectrum analyzer, and a signal generator.



<u>Figure 2-1</u> **Anechoic Chamber Setup for a Radar Test**

2.4.2.1.1 Ground Test High-Level Description

A radar-transmitted signal will be received by the horn antenna, attenuated, and transferred to the ODL through a coupler and an isolator. An ODL will introduce the delay, simulating signal propagation, according to the test program that is consistent with the target simulated range. The delayed signal replica will be mixed with the Doppler frequency simulated by the signal generator and delivered through the delay line completing the two-way path through the horn antenna at the RUT. The spectrum analyzer may register the frequency and timing of the reflected signal as well.

2.4.2.2 Flight Test Setup

Flight tests will be carried out as part of the verification of the requirements listed in Subsection 2.2. Some of the radar requirements cannot be readily tested on the bench, and hence flight tests will provide the most viable alternative.

The flights can be carried out with a complete DAA system or a surrogate controller that provides input data to the radar and receives radar output.

The radar may be installed on the intended UA or may be installed on a surrogate aircraft. During the test, the pilot will need to limit the surrogate aircraft performance to that of the UA. The navigation solution on the surrogate should be of equivalent quality to that in the UA.

Representative intruders for the three intruder categories will need to be tested:

- Large: A dual-engine aircraft such as Beechcraft B200, Cessna Citation
- Medium: A single-engine aircraft, such as Cessna 172, Piper 28
- Small: A glider. If a small intruder is not available, then the manufacturer needs to show comparison simulation data to provide performance data against small intruders.

A recommended list of statistical flight scenarios is provided in Table 2-8. Table 2-9 provides a list of individual, non-statistical flight tests.

- Statistical (22 flights): These tests include a variety of ownship and intruder speeds, altitudes and bearing angles with the purpose of creating statistical data for radar performance evaluation. In these flights the intruders fly starting at 2 NM distance before the RDR and continue until reaching the RCPR. The following is the breakdown of the flights:
    - 18 with one intruder flying at a predefined Constant Bearing (CB) angle to the ownship; suggested bearing angles are 0, ±10, ±20, ±45, ±75, ±95
    - 2 with an intruder vertical maneuver
    - 2 with an ownship vertical maneuver.
- Non Statistical (13 flights): Non-statistical tests are designed to verify a specific requirement. Hence, they represent stress cases where participating aircraft may not fly the full radar range from RDR to RCPR. The following is the breakdown of the flights:
    - 2 with an ownship horizontal maneuver
    - 2 with an intruder horizontal maneuver
    - 2 at the minimum altitude defined by manufacturer and over a highway
    - 2 with an intruder flying at 1,000’ AGL (minimum intruder altitude)
    - 2 with 5 intruders coming from different bearing angles
    - 1 ownship maneuver creating an encounter closer than RDR with a single intruder
    - 2 with 2 intruders with vertical and horizontal separation

Note:

1. *It is expected that, where possible, two encounters will be combined together creating a two-intruder flight to save time.*

2. *If the UA is not capable of the defined speed and climb rate, suitable substitutions should be made to ensure the flight envelope is tested.*

Table 2-8 Statistical Cases for Flight Encounters or Flight Test Scenarios

#	Description	Ownship Speed (Knots)	Ownship Altitude (Feet AGL)	Intruder Category	Intruder Speed (knots)	Intruder Bearing Angle (IBA) (deg)	Relative Intruder Altitude (Feet AGL)	Remarks
1	CB Medium Above	80	7000	Medium	130	5<IBA<15	500	None
2	CB Large Above	100	7000	Large	170	-15<IBA<-5	1000	None
3	CB Medium Below	130	8000	Medium	130	5<IBA<15	-1000	None
4	CB Large Below	170	8000	Large	170	-15<IBA<-5	-500	None
5	CB Medium Above	100	6000	Medium	130	15<IBA<25	500	None
6	CB Large Above	80	6000	Large	170	-25<IBA<-15	1000	None
7	CB Medium Below	170	5000	Medium	130	15<IBA<25	-1000	None
8	CB Large Below	130	5000	Large	170	-25<IBA<-15	-500	None
9	CB Medium Above	130	7000	Medium	130	40<IBA<50	500	None
10	CB Large Above	170	7000	Large	170	-50<IBA<40	1000	None
11	CB Medium Below	80	8000	Medium	130	40<IBA<50	-1000	None
12	CB Large Below	100	8000	Large	170	-50<IBA<-40	-500	None
13	CB Medium Above	170	6000	Medium	130	70<IBA<80	500	None
14	CB Large Above	130	6000	Large	170	-80<IBA<-70	-1000	None
15	CB Medium Below	100	5000	Medium	130	95<IBA<105	-500	None
16	CB large Below	80	5000	Large	170	-105<IBA<95	1000	None
17	CB Small Above	130	6000	Small	100	-5<IBA<5	500	None
18	CB Small Below	130	6000	Small	100	-5<IBA<5	-500	None
19	Intruder Climb	130	8000	Large	170	-5<IBA<5	-3000 to -1000	Intruder climbs from 3000’ to 1000’ below
20	Intruder Descent	130	5000	Large	170	-5<IBA<5	+3000 to +1000	Intruder descends from 3000’ above to 1000’ above
21	Ownship Climb	170	5000 to 7000	Medium	130	-5<IBA<5	8000	Ownship climbs from 3000’ to 1000’ below

#	Description	Ownship Speed (Knots)	Ownship Altitude (Feet AGL)	Intruder Category	Intruder Speed (knots)	Intruder Bearing Angle (IBA) (deg)	Relative Intruder Altitude (Feet AGL)	Remarks
22	Ownship Descent	170	8000 to 6000	Medium	130	-5<IBA<5	5000	Ownship descends from 3000’ above to 1000’ above

<u>Table 2-9</u> **Individual Cases for Flight Encounters or Flight Test Scenarios**

#	Description	Ownship Speed (Knots)	Ownship Altitude (Feet AGL)	Intruder Category	Intruder Speed (knots)	Intruder Bearing (deg)	Relative Intruder Altitude (Feet AGL)	Remarks
23	Ownship Right Turn	170	6000	Large or Medium	130-170	-5<IBA<5	+1000	None
24	Ownship Left Turn	170	6000	Large or Medium	130-170	-5<IBA<5	-1000	None
25	Intruder Right Turn'	130	6000	Large or Medium	130-170	-5<IBA<5	+1000	None
26	Intruder Left Turn	150	6000	Large or Medium	130-170	-5<IBA<5	-1000	None
27	Minimum Ownship Altitude	100	Defined by Mfr.	Large or Medium	130-170	-5<IBA<5	+500	None
28	Minimum Ownship Altitude	130	Defined by Mfr.	Large or Medium	130-170	-5<IBA<5	500	None
29	Minimum Intruder Altitude	130	3000	Large or Medium	130-170	-5<IBA<5	1000	Minimum intruder altitude defined as 1000’ AGL
30	Minimum Intruder Altitude	170	Min. Altitude	Large or Medium	130-170	-5<IBA<5	1000	Minimum intruder altitude defined as 1000’ AGL
31	5 Intruders	130	6000	Large or Medium	130-170	-45, -20, 0, 20, 45	Various	5 intruders come from various angles and altitudes
32	5 Intruders	130	6000	Large or Medium	130-170	-45, -20, 0, 20, 45	Above	5 intruders come from various angles and altitudes

#	Description	Ownship Speed (Knots)	Ownship Altitude (Feet AGL)	Intruder Category	Intruder Speed (knots)	Intruder Bearing (deg)	Relative Intruder Altitude (Feet AGL)	Remarks
33	Ownship ahead of the intruder, which is at a bearing of 120 degrees, 500’, 2-3 NM lateral separation. The ownship makes a 45-deg turn by starting a standard 3-degree turn (or ownship capability) and continues till the intruder is out of the FOR	100	6000	Medium	120	Not Applicable	500	Pop-up intruder due to ownship maneuver
34	Fly with 2 intruders, one 1,000’ above the ownship and one with 1,000’ below	130	6000	Medium/ Large	130	-5<IBA<5	±1000	Test vertical resolution
35	Fly with 2 intruders, with 2,000’ lateral separation	130	6000	Medium/ Large	130	-5<IBA<5	0	Test horizontal resolution

2.4.2.2.1 Flight Test Equipment and Configuration

In order to assess the in-flight performance of the RUT, a typical test procedure will include a two-step process: in-flight data collection and post-flight data analysis. The flight tests will be carried out once and collected test data will be used to verify specified requirements.

The test setup for in-flight data collection and post-flight analysis of collected data is shown in Figure 2-2.

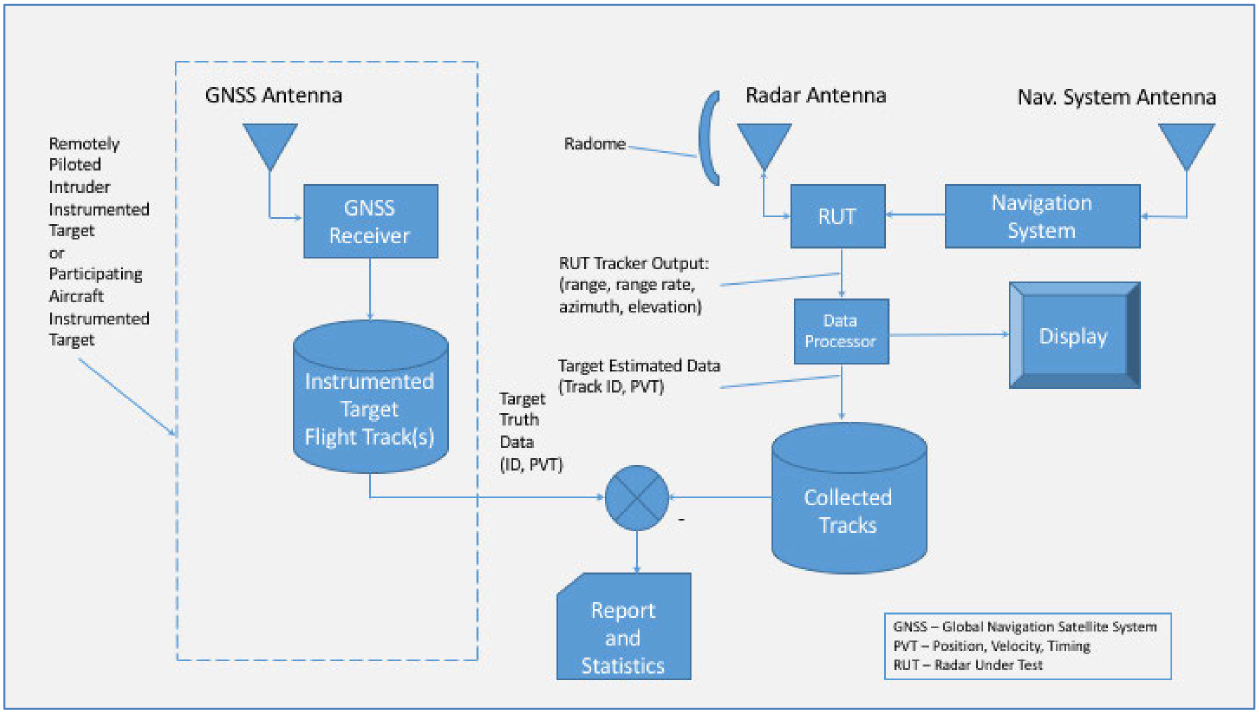


Figure 2-2 **DAA Radar Track Accuracy Test Setup**

The aircraft/UA platform with the RUT should have at a minimum a navigation system that will provide ownship data, and data collection and data recording device with a time-stamp capability to generate a report to store ownship and intruder tracks. The track report generated by the radar every second must be stored along with the ownship truth information.

The instrumented target aircraft/UA or intruder should be equipped with the Technical Standard Order (TSO) 145/146-compliant GNSS receiver and a data collection and recording device with a time-stamp capability. Each stored track must have information regarding position, velocity and timing at a minimum.

Note: *Based on the Wide-Area Augmentation System (WAAS) Performance Analysis Report (Report #56 covering January 1 to March 31, 2016), a maximum value over the Continental United States (CONUS) for WAAS horizontal accuracy (95%) of 1.4 m was recorded at an Atlantic City, New Jersey site, and a maximum value over CONUS for WAAS vertical accuracy (95%) of 1.7 m was recorded at a site in Miami, Florida.*

During post-flight analysis the position reports will be compared based on unique identifiers. Statistical data on track accuracy will be computed and presented in the test reports.

The flight tests will be carried out once and their data analyzed to verify the requirements. The following procedure is common to all the flight tests.

Equipment Required:

- UA or surrogate manned aircraft with similar navigation system
- RUT installed on the UA or surrogate

- Radar controller and status display unit installed on UA or surrogate
- Intruder aircraft equipped with WAAS capable and enabled GPS receivers compliant with TSO 145/146.
    - Ideally at least one aircraft representative of each category will be available; if the small category aircraft is not available, simulation may be used to verify its performance.
    - Five aircraft are available if the flight test for Subparagraph 2.2.7–4 is to be carried out.
- Other equipment as needed.

Flight Test Procedure:

Step 1: Fly and report at the initial waypoint position an aircraft/UA platform with the RUT.

Step 2: Verify that intruder aircraft are reporting at the pre-determined waypoint positions that allow the designated intruder aircraft to fly the designated flight test.

Step 3: Start the flight mission according to any of the above mentioned scenarios of choice.

Step 4: Record and collect record time, and the track data reported by the radar at 1-second intervals.

2.4.3 Detailed Test Procedures

The test procedures set forth below constitute a satisfactory method of determining required performance. Although specific test procedures are cited, it is recognized that other methods may be preferred. Such alternate methods may be used if the manufacturer can show that they provide at least equivalent information. Therefore, the procedures cited herein should be used as one criterion in evaluating the acceptability of the alternate procedures.

2.4.3.1 Ownship State Data (Subparagraph 2.2.2.1)

Equipment Required:

- Radar controller and status display unit
- Navigation system or an equivalent navigation system simulator
- Data recording device with a time-stamp capability to generate a report with status data output by the RUT.

Measurement Procedures:

Step 1: Connect all necessary test equipment as shown in Figure 2-1.

Step 2: Verify that all the parameters listed in Table 1-1, Ownship State Data, are received by the radar at the minimum update rate of 1 Hz in accordance to Paragraph 1.5.3, Ownship State Data Assumptions.

Note: *It is assumed that the DAA processor or the ownship will supply a timing reference to the radar in accordance to ownship state data assumptions listed in Paragraph 1.5.3.*

2.4.3.2 Radar States and Control (Subparagraph 2.2.2.2)

Equipment Required:

- Radar controller and status display unit
- Navigation system or an equivalent navigation system simulator
- Spectrum Analyzer: Agilent Keysight E4407B or equivalent to cover the range of RUT frequencies
- Other equipment as needed.

Measurement Procedures:

Step 1: Connect all necessary test equipment.

Step 2: Turn the radar on.

Step 3: Verify that the radar operates in standby mode after power has been applied.

Step 4: Verify that the radar does not transmit.

Step 5: Verify that there is an input available to switch between standby and transmit modes.

Step 6: Switch the radar mode to transmit mode.

Step 7: Verify that the radar is in transmit mode and transmitter generates output power.

Step 8: Switch the radar mode to standby mode.

Step 9: Verify that the radar switched to standby mode and the transmitter does not generate output power.

Step 10: Switch the radar mode to off mode.

Step 11: Verify that the radar switched to off mode and the transmitter does not generate output power.

2.4.3.3 Radar Output Data to the DAA Processor (Subparagraph 2.2.2.3)

Equipment Required:

- Radar controller and status display unit

Optional: Rotating platform for the radar stand (simulating vehicle movements around the yaw, pitch and roll axes)

Note*:* *In case of a test configuration where the RUT resides on a rotating platform, an inertial navigation system should be installed on the same platform.*

- Navigation system or an equivalent navigation system simulator
- Spectrum Analyzer: Agilent Keysight E4407B or equivalent to cover the range of RUT frequencies

- Signal Generator: Agilent Keysight E4423B or equivalent to cover the required range of Doppler shift frequencies
- Optical Delay Line: EasternOptX Series 1000 Fixed/Dual Delay Line
- Doppler Generator: EasternOptX Series 5000 Doppler Generator
- DAA Processor or its simulator
- Data recording device with a time-stamp capability to generate a report with status data output by the RUT
- Other equipment as needed.

Measurement Procedures:

Step 1: Connect all necessary test equipment.

Step 2: Turn the radar on and then switch the radar to transmit mode.

Step 3: Move the target(s) in reference to the RUT either via applying Doppler shift controlled by a signal generator, or by another means, such as using a radar target generator.

Optional: Use a turntable on the radar platform to change yaw/pitch/roll when applicable.

Step 4: Verify that the radar generates target/intruder track report that contains all of the parameters specified in Table 2-1, Track Output Data.

Step 5: Verify that the radar target/intruder data are generated and output into a track report at the average rate of no less than 1 Hz ± 20%.

2.4.3.4 Radar Status (Subparagraph 2.2.2.4)

Equipment Required:

- Radar controller and status display unit
- Navigation system or an equivalent navigation system simulator
- Data recording device with a time-stamp capability to generate a report with status data output by the RUT
- Other equipment as needed.

Measurement Procedures:

Step 1: Connect all necessary test equipment.

Step 2: Turn the radar on.

Step 3: Set radar for normal operations in order to generate “ready” status.

Step 4: Verify that under normal operational conditions the “ready” status is generated/displayed at intervals of one second or less.

Step 5: Verify that the radar provides an output status that the transmitter is OFF.

Step 6: Turn the transmitter ON and verify that the radar provides status that the transmitter is enabled.

Step 7: Simulate a faulted radar condition for the RUT.

Step 8: Verify that under faulted radar conditions the "faulted" status is generated/displayed at intervals of one or less seconds.

Step 9: Verify that in transmit mode and under faulted radar conditions the radar turns the transmitter off and transmitter does not generate power.

Step 10: Verify that in standby mode and under faulted radar conditions the radar transmitter remains off and transmitter does not generate power.

Step 11: Verify that the radar provides an output status to indicate whether radar transmitter enabled or disabled.

2.4.3.5 Radar Frequency Bands (Paragraph 2.2.3)

Equipment Required:

- Radar controller and status display unit
- Navigation system or an equivalent navigation system simulator
- Spectrum Analyzer: Agilent Keysight E4407B or equivalent to cover the range of frequencies of the RUT
- Other equipment as needed.

Measurement Procedures:

Step 1: Connect all necessary test equipment.

Step 2: Turn the radar on, and switch radar to transmit mode.

Step 3: Adjust the spectrum analyzer for the peak reading and determine the frequency.

Step 4: Verify that the frequency read by the spectrum analyzer falls within one of the bands in Table 2-2 or an agreed upon frequency.

2.4.3.6 Radar Frequency Channels (Paragraph 2.2.4)

Equipment Required:

- Radar controller and status display unit
- Navigation system or an equivalent navigation system simulator
- Spectrum Analyzer: Agilent Keysight E4407B or equivalent to cover the range of frequencies of the RUT
- Other equipment as needed.

Measurement Procedures:

Step 1: Connect all necessary test equipment.

Step 2: Turn the radar on and switch radar to transmit mode.

Step 3: Simulate conditions leading to a frequency channel change of the radar; e.g., by inserting interference into the channel.

Step 4: Adjust the spectrum analyzer for the peak reading and determine the frequency.

Step 5: Verify that the frequency read by the spectrum analyzer is a different frequency channel than the one obtained from Subparagraph 2.4.3.5.

Step 6: Repeat this procedure for at least one more frequency and verify the results, simulating conditions leading to a frequency change.

2.4.3.7 Operation in Rain and Instrument Meteorological Conditions (IMC) (Paragraph 2.2.5)

Flight Test Procedure:

The statistical flight test scenarios (1-22) may be used to test operation in rain (Paragraph 2.2.5).

It is expected that Scenarios 1-22 will be run in clear weather conditions. To adjust for performance in rain, the radar accuracy performance test as described in Subparagraph 2.4.3.10 will be carried out between the rain-adjusted RDR and RCPR. Table 2-10 below shows the rain-adjusted RDR for various frequency bands and at different bearing angles. This is the combination of Table 2-3, Table 2-4 and Requirements 2.2.7-11, 12, 13 and 14.

Table 2-10 Rain-Adjusted RDR: Various Bearing Angles & Intruder Categories: C Band

Intruder Bearing Angle	C Band Rain-Adjusted RDR (NM)		
	Small	**Medium**	**Large**
|angle| < 30	5.4	6.0	6.7
30 ≤ |angle| < 60	3.6	4.7	5.6
60 ≤ |angle| < 90	2.4	3.1	4.0
|angle| ≥90	1.9	2.6	3.7

Table 2-11 Rain-Adjusted RDR: Various Bearing Angles & Intruder Categories: Ku Band

Intruder Bearing Angle	X Band Rain-Adjusted RDR (NM)		
	Small	**Medium**	**Large**
|angle| < 30	5.5	6.2	6.9
30 ≤ |angle| < 60	3.7	4.8	5.8
60 ≤ |angle| < 90	2.5	3.2	4.1
|angle| ≥90	1.9	2.6	3.7

Table 2-12 Rain-Adjusted RDR: Various Bearing Angles & Intruder Categories: X Band

Intruder Bearing Angle	Ku Band Rain-Adjusted RDR (NM)		
	Small	**Medium**	**Large**
|angle| < 30	5.7	6.4	7.2
30 ≤ |angle| < 60	3.8	4.9	6.0
60 ≤ |angle| < 90	2.5	3.2	4.2
|angle| ≥90	1.9	2.7	3.8

2.4.3.8 Radar Field of Regard (FOR) (Paragraph 2.2.6)

This field of regard test can be accomplished with the use of data collected across a number of flight tests where encounters include intruders at the extent of the FOR. Verify that the reported intruder azimuth and elevation angles during the flights include angle close to ±110º in Azimuth and ±15º in elevation.

Equipment Required:

- Radar controller and status display unit
- Navigation system or an equivalent navigation system simulator
- Angular sensor if using a mechanically tilting antenna that measures the relative angular position of the antenna feed and reflector
- Options include optical sensors or magnetically referenced systems
- Other equipment as needed.

Alternate Test Method 1:

Measurement Procedures – Azimuth:

Step 1: Connect all necessary test equipment.

Step 2: Mount antenna and attach the angular measurement sensor to the antenna feed.

Step 3: Turn the radar on and switch to transmit mode.

Step 4: Measure the azimuth angle of the antenna as follows.

Step 4a: Place the antenna horn in the test setup for each azimuth extent of the scan requirements in Subparagraph 2.2.6-1 (±110º).

Step 4b: Verify that the radar processor is outputting azimuth information for horizontal FOR at a minimum of ±110° with respect to the longitudinal axis of the UAS.

Measurement Procedures – Elevation:

Step 1: Connect all necessary test equipment.

Step 2: Turn the radar on and switch to transmit mode.

Step 3: Measure the elevation angle of the antenna as follows:

Step 3a: Place the antenna horn in the test setup for each of the extents of the scan requirements of elevation.

Step 3b: Verify that the radar processor is outputting elevation information for vertical FOR at a minimum of ±15° vertically referenced to the flight path of the UA (UA body frame corrected by the aircraft angle of attack), limited to intruders above 1,000’ AGL.

Note: *Include the 5-degree offset within the measurements (to account for angle of attack). This could be done by adding five to the vertical extent of the horn, or by rotating the mount for the radar by 5 degrees of pitch.*

Alternate Test Method 2:

Measurement Procedures for Mechanically Steerable Antennas

Step 1. Mount antenna and attach the angular measurement sensor to the antenna feed.

Step 2. Compare commanded tilt with measured elevation angle: Set pitch and roll inputs to zero. Command the tilt to zero degrees.

Step 3. Verify performance: Verify that the difference between the tilt of the angular measurement sensor and the commanded tilt are within specified levels of ±110 degrees across the azimuth scan and ±15 degrees of vertical scan.

Step 4. Repeat for tilt extremes: Repeat at the positive and negative tilt extremes.

Step 5. Consider this requirement as two-dimensional (2D) in which the extents of both dimensions are considered together; that is, testing the combination of extents of azimuth and elevation, including the upper and lower right and left extents.

Alternate Test Method 3:

Measurement Procedures for Electronically Steerable or “Overscanning” Antennas)

Measurement Procedures:

Step 1: For electronically steerable antennas, measure the antenna on a range to determine that the pointing angles coincide with the beam steering angles per design specifications. Note the relationship between the beam steering signals and the antenna pointing angle.

This may be accomplished by placing targets on a range or in a lab with shorter ranges if there are viable range-managing techniques. To minimize the overall volume requirements for the tests, the radar antenna itself can be rotated such that a target of interest is at the extents of the field of regard.

Step 2: Measure at Different Commanded Tilts:

1. Command the antenna to a zero tilt angle and note the beam steering signals. Repeat with the commanded tilt set in one of its extreme positions and note the beam steering signals. Repeat again with the commanded tilt set in the other extreme position and note the beam steering signals. Determine the corresponding number of degrees change in antenna pointing angle.
2. Alternatively, if the radar is configured to scan the conservative FOR, then its normal operations can yield valid results. That is, the intruders can be placed at the center and at the extents of the FOR and the returns validated against the actual extents.
3. Verify that the vertical FOR of the radar is at a minimum of ±15° vertically referenced to the flight path of the UA (UA body frame corrected by the aircraft angle of attack), limited to intruders above 1,000’ AGL.

2.4.3.9 Radar Tracks (Paragraph 2.2.7)

Measurement Procedures:

1. Verify a unique ID for each established radar track. (2.2.7-1)

   There are two possibilities for verifying this requirement:

   a. Use the data collected for the radar output test in Subparagraph 2.4.3.3 and verify that each created track has a unique ID
   b. Use flight data from Scenarios 1-35 and verify that the radar produces a unique ID for each track.

2. Verify the ability to provide tracks for up to 20 aircraft within the FOR. (2.2.7-2)

In order to satisfy the maximum target tracking capacity requirement of the RUT, the manufacturer will provide documented evidence of the radar design analysis and results to demonstrate that the radar is capable of tracking up to 20 intruders within the FOR at distances between RDR and RCPR.

Provide the analysis methodology and the results. Verify that the radar is capable of tracking up to 20 intruders within the FOR at distances between the RDR and RCPR.

3. Prioritize intruder tracks. (2.2.7-3)
   a. Use data from flight Scenarios 31-32 or any other scenario that shows 2 or more intruders.
   b. Record information on intruders that includes track ID, time, range and range rate and the radar system's computed Tau values. Use truth data about the intruders to compute true Tau values.
   c. Verify the prioritization of tracks by comparing priority values with truth values.

   Note: *In order to test just the prioritization algorithm itself, the simulated scenario data may be used as an input to the radar.*

4. Track accuracy for the five highest priority intruders. (2.2.7-4)
   a. Use data from Scenarios 31-32. These tests should either be run as a flight test with 5 intruders, or as simulated targets if 5 intruder aircraft are not available.
   b. The flights should be arranged so that the 5 intruders are high priority (Modified Tau < 85 seconds) at the same time(s).
   c. Record truth data on the time, track ID, range, range rate, azimuth, and elevation of intruders. Record the radar's output of these values.
   d. Verify that the values for the five intruders are treated as high priority tracks.
5. Track the minimum number of high priority intruders. (2.2.7-5)
   a. Use data from any of the Scenarios 1-35.
   b. Identify cases where there is no real high priority track (e.g., the case where the intruder is farther out than RDR).
   c. Verify that at least the two highest priority targets are always identified as priority intruders irrespective of their RDR or tau values.
6. Verify that the track accuracy associated with the intruders is met and indicated for the required targets. (Tracks intruders 95% within the FOR starting at the RDR. (2.2.7-6)
   a. Use data from Scenarios 1-22 that exercise track performance.
   b. Verify that an intruder track is established at or before the rain-adjusted RDR 95% of the flights.
   c. Alternatively, the manufacturer can produce simulation or analysis that proves that the radar will establish a track 95% of all high priority tracks before the rain-adjusted RDR.
7. Verify high-priority track performance 90% of the time. (2.2.7-7)
   a. Use flight Scenarios 1-22. Scenarios should run from 2 NM before the rain-adjusted RDR (assuming the flights are carried out in clear weather) and up to the RCPR. The rain-adjusted RDR values are given in Table 2-10.

b. Calculate the mean and the standard deviation for each of the four parameters; range, range rate, azimuth, and elevation angles, and accuracy metrics for each flight between the rain-adjusted RDR and the RCPR.

c. Verify that 90% of the flights meet the accuracy requirements as defined in Paragraph 2.2.8.

Step 1: Verify that the mean error of the radar track range within the FOR and between the RDR and the RCPR does not exceed 50' and a standard deviation does not exceed 70'. If the RMSE or 95% containment parameters were used instead of accuracy estimation using mean and standard deviation, then the manufacturer will use the conversion factors in Table 2-5.

Step 2: Verify that the mean error of the track range rate within the FOR and between the RDR and the RCPR does not exceed 8 ft/sec and a standard deviation does not exceed 10 ft/sec. If the RMSE or 95% containment parameters were used instead of accuracy estimation using mean and standard deviation, then the manufacturer will use the conversion factors in Table 2-5.

Step 3: Verify that the radar track mean angular error in azimuth within the FOR and between the RDR and the RCPR does not exceed 0.5 degrees and a standard deviation does not exceed the maximum of 100 feet or 1 degree referenced from the platform's body frame of reference. If the RMSE or 95% containment parameters were used instead of accuracy estimation using mean and standard deviation, then the manufacturer will use the conversion factors in Table 2-5.

Step 4: Verify that the radar track mean angular error in elevation within the FOR and between the RDR and the RCPR does not exceed 0.5 degrees and a standard deviation does not exceed the maximum of 100 feet or 1 degree referenced from the platform's body frame of reference. If the RMSE or 95% containment parameters were used instead of accuracy estimation using mean and standard deviation, then the manufacturer will use the conversion factors in Table 2-5.

Step 5: Verify that for each intruder track, and only for the track points generated between RDR and RCPR, the assigned accuracy indices for range, range rate, azimuth and elevation angles as defined in Table 2-6 are correct for at least 80% of all track update instances of high priority tracks.

Step 6: Verify that the error bound for a high priority track corresponds to Accuracy Index 4 or lower for 80% of the track updates.

8. Establish intruder tracks before RCPR more than 99% of the time. (2.2.7-8)

   The manufacturer will provide analysis or simulation that verifies that an intruder track is established before RCPR more than 99% of the time.

9. Verify track continuity. (2.2.7-9)

   a. Use data from Scenarios 1-22 that exercise track performance. Identify the cases where the intruder track is discontinued.

   b. Calculate the total time of the discontinuities for the 22 scenarios, and verify it does not exceed 5% of 22 total track time between RDR and RCPR.

10. Verify performance with split tracks. (2.2.7-10)

   a. Use data from Scenarios 1-22 that exercise track performance. Identify the cases where the intruder track is split.

   b. Calculate the total time of the split track for the 22 scenarios, and verify it does not exceed 10% of the 22 total track times between RDR and RCPR.

11. Verify small intruder RDR. (2.2.7-11)

    This requirement is verified as part of the verification for 2.2.7-7 if the Scenarios 1-22 included small intruders. If it did not, the manufacturer should provide analysis or simulation that proves that this requirement is met.

12. Verify Medium intruder RDR. (2.2.7-12)

    This requirement is verified as part of the verification for 2.2.7-7 using Scenarios 1-22, which include a medium intruder.

13. Verify Large intruder RDR. (2.2.7-13)

    This requirement is verified as part of the verification for 2.2.7-7 using Scenarios 1-22, which include a large intruder.

14. Verify RDR for non-head-on intruders. (2.2.7-14)

    This requirement is verified as part of the verification for 2.2.7-7 using Scenarios 1-22, which include intruders from different bearing angles.

15. Verify that RCPR is 4000 feet for all intruder categories and angles. (2.2.7-15)

    This requirement is verified as part of the verification for 2.2.7-7 using Scenarios 1-22, which verify performance between RDR and RCPR.

16. Verify radar latency reporting updates are less than 0.5 second. (2.2.7-16)

    a. For one of the Scenarios 1-22, compare the record of the time stamp of the time applicability of the radar track update to the time stamp of the DAA processor when it received the track update from the radar.

    b. Verify that the difference between the two times is less than 0.5 second.

17. Verify radar tracking performance during the intruder horizontal maneuver. (2.2.7-17)

    a. Use Scenarios 25-26, which include an intruder horizontal maneuver.

    b. Verify that the radar maintains the intruder track while the intruder is performing a horizontal maneuver with horizontal acceleration of up to 1.5 g.

    c. Note if the intruder cannot achieve that acceleration, then perform the test at the intruder aircraft capability and the manufacturer will provide analysis or simulation that proves that the radar can perform up to the specification.

18. Verify radar tracking performance during the intruder vertical maneuver. (2.2.7-18)

    a. Use Scenarios 19-20 to exercise vertical maneuvers up to the vertical performance limit within the radar FOR.

    b. Verify that the radar maintains the intruder track if the intruder is performing a vertical maneuver up to a rate of ±5,000 ft/min.

    c. Note if the used intruder cannot achieve the above rate, then perform test at intruder aircraft capability and the manufacturer will provide analysis or simulation that proves that the radar can perform up to the specification.

19. Verify radar tracking performance during an ownship horizontal turn maneuver. (2.2.7-19)

a. Run Scenarios 23-24 to exercise ownship maneuvers in a horizontal turn up to six deg/sec or UA capability.

b. Record time, track ID, range, range rate, azimuth and elevation.

c. Verify that the radar maintains the intruder track while the ownship is performing a horizontal maneuver up to a rate of ±6 deg/sec or ownship capability.

20. Verify radar tracking performance during an ownship vertical maneuver (maximum rate of climb). (2.2.7-20)

a. Run Scenarios 21-22 to exercise ownship maneuvers up to a maximum rate climb.

b. Record time, track ID, range, range rate, azimuth and elevation.

c. Verify that the radar maintains the intruder track if the ownship is performing a vertical maneuver at the maximum rate of climb that can be performed by the ownship.

21. Verify minimum radar operational altitude (example). (2.2.7-21)

a. Use Scenarios 27-28 with the ownship flown at minimum altitude defined by the manufacturer. The area should include a busy highway and flights made along the highway and perpendicular to it.

b. Verify that the intruder is defined as a high priority track when its modified Tau is less than 85 seconds.

c. Compare and verify that the intruder track has the accuracies expected for a high priority track with no excessive discontinuity and track splits.

d. Verify that ground moving targets do not exceed four tracks at any time.

22. Verify an intruder's entry into the FOR within the RDR due to an ownship maneuver. (2.2.7-22)

a. Use Scenario 33.

b. Verify that the radar establishes an intruder's track that meets accuracy requirements in no less than 15 seconds after the intruder enters the FOR.

c. Since the requirement is statistical in nature, the test may be repeated if it fails once. The manufacturer will provide data to justify the failure as part of a statistical variation.

d. Since the requirement is statistical in nature, the manufacturer should provide an analysis or simulation that shows that the accuracy requirement is met 90% of the time.

23. Verify radar horizontal and vertical resolution.(2.2.7-23)

a. Use Flights 34-35 for horizontal and vertical resolution.

b. Verify that the radar discriminates between the two intruder aircraft separated vertically or horizontally by a minimum of 2,000' at a range of the lesser of RDR or 4.8 NM with at least 90% probability.

2.4.3.10 Track Accuracy (Paragraph 2.2.8)

The verification for these requirements was carried out with the tests performed in Subparagraph 2.4.3.9.

2.4.3.11 Radar False and Ground Tracks (Paragraph 2.2.9)

1. False tracks: In order to demonstrate the ability of the RUT to minimize the occurrence of false tracks, the following two-step test process, including system design analysis and a post-flight statistical analysis, is recommended:

    a. System Design Analysis

    b. Post Flight Procedure Analysis.

    It is assumed that the manufacturer will provide radar design analysis to demonstrate that radar performance overall, (including detector thresholds for probability of false alarm and constant false alarm rate) will not cause conditions leading to false track occurrence in excess of one per hour.

    All flight tracks collected during the entire radar flight test program will be analyzed for any evidence of being false tracks. The manufacturer will check that no false tracks due to ground clutter were generated.

2. Ground tracks: the test of Subparagraph 2.4.3.9-21will verify this requirement.

2.4.3.12 Radar Health Monitoring (Paragraph 2.2.10)

This requirement is verified in Subparagraph 2.4.3.4. Alternatively it can be verified by completing the following test procedure:

Step 1. Verify by demonstration that each radar subsystem equipment article provides 100% failure detection for the subsystem functional elements that contribute to Hazardous and Misleading Information (HMI) via appropriate failure analysis (including failure modes and effects), that properly accounts for detection interference. Users should reference the Society of Automotive Engineers Aerospace Recommended Practice 4761 for appropriate failure analysis methods.

Setup: Compel, either by simulation or by actual manipulation, each radar subsystem equipment article into normal operation while on the ground.

Step 2: Start up the radar system from a power off state.

Step 3: Verify a Ready system health status.

Step 4: Identify all subsystem tests that detect and isolate HMI failures.

Step 5: Select 10% of the above subsystem HMI tests for each subsystem equipment article to create a subsystem 10% test list. In the subsystem 10% test list, ensure the test list includes tests that execute only on-ground, only airborne, and execute during both on ground & airborne phases.

Step 6: For a test from the above subsystem 10% test list, compel, either by simulation or by actual manipulation, a condition that causes a “Failed” operational status and execute that test. Repeat this on ground and airborne when a test executes in both flight phases.

Step 7: Verify the radar function stops processing and transmits a failed health status.

Step 8: Clear the failure condition, perform a restart and ensure normal processing resumes.

Step 9: Repeat through each subsystem until the subsystem 10% test list completes.

2.4.4 Traceability

The tables below provide a means of traceability in order to map necessary test procedures to the respective requirements.

2.4.4.1 Test-to-Requirements Traceability

Table 2-13 Test Procedure-to-Requirements Matrix

Item	Test Procedure	Requirement	Requirement Title
1	2.4.3.1	2.2.2.1	Ownship State Data
2	2.4.3.2	2.2.2.2	Radar States and Control
3	2.4.3.3	2.2.2.3	Radar Output Data to the DAA Processor
4	2.4.3.4	2.2.2.4	Radar Status
5	2.4.3.5	2.2.3	Radar Frequency Bands
6	2.4.3.6	2.2.4	Radar Frequency Channels
7	2.4.3.7	2.2.5	Operation in Rain and IMC
8	2.4.3.8	2.2.6	Radar Field of Regard
9	2.4.3.9	2.2.7	Radar Tracks
10	2.4.3.10	2.2.8	Radar Track Accuracy
11	2.4.3.11	2.2.9	Radar False and Ground Tracks
12	2.4.3.12	2.2.10	Radar Health Monitoring

2.4.4.2 Requirements-to-Test Procedure Traceability

Table 2-14 Requirements-to-Test Procedure Traceability Matrix

Item	Requirement	Test Procedure	Requirement Title
1	2.2.2.1	2.4.3.1	Ownship State Data
2	2.2.2.2	2.4.3.2	Radar States and Control
3	2.2.2.3	2.4.3.3	Radar Output Data to the DAA Processor
4	2.2.2.4	2.4.3.4	Radar Status
5	2.2.3	2.4.3.5	Radar Frequency Bands
6	2.2.4	2.4.3.6	Radar Frequency Channels
7	2.2.5	2.4.3.7	Operation in Rain and IMC
8	2.2.6	2.4.3.8	Radar Field of Regard
9	2.2.7	2.4.3.9	Radar Tracks
10	2.2.8	2.4.3.10	Radar Tack Accuracy
11	2.2.9	2.4.3.11	Radar False and Ground Tracks
12	2.2.10	2.4.3.12	Radar Health Monitoring

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3 MANUFACTURER CONSIDERATIONS FOR INSTALLED EQUIPMENT

This section contains no design requirements. The purpose of this section is to provide useful considerations regarding equipment designed to meet these MOPS when that equipment is installed and used on an aircraft.

For the most part, installed performance requirements are the same as those contained in Section 2, some of which were verified through bench and environmental test, and some through flight tests. If the flight tests were carried out on the intended target aircraft, then no further installed tests would be needed. If the tests were carried out on a surrogate aircraft, then the requirements affected by the physical installation (e.g., antenna patterns) need to be verified after installation. The installed performance limits or validation requirements are generally provided in separate installation guidance related to the function(s) provided. These are often provided in the form of Advisory Circulars (ACs) specific to aircraft installation, or their non-U.S. equivalents.

Equipment designed to meet these MOPS generally requires separate approval for installation and use on an aircraft. This section is intended to provide some aircraft installation related considerations that the designer may want to consider in the design such that the equipment may also be able to obtain any additional approvals required for installation or use when correctly installed in an aircraft.

3.1 Equipment Installation

3.1.1 Accessibility

Equipment designed to meet these MOPS should be reasonably accessible to aircraft maintenance personnel for installation, maintenance and removal.

Please see the Paragraph 3.1.1 of the DAA MOPS for requirements related to accessibility to radar controls at the Control Station.

3.1.2 Aircraft Environment

Equipment should be compatible with the environmental condition present in the specific location in the aircraft where the equipment is installed.

3.1.3 Display Visibility

Please see the Paragraph 3.1.3 of the DAA MOPS for requirements related to display visibility at the Control Station.

3.1.4 Dynamic Range

Operation of the equipment should not be adversely affected by aircraft maneuvering or changes in attitude encountered in normal flight conditions.

3.1.5 Failure Protection

Any probable failure of the equipment should not degrade the normal operation of equipment or systems connected to it. Likewise, the failure of interfaced equipment or systems should not degrade normal operation of this equipment.

3.1.6 Interference Effects

The equipment should not be the source of harmful conducted or radiated interference nor be adversely affected by conducted or radiated interference from other equipment or systems installed in the aircraft.

3.1.7 Inadvertent Turnoff

Appropriate protection should be provided to avert inadvertent turnoff of the equipment.

3.1.8 Aircraft Power Source

Unless otherwise specified, tests should be conducted with the radar equipment powered by the aircraft's electrical power generating system.

Note: *Simulate a fault condition of the radar. Different categories of aircraft and different types of equipment may have different requirements for operation through momentary loss of power or during switching of power sources. Equipment designers should consider the intended types of installation for the equipment and any aircraft-level requirements for availability of function.*

3.1.9 Safety Precautions

Before turning on transmission on the ground, be sure microwave radiation safety precautions including both fuel and personnel safety considerations have been observed. These include clearing all personnel to an area beyond the maximum permissible exposure level boundary as computed by the equipment manufacturer or another approved source.

3.2 Installed Equipment Performance Considerations

As mentioned earlier, some of the requirements in Subsection 2.2 will be verified with a flight test. If these tests were carried out in the intended UA, then no additional tests would be needed. If these were carried out in a surrogate installation on a different aircraft the following items will need to be verified with installed tests.

3.2.1 Antenna Radome and Antenna Pattern

The radome will add attenuation to the transmission path, and may cause deflections on the waveform, which may affect angle measurement accuracy. Also, the antenna pattern may be affected by its installed location. Some flight tests should be carried out to verify performance.

3.2.2 Installation Accuracy

When installed, the antenna has to be aligned with the ownship navigation equipment that is producing the ownship state sent to the radar. Any misalignment will show as bias errors in the radar angular accuracy.

3.2.3 Environmental Checks

Flight testing, including ownship vertical and horizontal maneuvers, will test the radar ability to withstand any vibration and shock environment that it will encounter.

3.3 Installed Equipment Tests

If the flights in Table 2-8 and Table 2-9 were carried out on a surrogate aircraft, a subset of the flight tests as shown in Table 3-1 will be repeated to verify the installed performance.

Table 3-1 Installed Performance Flight Tests

#	Description	Ownship Speed (Knots)	Ownship Altitude (Feet AGL)	Intruder Category	Intruder Speed (knots)	Intruder Bearing (deg)	Relative Intruder Altitude (Feet AGL)	Remarks
1	CB Medium Above	80	7000	Medium	130	5<IBA<15	500	None
2	CB Large Above	100	7000	Large	170	-15<IBA<-5	1000	None
7	CB Medium Below	170	5000	Medium	130	15<IBA<25	-1000	None
8	CB Large Below	130	5000	Large	170	-25<IBA<-15	-500	None
9	CB Medium Above	130	7000	Medium	130	40<IBA<50	500	None
10	CB Large Above	170	7000	Large	170	-50<IBA<40	1000	None
22	Ownship Descent	170	8000 to 6000	Medium	130	-5<IBA<5	5000	Ownship descends from 3000’ above to 1000’ above
23	Ownship Right Turn	170	6000	Large or Medium	130 to 170	-5<IBA<5	+1000	None

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4 AIRCRAFT OPERATIONAL PERFORMANCE CHARACTERISTICS

When equipment is designed, and manufactured to meet these MOPS, and it is properly installed in an aircraft in accordance with applicable installation and operational approval guidance and regulations, it is expected that all aircraft-level functional and operational performance criteria will be met.

The equipment when installed contributes to the operation and performance of the MOPS functions at the aircraft level. Other aircraft-level contributions such as redundant or additional equipment may also be required. The equipment design should consider the types and characteristics of aircraft for which installation of this equipment is intended as well as the MOPS function at an aircraft level, and the equipment should be designed such that the equipment's contribution to aircraft-level operational and functional requirements is adequate.

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A APPENDIX A FREQUENCY BANDS FOR DETECT AND AVOID (DAA) RADAR

A.1 INTRODUCTION

Bands of the radiofrequency spectrum are not created equal. In addition to technical design considerations, the proper consideration of frequency band selection must account for national and international regulations. For example, radiofrequency spectrum in any band could be allocated to several different users on a Primary, Secondary, or Non-Interference basis. A further complication is that even within these status categories some systems may have priority over other systems in that category.

Frequency bands for aeronautical DAA Radars are those bands with a primary Aeronautical Radionavigation Service (ARNS) allocation or a general Radionavigation Service allocation where ARNS could be compatibly operated. Frequency bands that have one of these allocations have an appropriate level of protection to ensure that adequate protection is afforded to these safety-critical systems and that any reports of interference from other systems are resolved in an expeditious manner. Thus, DAA radars need to operate within a frequency band that has an ARNS allocation. Within the United States (US), development of DAA systems by the private sector may occur under a Federal Communications Commission (FCC) experimental license, but the final frequency band of operation must be either a designated ARNS or an appropriate Radionavigation Service band so the operational system can receive full regulatory protection.

Global radiofrequency band allocations are made through the International Telecommunications Union (ITU), which is the United Nations specialized agency for information and communication technologies. The ITU allocations can be found in the 2016 version of the ITU Radio Regulations, which are reviewed and updated approximately every four years. The United States incorporates the ITU Radio Regulations into the FCC rules and National Telecommunications and Information Administration (NTIA) rules found in Title 47 of the Code of Federal Regulations.

In November 2010 the ITU Radiocommunications Sector (ITU-R) prepared a report[1] identifying existing ARNS allocations that would be suitable for Unmanned Aircraft Systems (UAS) DAA applications. This report was largely the result of contributions from RTCA Special Committee 203 (SC-203) members and was intended to identify frequency bands for DAA applications. The bands identified for airborne DAA applications were:

- 4,200 – 4,400 Megahertz (MHz) (see Table 3 in Section 4.1 of the ITU Report)
- 5,350 – 5,470 MHz (see Table 3 in Section 4.1 of the ITU Report)
- 8,750 – 8,850 MHz (see Table 3 in Section 4.1 of the ITU Report)
- 9,300 – 9,500 MHz (see Table 3 in Section 4.1 of the ITU Report)
- 13.25 – 13.40 Gigahertz (GHz) (see Table 3 in Section 4.1 of the ITU Report)
- 15.40 – 15.70 GHz (see Table 5 in Section 4.3 of the ITU Report).

[1] Report ITU-R M.2204, "Characteristics and spectrum considerations for sense and avoid systems use on unmanned aircraft systems," November 2011.

In addition, two other frequency bands that can be used for UAS DAA were inadvertently left out of the ITU-R Report. The bands are for general radionavigation, which includes aeronautical, maritime, and land applications. These bands are:

- 24.45 – 24.65 GHz
- 32.3 – 33.4 GHz.

These two bands are appropriately identified in the FCC and NTIA rules.

A.2 DISCUSSION AND RECOMMENDATION

Below is a summary of the situation in each of these bands. Developers must carefully review the rules of the ITU, NTIA and the FCC to better determine the other authorized users and regulations for these bands. Developers should also quantify the electromagnetic interactions with the other users of a band to assist developing appropriate technical sharing conditions. The acceptance of those conditions by appropriate governmental authorities and existing users may require considerable interference analysis, testing, and verification and validation.

4,200-4,400 Megahertz (MHz): For many decades this band has been used by radio altimeters. The 2015 ITU-sponsored World Radiocommunication Conference (WRC) granted regulatory protection for aircraft onboard wireless (non-passenger) applications, such as backup flight controls. It is recommended that this band not be used for DAA, otherwise the DAA user of this band will have to show that they can fully protect onboard and nearby altimeters and wireless (non-passenger) applications. For example characteristics for radio altimeters and wireless (non-passenger) applications can be found in:

- ITU Recommendation 2059, Operational and technical characteristics and protection criteria of radio altimeters using the band 4,200-4,400 MHz
- ITU Recommendation M.2067, Technical characteristics and protection criteria for Wireless Avionics Intra-Communication systems
- ITU Recommendation 2085, Technical conditions for the use of wireless avionics intra-communication systems operating in the aeronautical mobile service in the frequency band 4,200- 4,400 MHz.

5,350-5,470 MHz: Characteristics of some ARNS applications can be found in ITU Recommendation M.1638 and Technical Standard Order (TSO) C63c, but neither are specific to DAA systems. In addition to ARNS systems, high-power radars and active space sensors are also allowed to use this frequency range. Federal agencies are currently conducting studies to develop a position on WRC-19's proposed addition of in the 5350-5470 MHz frequency range while ensuring the protection of incumbent and federal systems per the Spectrum Act.[1] Proponents should understand these evolving changes when considering this band for DAA.

8,750-8,850 MHz: Radar manufacturers worked within the ITU to create a co-primary ARNS allocation in this spectrum and parameters of these systems are documented in ITU Recommendation ITU-R M.1796-2, dated February 2014. This recommendation documents characteristics and sharing criteria for airborne weather avoidance, ground mapping, and search radars. However, Article 4.10 of the ITU Radio Regulations, gives

[1] Spectrum Act Sec. 6406. Unlicensed Use in the 5 GHz Band (Middle Class Tax Relief and Job Creation Act of 2012, Publication L. No. 112-96, § 6406, 126 Stat. 156, 231 (2012)), 47 United States Code §1453.

aeronautical safety applications precedence over other co-primary services, so internationally there is no issue. Manufacturers considering using this band should be aware of the US footnote to the table of allocations (US53), quoted below. Manufacturers should understand this footnote and determine the suitability for use for DAA.

> "US53--In view of the fact that the band 13.25-13.4 GHz is allocated to Doppler navigation aids, Government and non-Government airborne Doppler radars in the aeronautical radio navigation service are permitted in the band 8,750-8,850 MHz only on the condition that they must accept any interference which may be experienced from stations in the radiolocation service in the band 8,500-10,000 MHz."

9,300-9,500 MHz: This band will be shared with airborne and probably ground weather radar. This band has been used by radar manufacturers under an FCC experimental license; however, operational DAA systems may not use experimental licenses since they are issued on a non-interference basis. Interference from weather radars has been noted. Users will need to adapt to the expected interference, as there are widespread incumbent users.

13,250-13,400 GHz: Characteristics of some ARNS applications in this band can be found in ITU-R Recommendation M.2008-1, dated February 2014, and TSO C65a, but neither are specific to DAA applications.

15,400-15,700 GHz: Existing ARNS systems in this band should comply with TSO C63c. At present there are few systems in this band. A change in the FCC rules may be needed for this band to be used.

24,450 – 24,650 GHz: This band is available for DAA applications in the Americas and Asia but not in Europe, Africa, or the Middle East. In all cases, DAA would have to share spectrum with maritime and land based radionavigation systems as well as inter-satellite links in the US and fixed and mobile systems in some other areas of the world.

32.3 – 33.4 GHz: This band is available for DAA applications but must share with Maritime and Land based radionavigation systems, as well as fixed and inter-satellite systems. The fixed service is, however, required to minimize the potential interference between stations in the fixed service and airborne stations in the radionavigation service (ITU Footnote 5.547A).

A.3 OTHER CONSIDERATIONS

There may be additional bands at higher frequencies with radionavigation protection; however, additional international and domestic rulemaking would be required to use such spectrum.

Reallocation of other spectrum for DAA applications may be possible; however, it is subject to the four-year ITU review cycle for the Radio Regulations. Given that the work toward identification of a candidate international DAA frequency bands must initially occur at ITU Working Party meetings that are scheduled twice a year, about half of the preparation cycle to get a DAA radar spectrum item on the agenda for the 2019 WRC has already passed. Thus, the earliest reallocation could occur is 2023 assuming the issue has been submitted to the 2019 WRC for inclusion on the agenda for the 2023 WRC. The process to submit an issue for the 2019 WRC must be initiated by the later part of 2018.

In addition to the TSO certification process necessary for these DAA applications, the equipment will also have to obtain certification under the FCC rules (see 47 CFR Part 2) or the NTIA rules (see Chapter 10 of the NTIA Manual (a.k.a., 47 CFR Part 300)).

B APPENDIX B REQUIRED MAXIMUM RANGE SIMULATION AND ANALYSIS

B.1 OBJECTIVE

This appendix provides some background on analysis done to identify the Radar Declaration Ranges (RDRs) for a number of encounters involving an Unmanned Aircraft (UA) flying at various speeds and a single non-cooperative intruder approaching from a variety of relative bearings and speeds. The resulting data represents the alerting threshold as a horizontal range between the two aircraft. The data is then normalized relative to the worst case (head-on) to determine RDR correction factors corresponding to bearings out to ±90°. The results are minimum ranges at which an intruder track has to meet accuracy requirements to support full Detect and Avoid (DAA) functionality as a function of intruder speed and encounter bearing. Requirements flow up to the main body of these Minimum Operational Performance Standards (MOPS).

B.2 DATA GENERATION PROCESSES AND ASSUMPTIONS

B.2.1 Unmanned Aircraft Performance

The UA airspeed was varied between 40 and 200 Knots Indicated Airspeed (KIAS) (46 to 291 knots true airspeed) at 10,000’ Mean Sea Level (MSL). The speed limit is consistent with assumptions in Paragraph 1.5.1. The mitigation maneuver is a constant airspeed, constant rate, level right turn at 3.0 or 1.5 degrees/second (deg/s) (standard rate and half-standard rate respectively). A roll rate of 5 deg/s was used in all cases.

B.2.2 Intruder Aircraft Performance and Encounter Geometry

The non-accelerating intruder aircraft approaches from a relative bearing of 0, ±30, ±60, and ±90 degrees (constant if no maneuver is made) at airspeeds of 100, 130, and 170 Knots True Airspeed (KTAS) corresponding to the intruder categories outlined in Paragraph 1.7.3. The encounter geometry is set up in such a way that the intruder is flying a course that will intercept the trajectory of the UA, resulting in a direct collision if no mitigation maneuver is performed.

B.2.3 Geometric Constraint

Specifying an intruder airspeed and relative bearing results in a geometric constraint on the maximum velocity the UA can fly (V_{UA}) and have a collision with that intruder. The maximum airspeed is constrained by the following equation:

$$V_{UA} \leq \frac{V_{intruder}}{sin(Bearing)}$$

Application of this constraint results in Figure B-1 and Table B-1, which show the maximum UA airspeed as a function of intruder airspeed and relative bearing.

Table B-1 **Geometric Constraint**

Intruder Airspeed (KTAS)	Relative Bearing (Degrees)	Maximum Ownship Airspeed (KTAS)
100	30	200
	60	115.5
	90	100
130	30	260
	60	150.1
	90	130
170	30	340
	60	196.3
	90	170

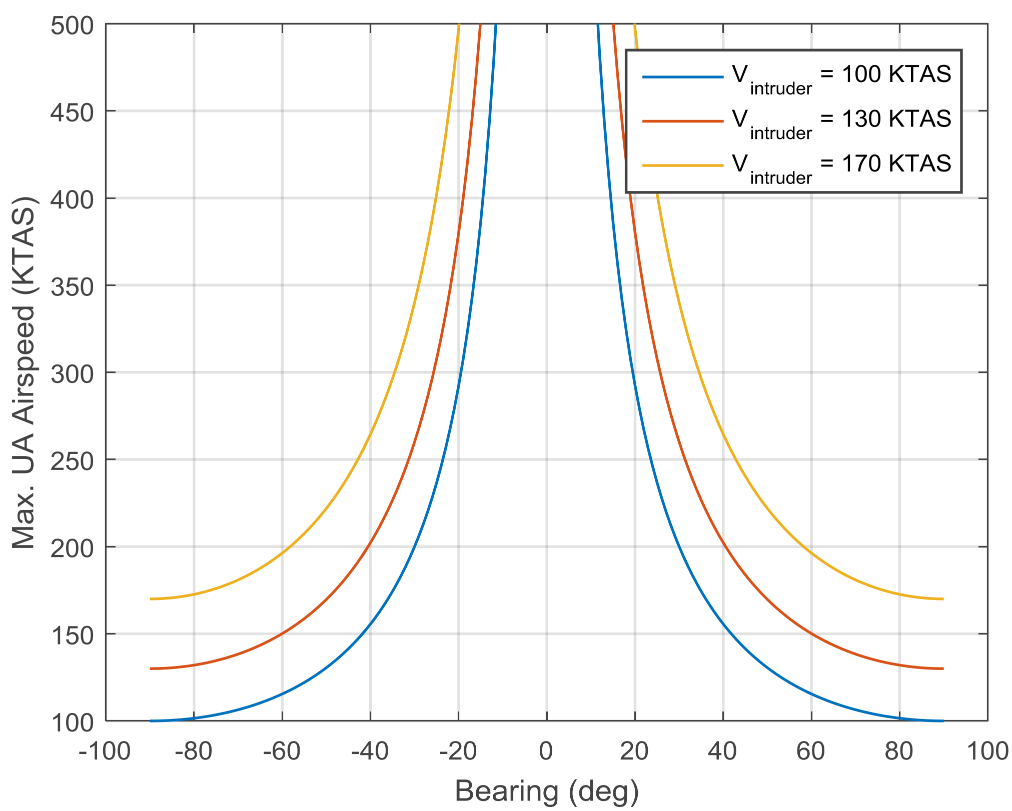


Figure B-1 **Geometric Constraint**

Figure B-2 shows a graphical depiction of the encounter geometry. The figure shows an intruder with a positive bearing and an intruder with a negative bearing. Each intruder is initialized on a direct collision course (i.e., constant relative bearing (φ)) with the ownship.

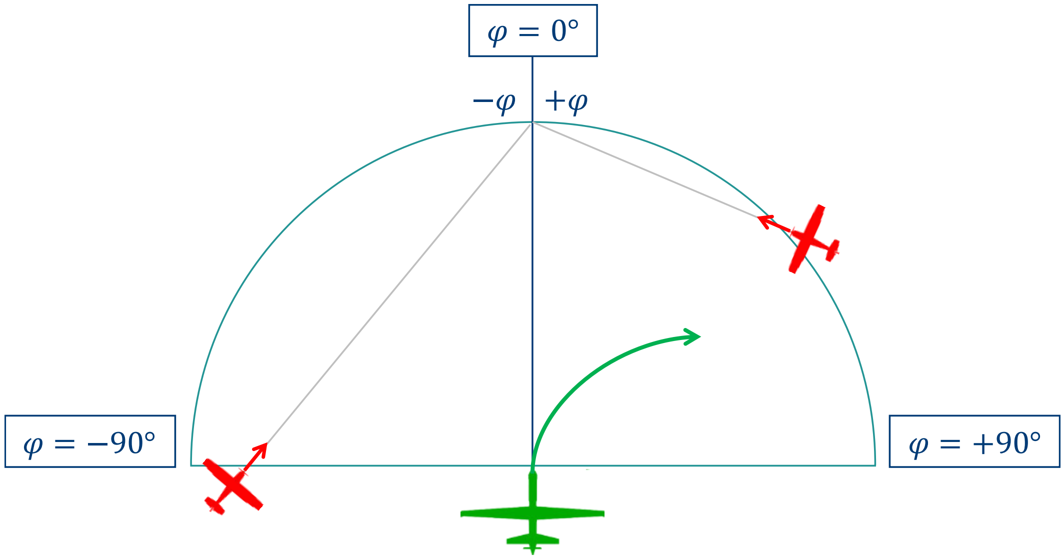


Figure B-2 Encounter Geometry

B.3 ASSUMPTIONS

B.3.1 Mitigation Maneuver

The UA performed a constant-rate turn towards the positive relative heading for all maneuvers in this analysis. Therefore, for all relative bearings less than zero the mitigation maneuver was performed away from the intruder and for all relative bearings greater than zero the UA turned toward the intruder aircraft (Figure B-2). The minimum DAA alerting threshold is based on maneuvers away from the intruder aircraft, which are approaching from a negative bearing, as depicted in Figure B-2.

B.3.2 PIC Response and ATC Coordination Time

The analysis performed initially determined the DAA execution threshold, defined as the last moment at which an aircraft must begin maneuvering in order to maintain DAA Well Clear (DWC). In order to determine the associated ranges required for alerting the Pilot-in-Command (PIC) and coordination with Air Traffic Control (ATC), a constant 25 seconds was added to the timeline. Thus, the ranges presented herein are the required intruder track acquisition time to provide an alert 25 seconds before the DAA execution threshold.

B.4 RESULTS

The results are presented below. Figure B-3 through Figure B-23 show the range requirements for a UA capable of sustaining a 3.0-degree-per-second (deg/s) turn. Figure B-24 through Figure B-44 show the range requirements for a UA only capable of sustaining at least a 1.5-deg/s turn. The figures show the range between the UA and intruder aircraft at the latest instance that the DAA system may provide an alert to the PIC while allowing 25 seconds for the PIC to coordinate with ATC and initiate a maneuver and Maintain DAA Well Clear (DWC) as a function of UA airspeed. In the figures, if a UA is in the range in green, there is sufficient range to maintain DWC, while in the red a LoWC will occur. The range is presented for each combination of intruder airspeed, relative bearing, and UA turn rate. The largest range in each figure becomes the requirement for a UA with a given sustained turn rate capability. The largest range requirement for a given intruder airspeed corresponds to the head-on, zero-degree relative bearing in all cases.

The head-on range requirement is the nominal range requirement for each intruder class. A RDR correction factor is then used to determine the range requirements for non-head-on encounters. The RDR correction factor is the normalization of the maximum range for each bearing to the range of the head-on encounter for the same intruder speed.

Analyzing the maximum range for each set of intruder airspeed, relative bearing, and UA turn rate, and normalizing with respect to the maximum range for each intruder airspeed provides the RDR correction factor. Table B-2 shows the reference range values associated with head-on encounters for different intruder speeds used to calculate the bearing adjustment factor. The variation in the bearing adjustment factor is small between the two UA turn rates, although the necessary ranges are quite different, as evident in the figures. This indicates that the RDR correction factor is independent of the maneuverability of the UA (at least for these benign maneuvers), but more dependent on the encounter geometry.

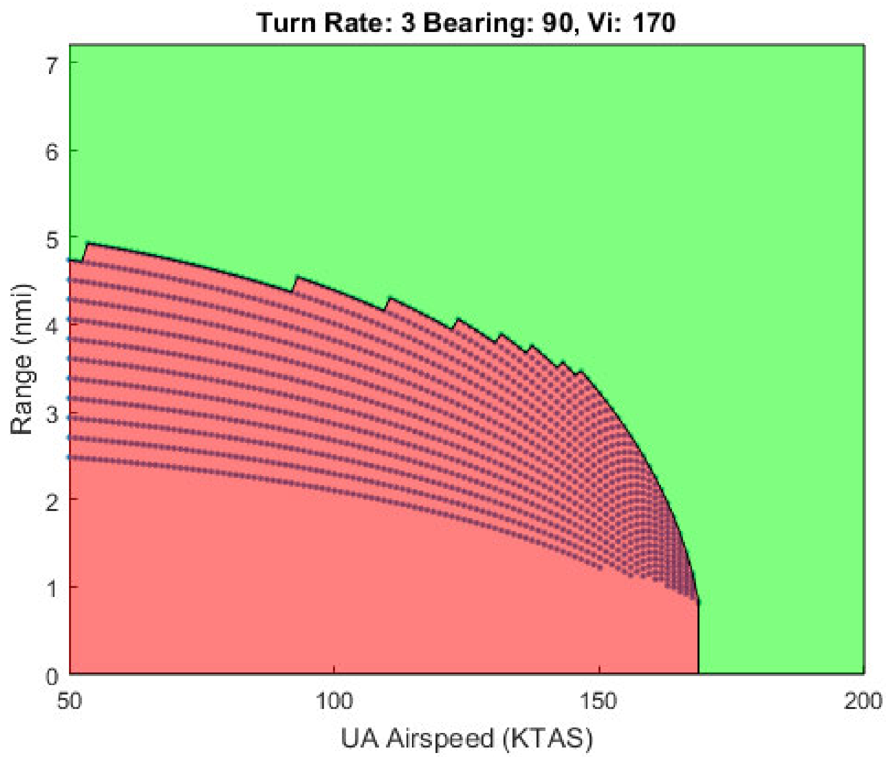
Table B-2 Reference Slant Range in NM

Intruder Airspeed (VI)	Mitigation Maneuver Rate	
	1.5 deg/s	3.0 deg/s
100 KTAS	5.82	5.40
130 KTAS	6.40	5.94
170 KTAS	7.17	6.66

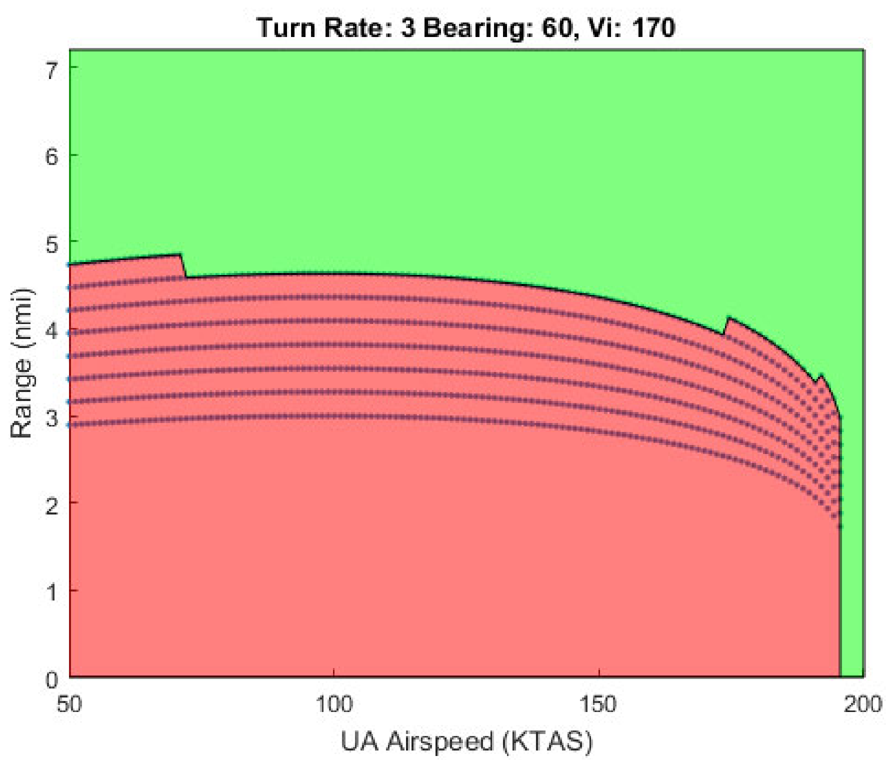
Given the negligible difference in the RDR correction factor for UA turn rates up to 3.0 deg/s, the 1.5 and 3.0 deg/s factors were combined and are presented in Table B-3.

Table B-3 RDR Correction Factor – Up to 3 deg/s

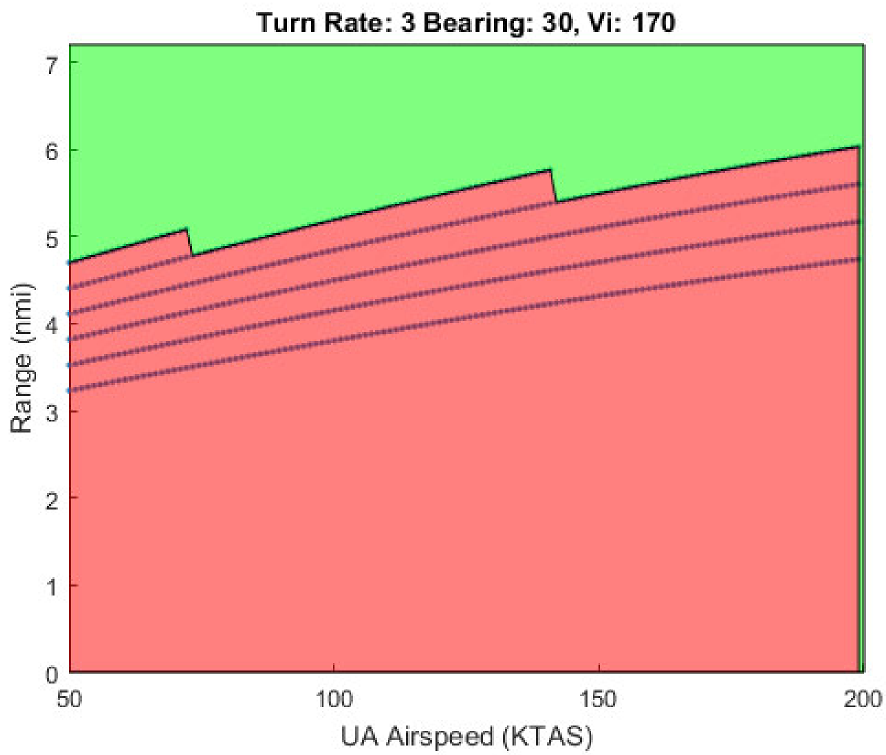
Intruder Airspeed (KTAS)	Relative Bearing (Degrees)						
	-90	-60	-30	0	30	60	90
100	0.34	0.44	0.67	1.00	0.77	0.59	0.57
130	0.43	0.52	0.78	1.00	0.87	0.66	0.65
170	0.55	0.60	0.84	1.00	0.91	0.73	0.74



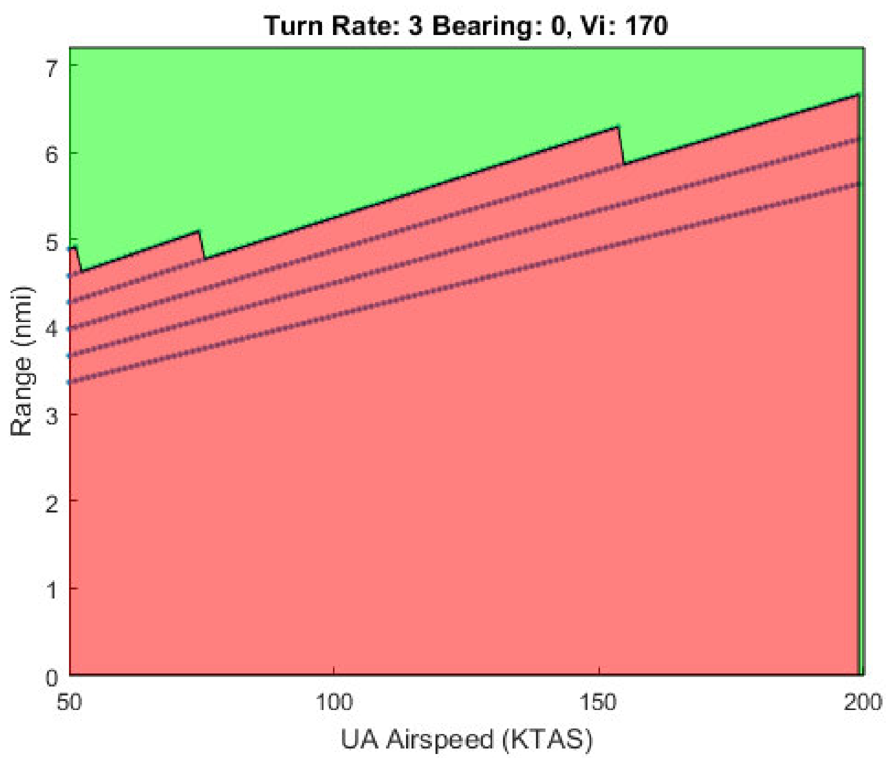
<u>Figure B-3</u> **RDR – Turn Rate: 3.0 deg/s, Bearing: 90 deg, Intruder Airspeed: 170 KTAS**



<u>Figure B-4</u> **RDR – Turn Rate: 3.0 deg/s, Bearing: 60 deg, Intruder Airspeed: 170 KTAS**



<u>Figure B-5</u> **RDR – Turn Rate: 3.0 deg/s, Bearing: 30 deg, Intruder Airspeed: 170 KTAS**



<u>Figure B-6</u> **RDR – Turn Rate: 3.0 deg/s, Bearing: 0 deg, Intruder Airspeed: 170 KTAS**

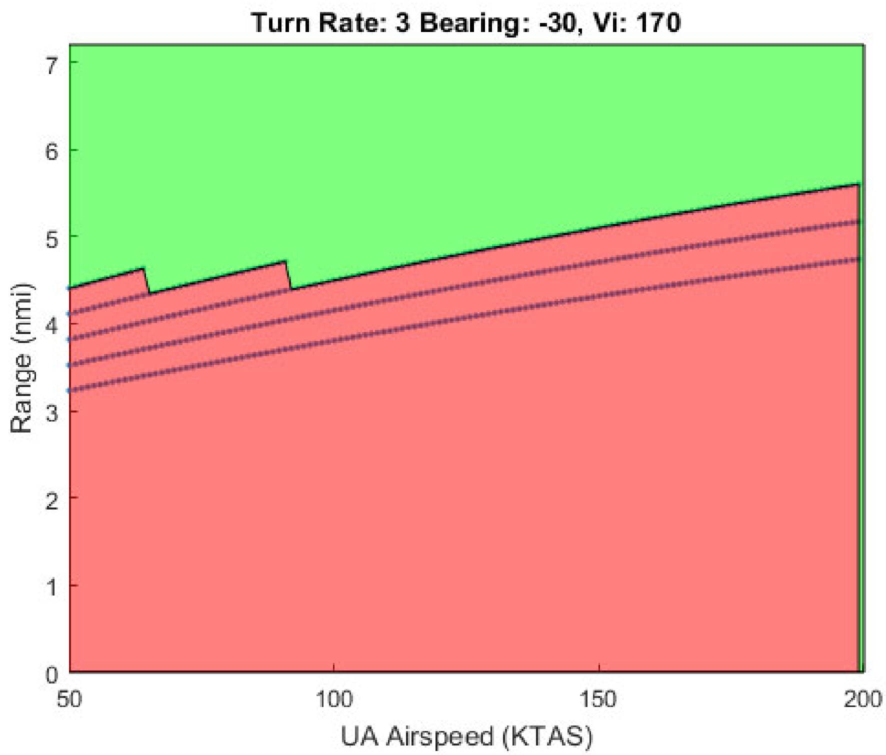


Figure B-7 RDR – Turn Rate: 3.0 deg/s, Bearing: -30 deg, Intruder Airspeed: 170 KTAS

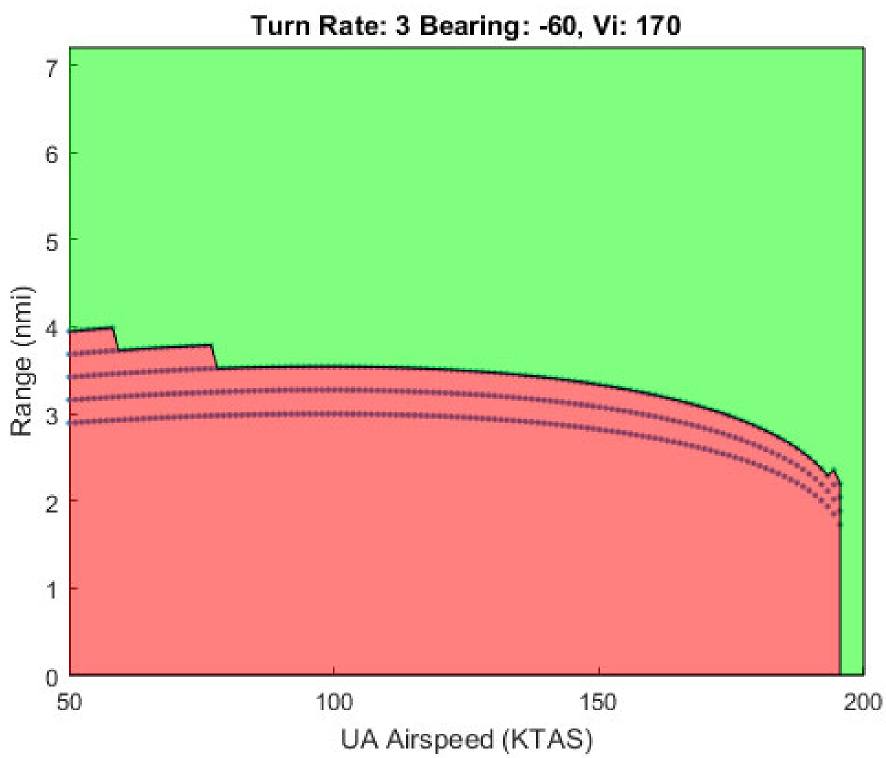


Figure B-8 RDR – Turn Rate: 3.0 deg/s, Bearing: -60 deg, Intruder Airspeed: 170 KTAS

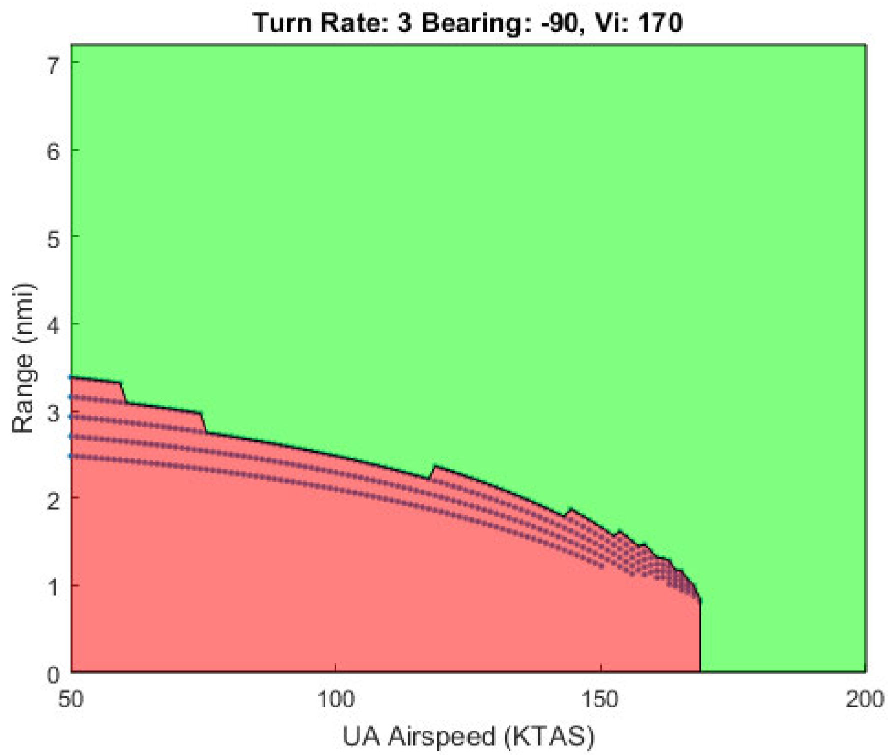


Figure B-9 **RDR – Turn Rate: 3.0 deg/s, Bearing: -90 deg, Intruder Airspeed: 170 KTAS**

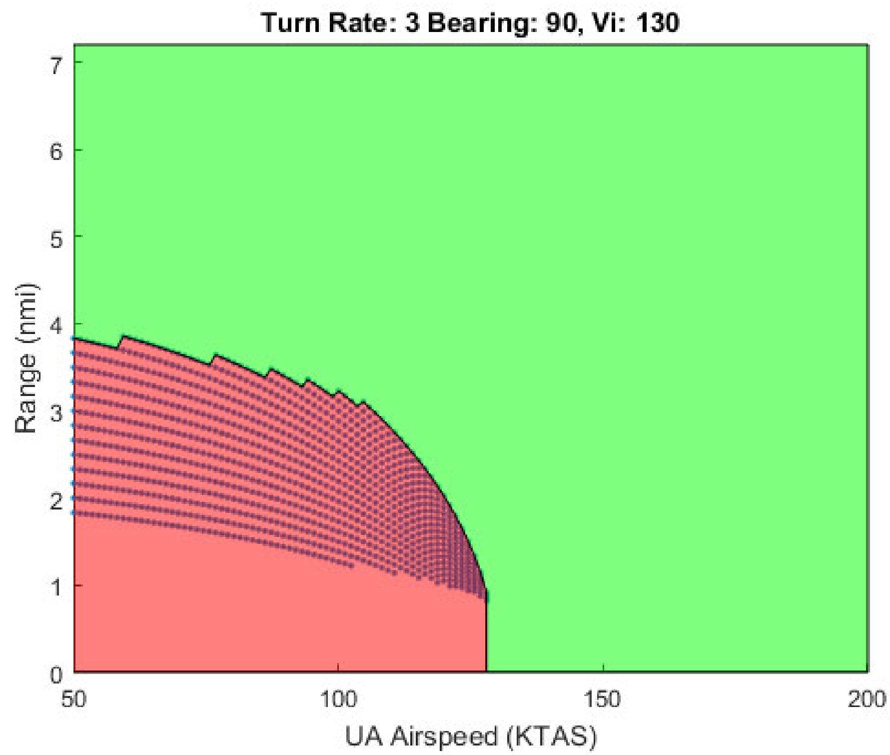


Figure B-10 RDR – Turn Rate: 3.0 deg/s, Bearing: 90 deg, Intruder Airspeed: 130 KTAS

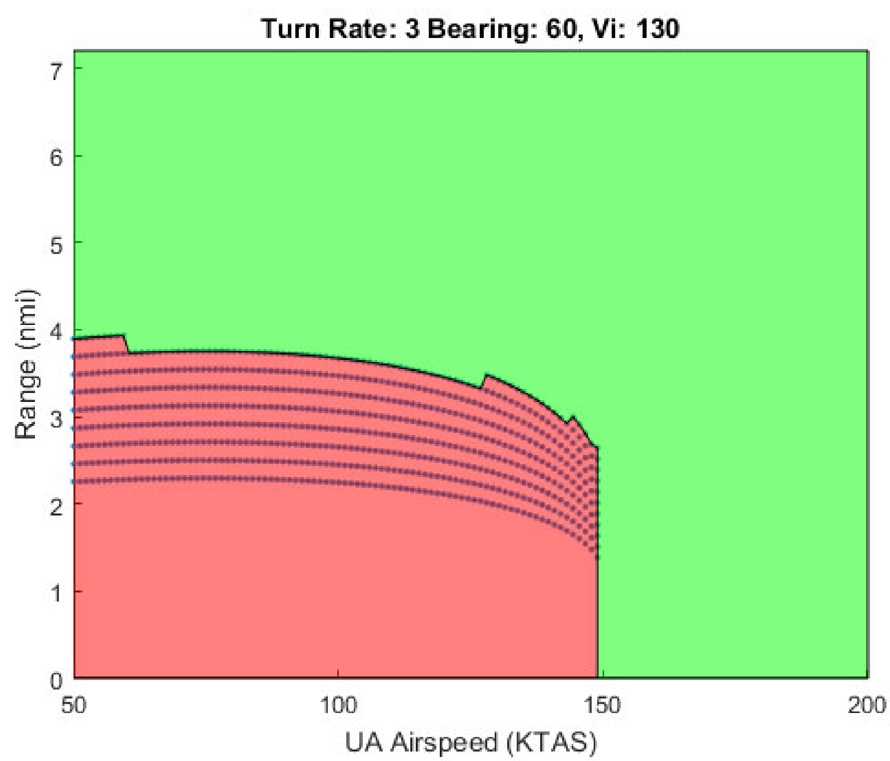


Figure B-11 RDR – Turn Rate: 3.0 deg/s, Bearing: 60 deg, Intruder Airspeed: 130 KTAS

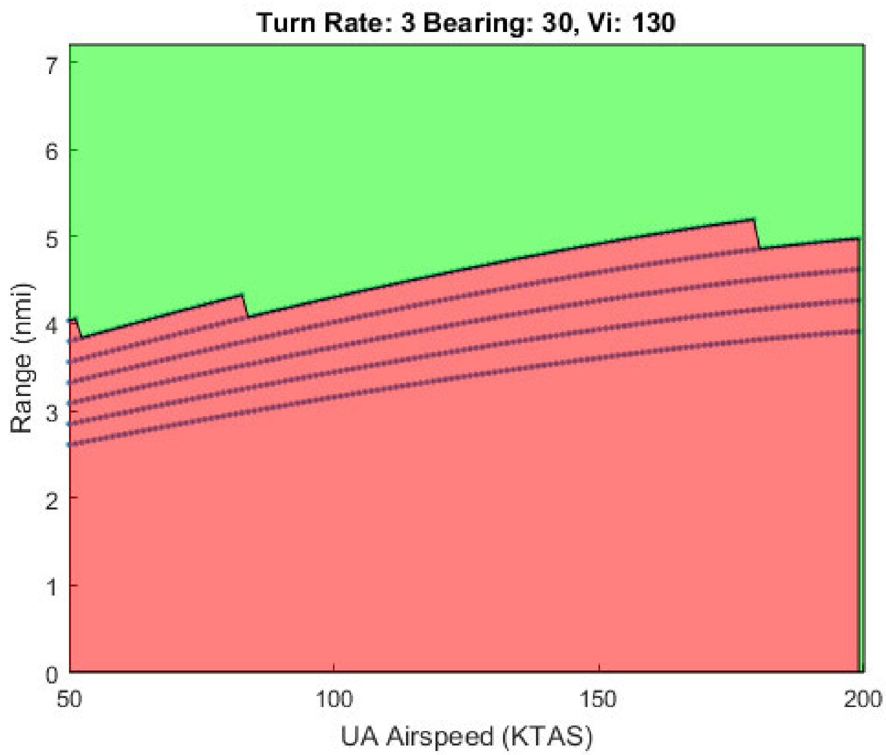


Figure B-12 **RDR – Turn Rate: 3.0 deg/s, Bearing: 30 deg, Intruder Airspeed: 130 KTAS**

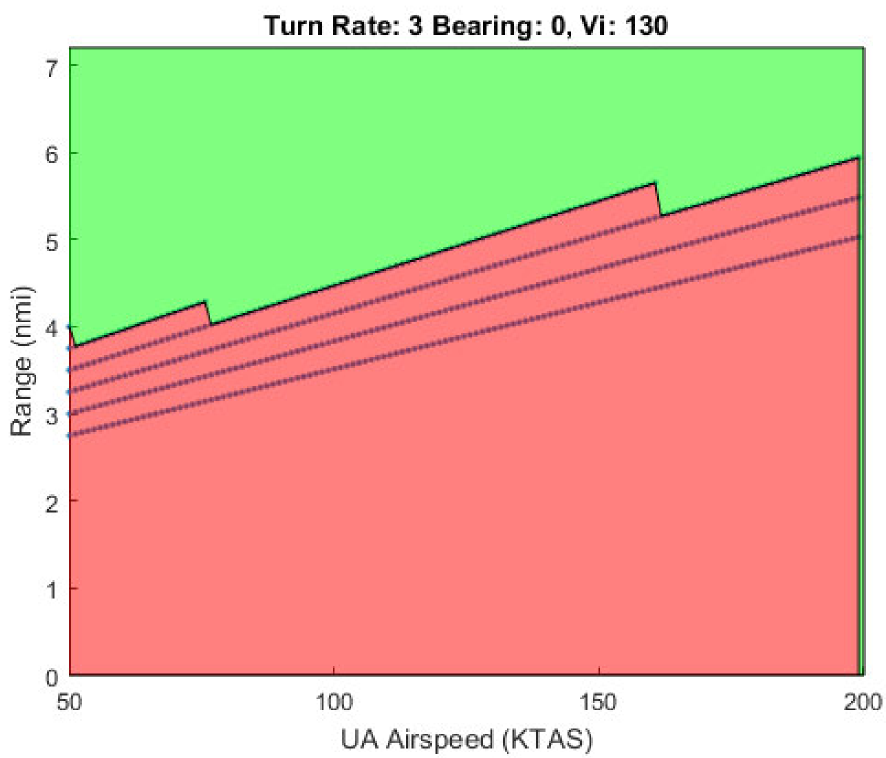
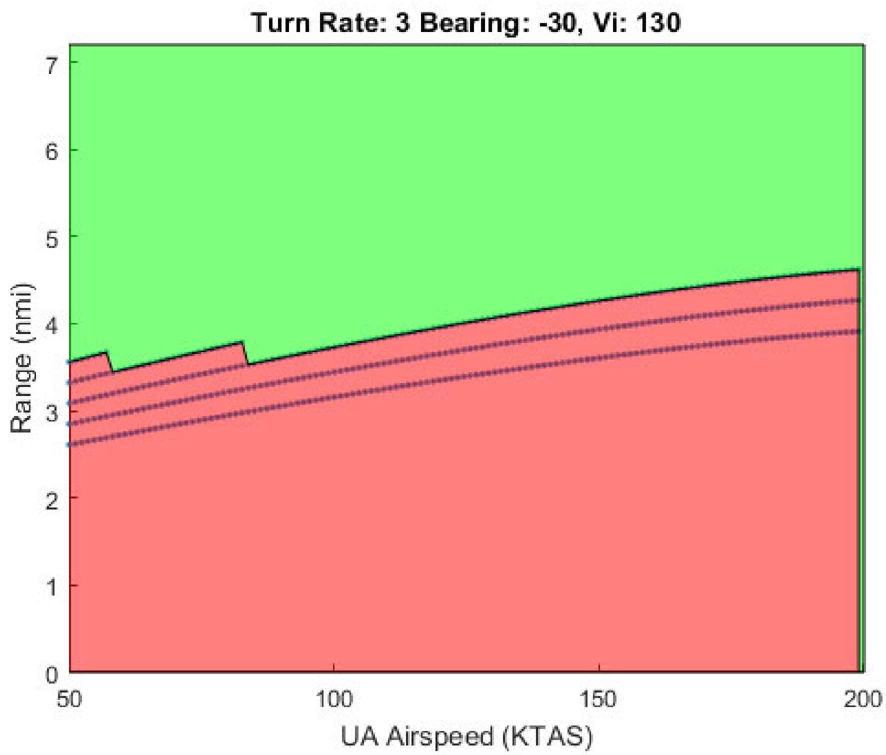
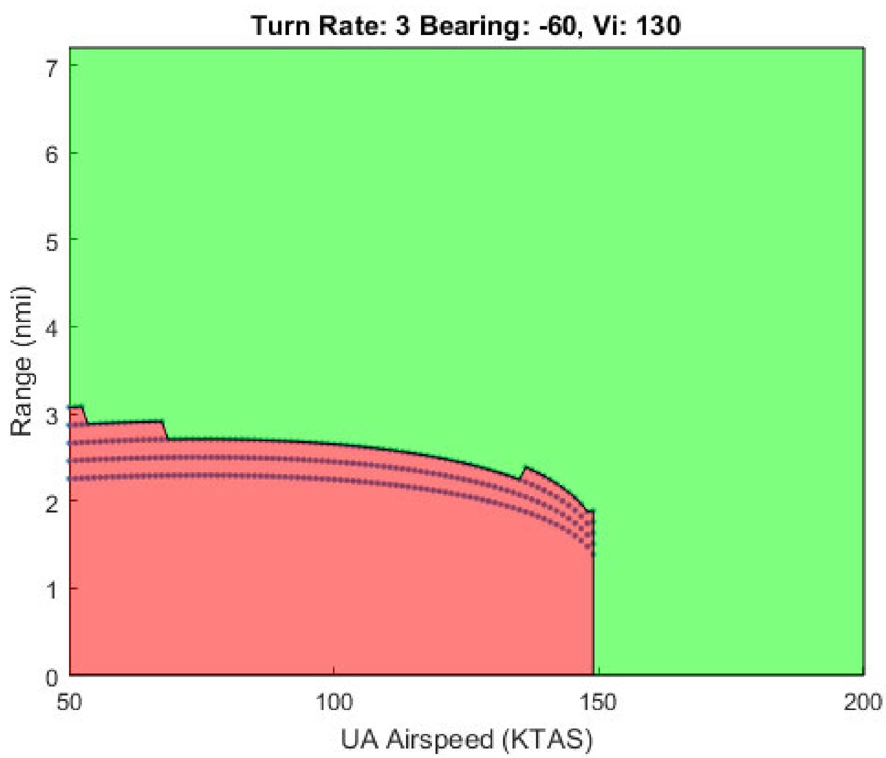


Figure B-13 **RDR – Turn Rate: 3.0 deg/s, Bearing: 0 deg, Intruder Airspeed: 130 KTAS**



<u>Figure B-14</u> RDR – Turn Rate: 3.0 deg/s, Bearing: -30 deg, Intruder Airspeed: 130 KTAS



<u>Figure B-15</u> RDR – Turn Rate: 3.0 deg/s, Bearing: -60 deg, Intruder Airspeed: 130 KTAS

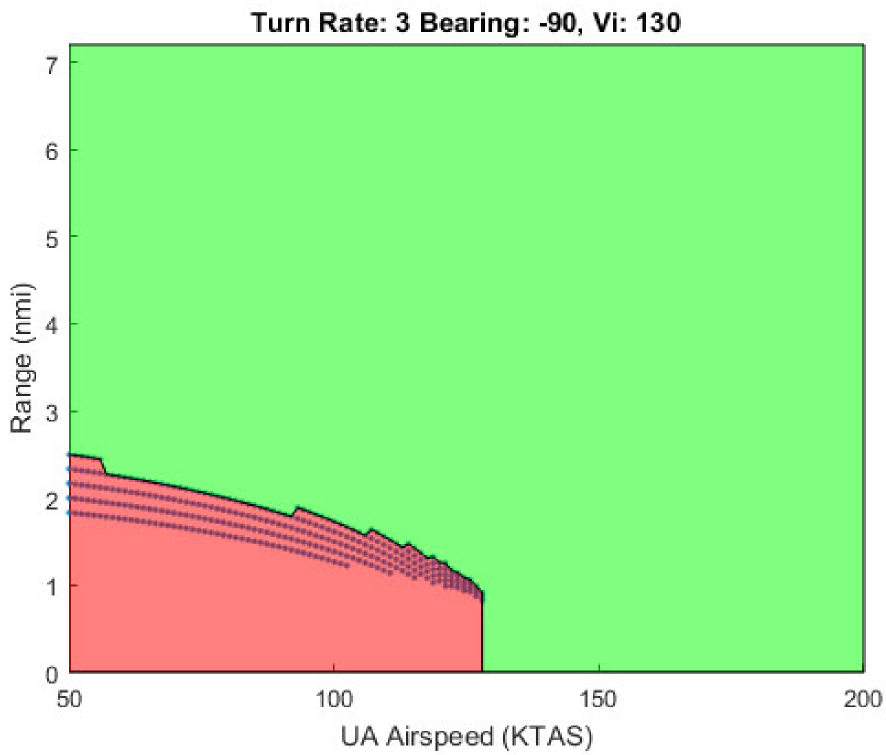


Figure B-16 **RDR – Turn Rate: 3.0 deg/s, Bearing: -90 deg, Intruder Airspeed: 130 KTAS**

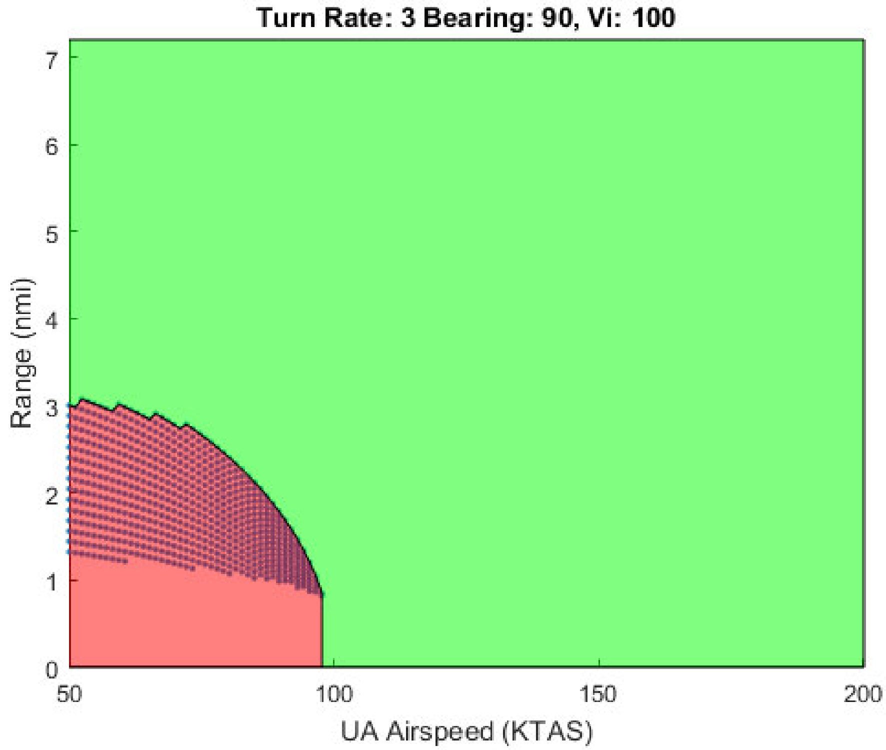


Figure B-17 **RDR – Turn Rate: 3.0 deg/s, Bearing: 90 deg, Intruder Airspeed: 100 KTAS**

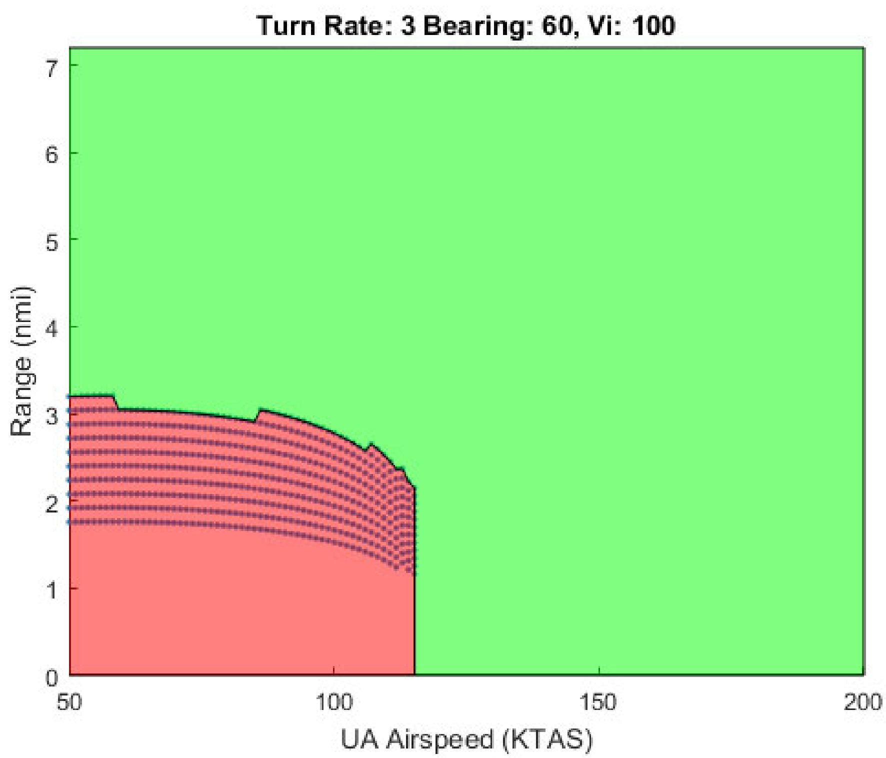


Figure B-18 **RDR – Turn Rate: 3.0 deg/s, Bearing: 60 deg, Intruder Airspeed: 100 KTAS**

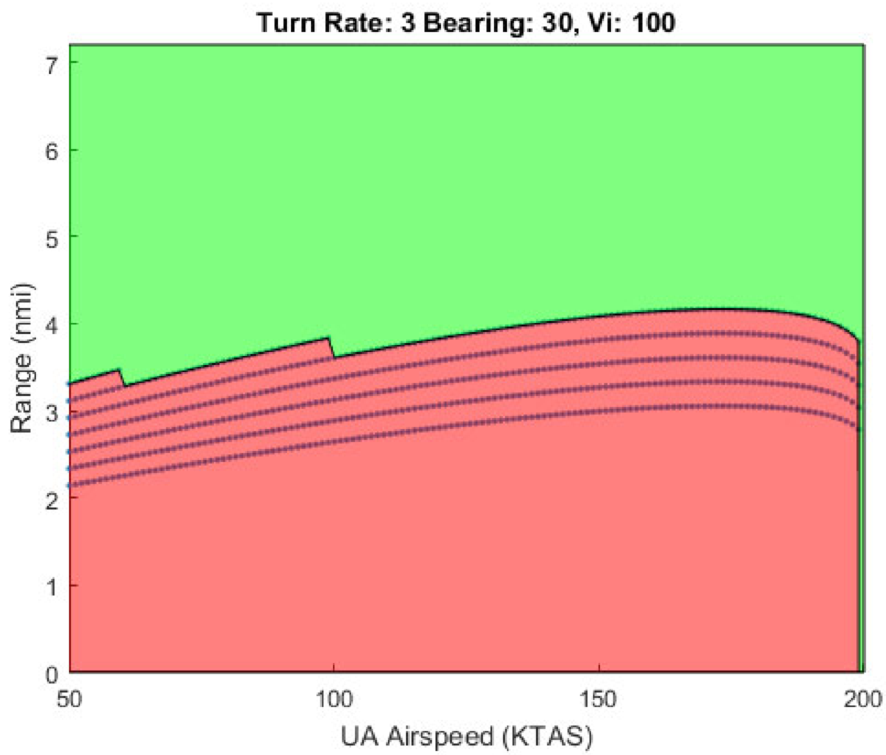


Figure B-19 **RDR – Turn Rate: 3.0 deg/s, Bearing: 30 deg, Intruder Airspeed: 100 KTAS**

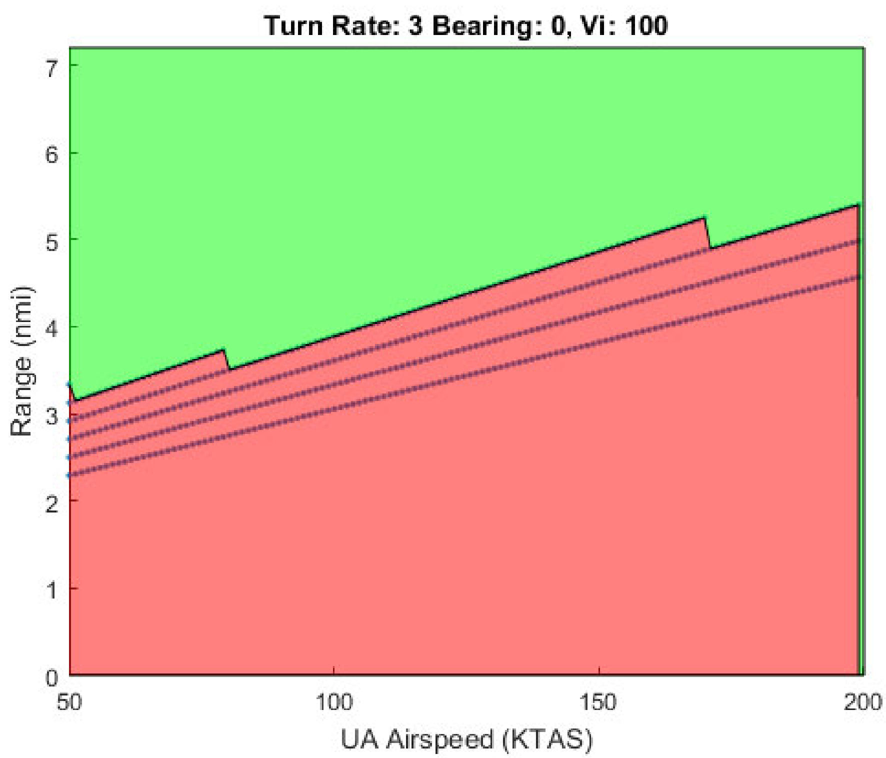
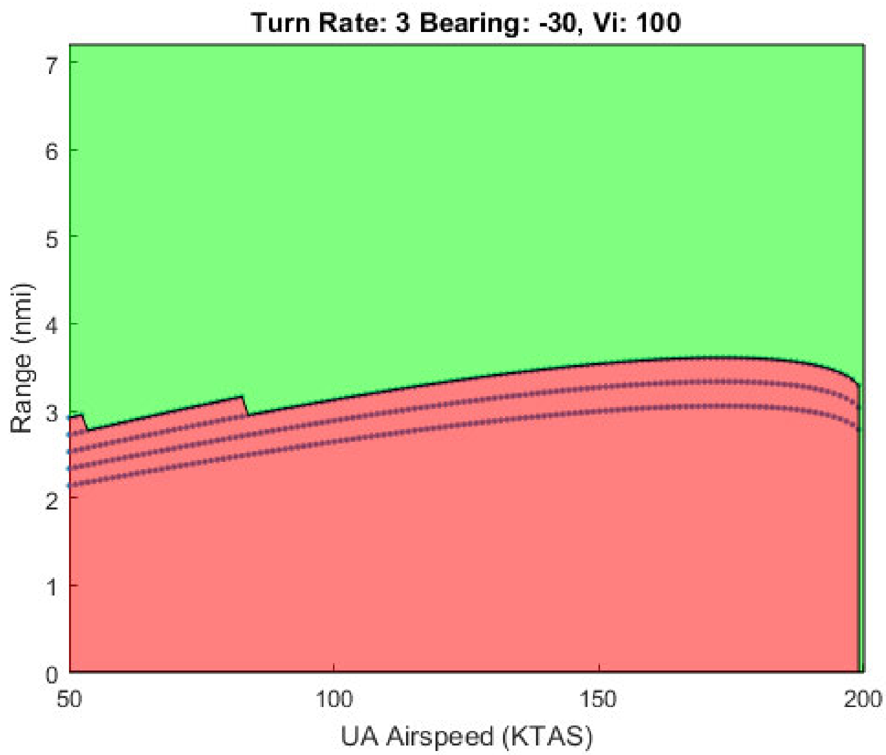
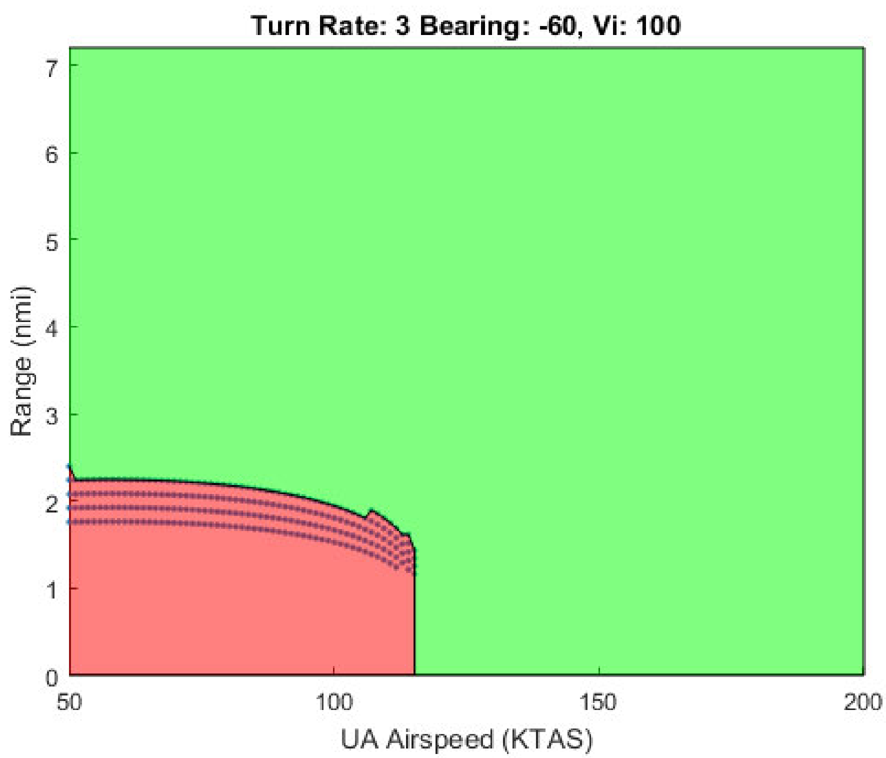


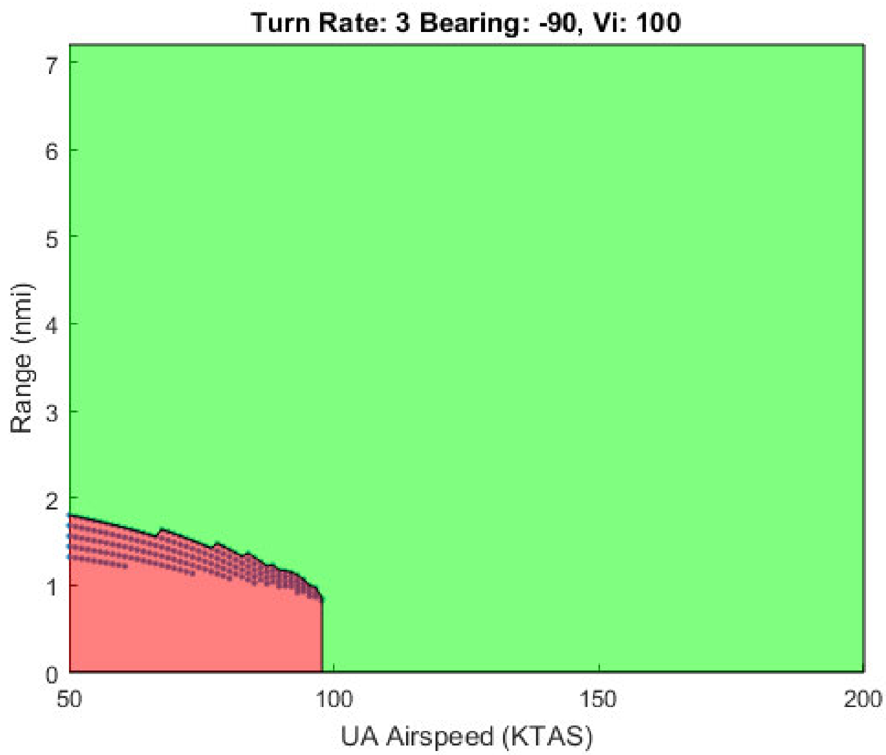
Figure B-20 **RDR – Turn Rate: 3.0 deg/s, Bearing: 0 deg, Intruder Airspeed: 100 KTAS**



<u>Figure B-21</u> **RDR – Turn Rate: 3.0 deg/s, Bearing: -30 deg, Intruder Airspeed: 100 KTAS**



<u>Figure B-22</u> **RDR – Turn Rate: 3.0 deg/s, Bearing: -60 deg, Intruder Airspeed: 100 KTAS**



<u>Figure B-23</u> **RDR – Turn Rate: 3.0 deg/s, Bearing: -90 deg, Intruder Airspeed: 100 KTAS**

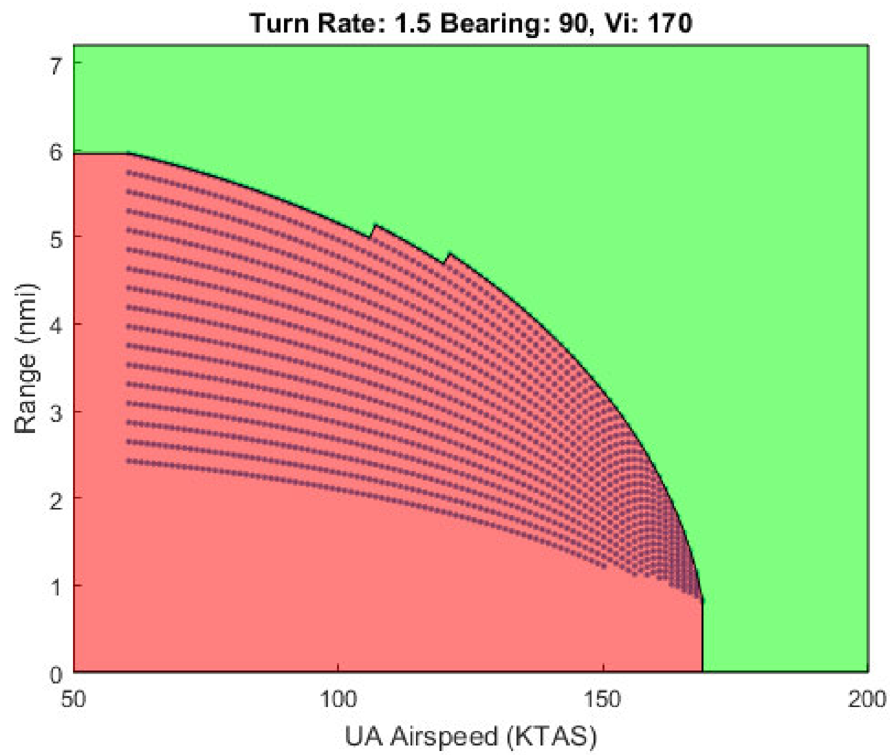


Figure B-24 RDR – Turn Rate: 1.5 deg/s, Bearing: 90 deg, Intruder Airspeed: 170 KTAS

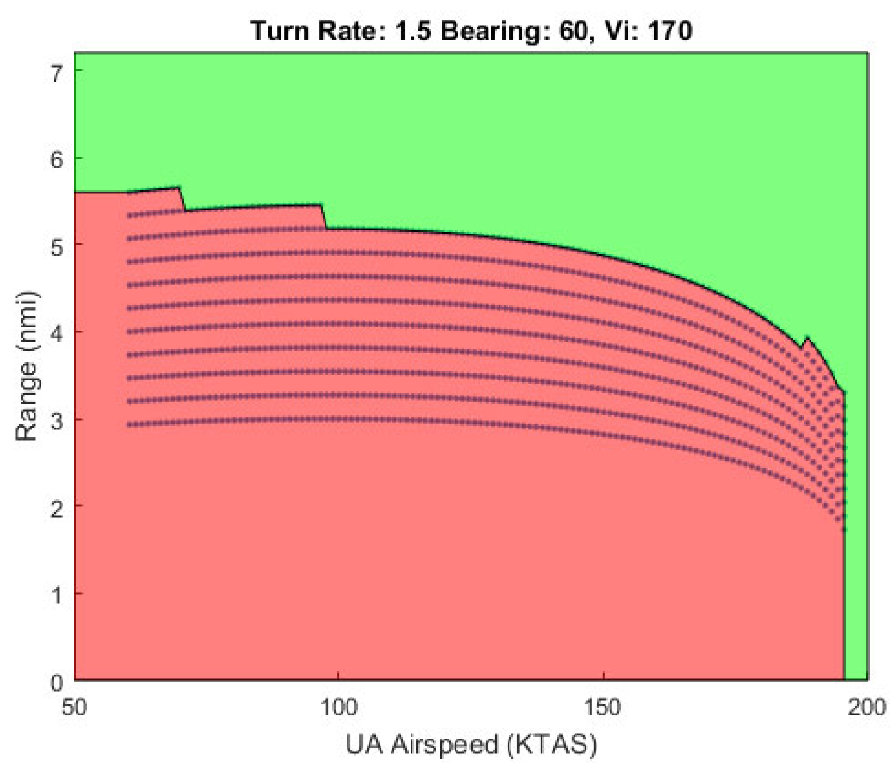
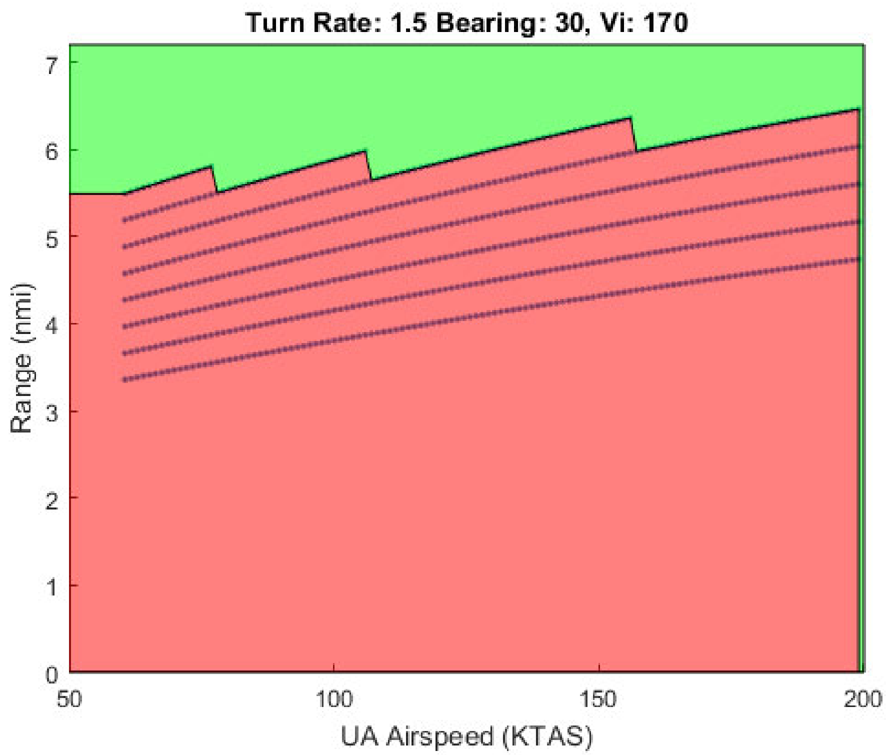
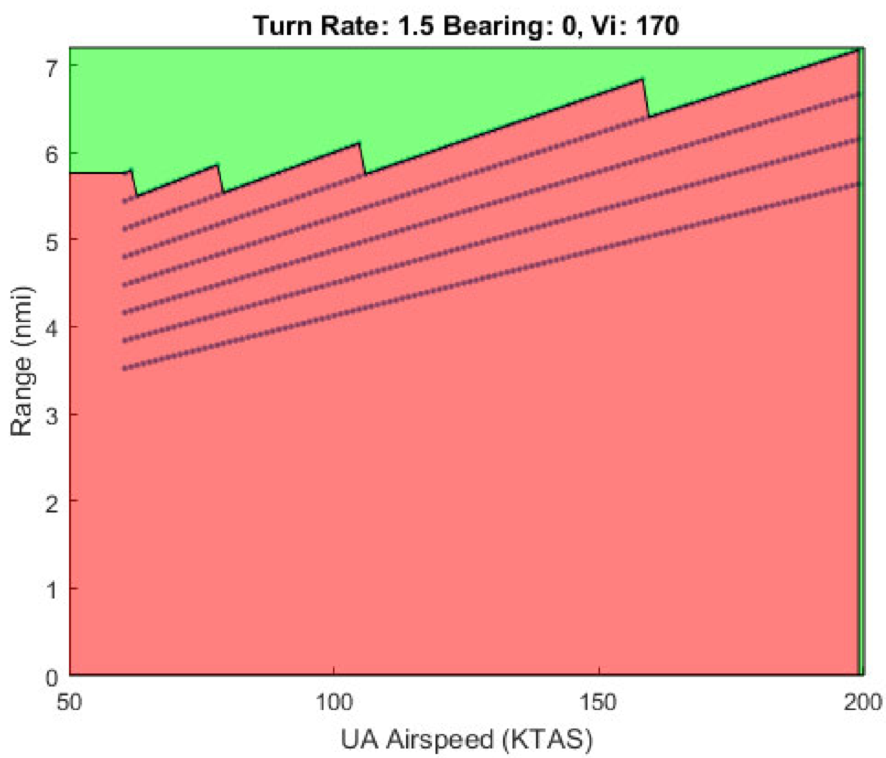


Figure B-25 RDR – Turn Rate: 1.5 deg/s, Bearing: 60 deg, Intruder Airspeed: 170 KTAS



<u>Figure B-26</u> **RDR – Turn Rate: 1.5 deg/s, Bearing: 30 deg, Intruder Airspeed: 170 KTAS**



<u>Figure B-27</u> **RDR – Turn Rate: 1.5 deg/s, Bearing: 0 deg, Intruder Airspeed: 170 KTAS**

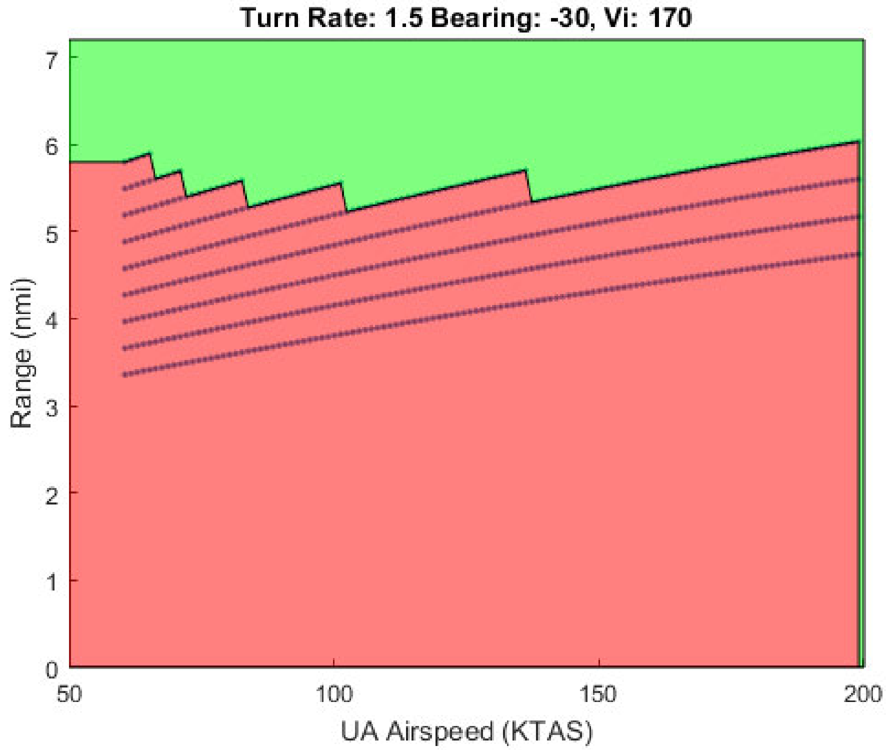


Figure B-28 **RDR – Turn Rate: 1.5 deg/s, Bearing: -30 deg, Intruder Airspeed: 170 KTAS**

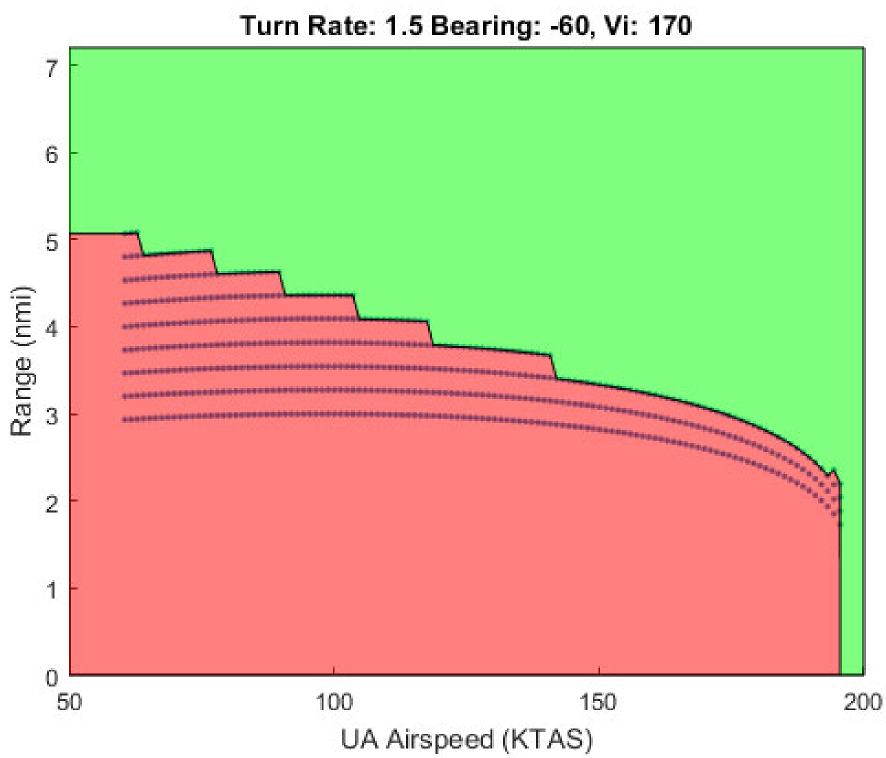
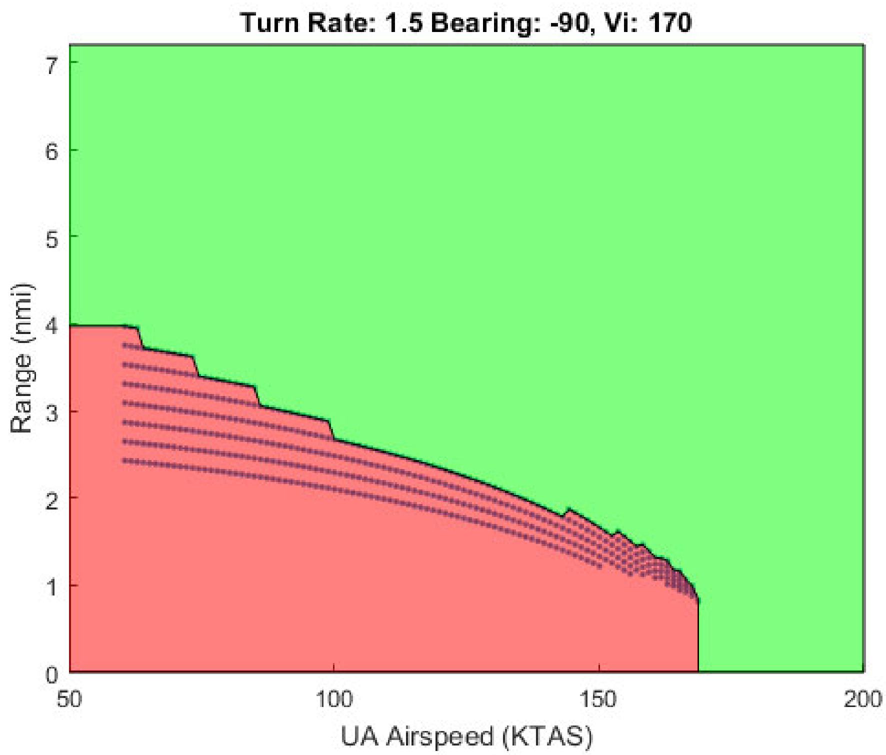


Figure B-29 **RDR – Turn Rate: 1.5 deg/s, Bearing: -60 deg, Intruder Airspeed: 170 KTAS**



<u>Figure B-30</u> **RDR – Turn Rate: 1.5 deg/s, Bearing: -90 deg, Intruder Airspeed: 170 KTAS**

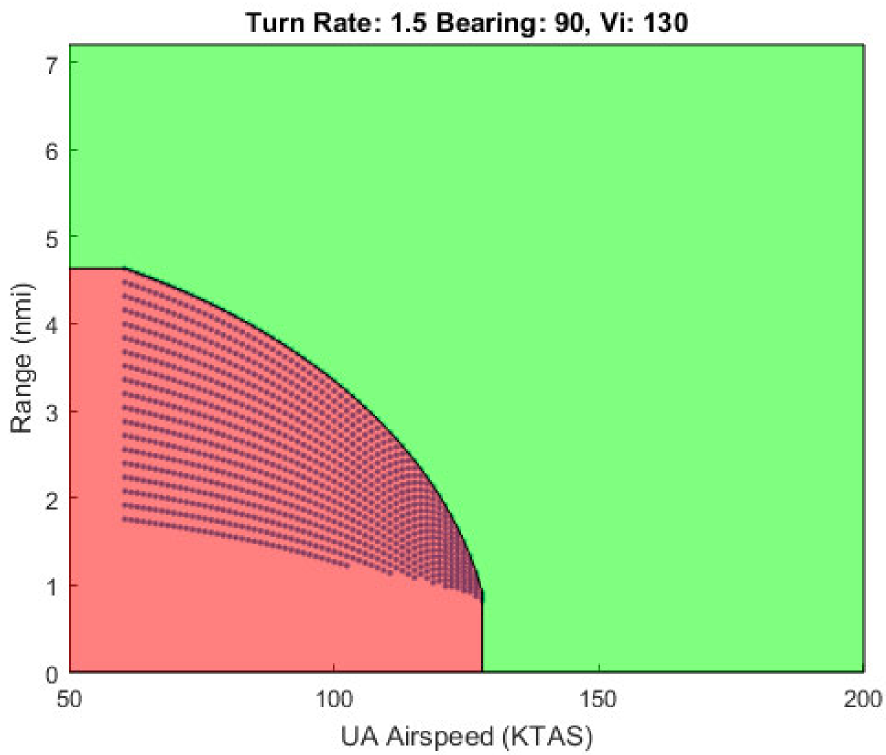


Figure B-31 **RDR – Turn Rate: 1.5 deg/s, Bearing: 90 deg, Intruder Airspeed: 130 KTAS**

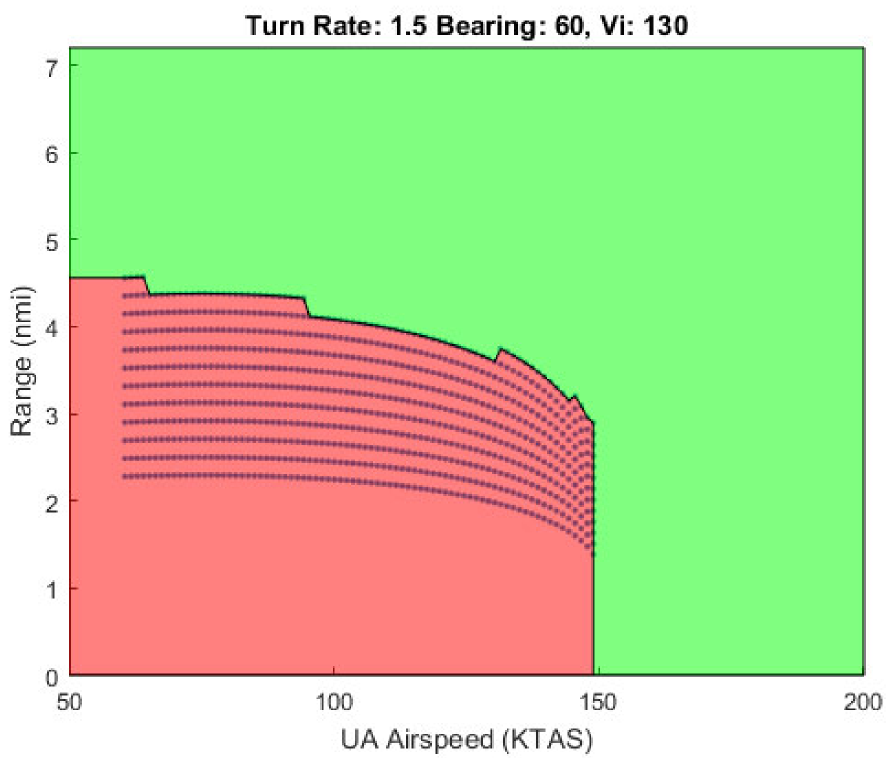


Figure B-32 **RDR – Turn Rate: 1.5 deg/s, Bearing: 60 deg, Intruder Airspeed: 130 KTAS**

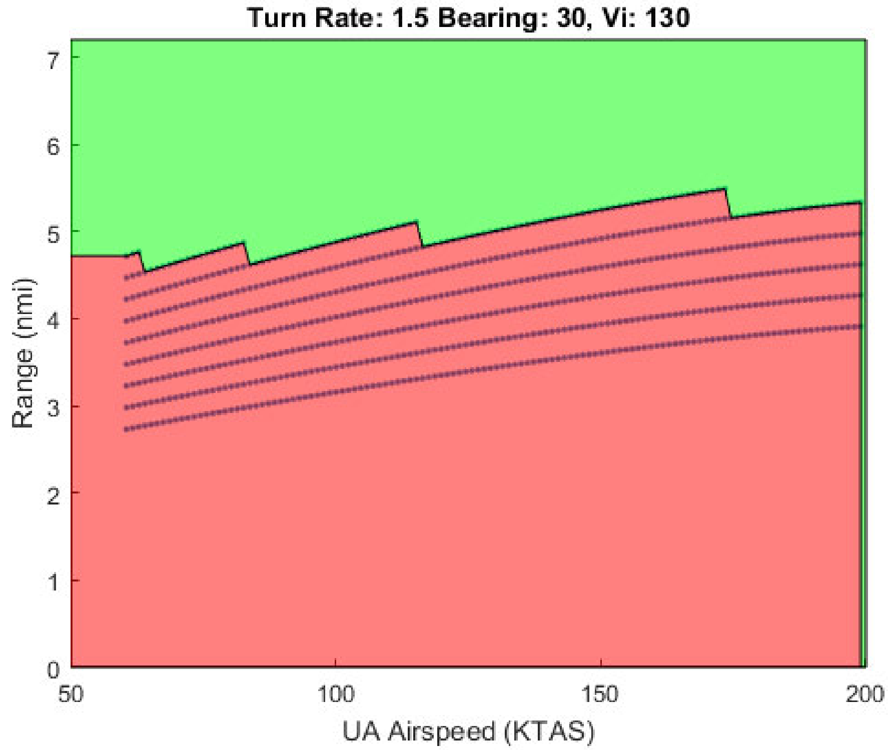


Figure B-33 **RDR – Turn Rate: 1.5 deg/s, Bearing: 30 deg, Intruder Airspeed: 130 KTAS**

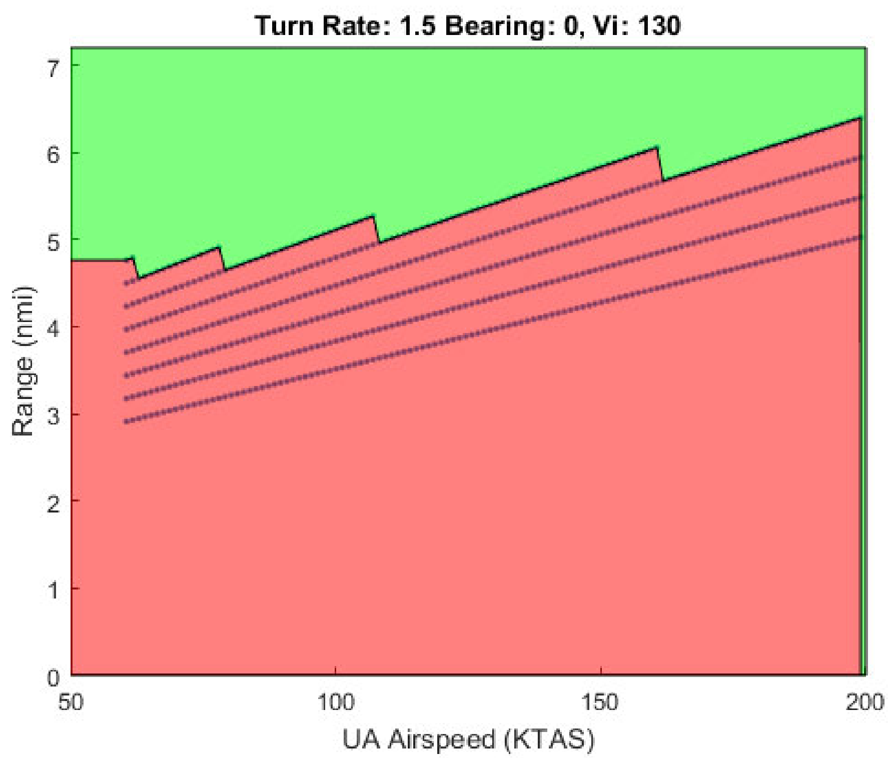


Figure B-34 **RDR – Turn Rate: 1.5 deg/s, Bearing: 0 deg, Intruder Airspeed: 130 KTAS**

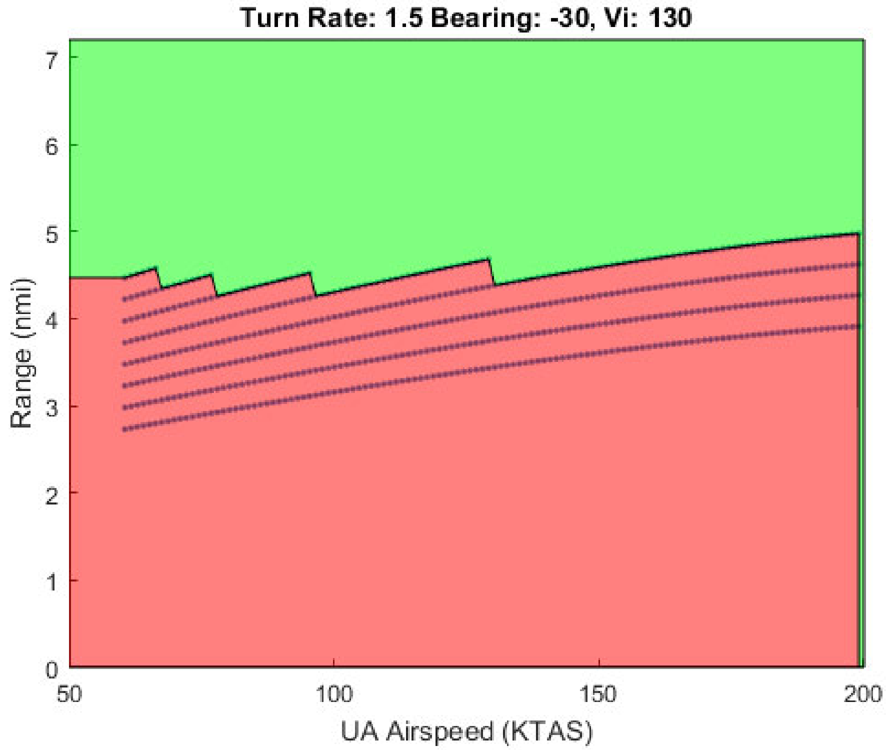


Figure B-35 **RDR – Turn Rate: 1.5 deg/s, Bearing: -30 deg, Intruder Airspeed: 130 KTAS**

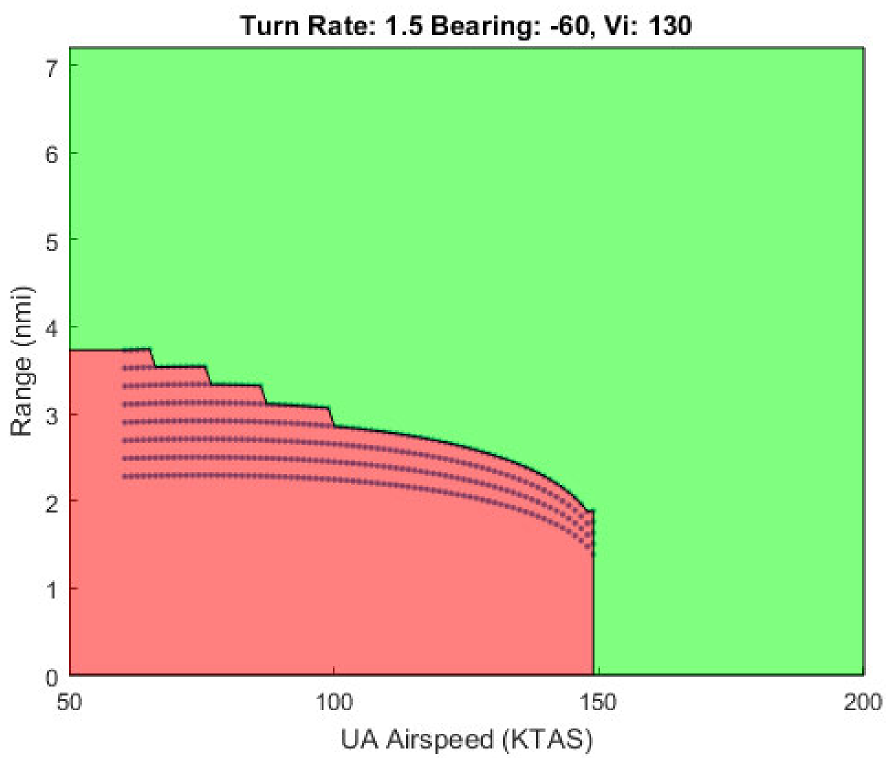


Figure B-36 **RDR – Turn Rate: 1.5 deg/s, Bearing: -60 deg, Intruder Airspeed: 130 KTAS**

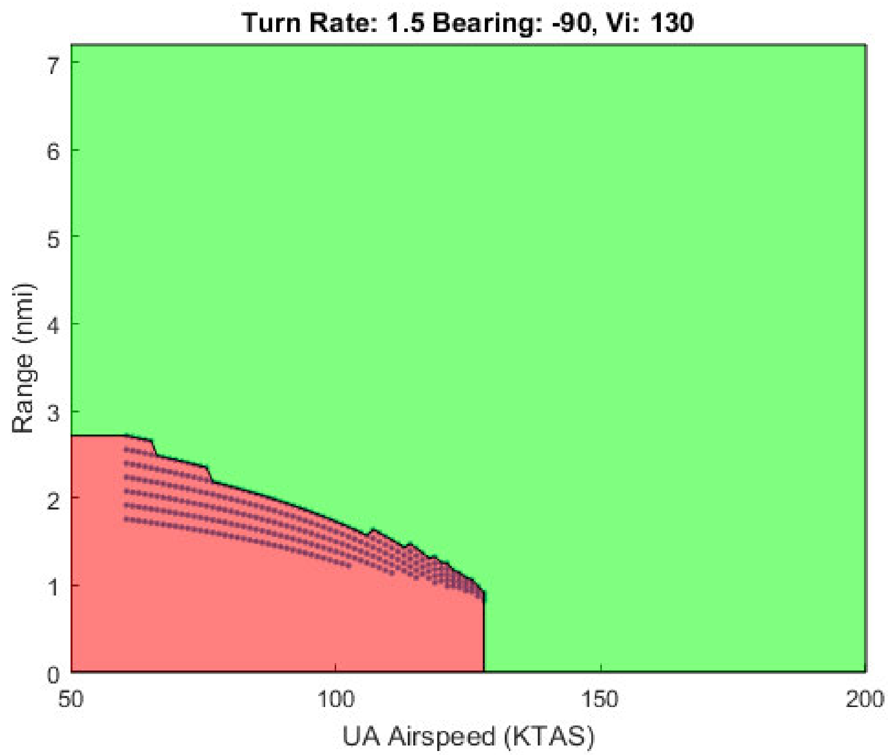


Figure B-37 RDR – Turn Rate: 1.5 deg/s, Bearing: -90 deg, Intruder Airspeed: 130 KTAS

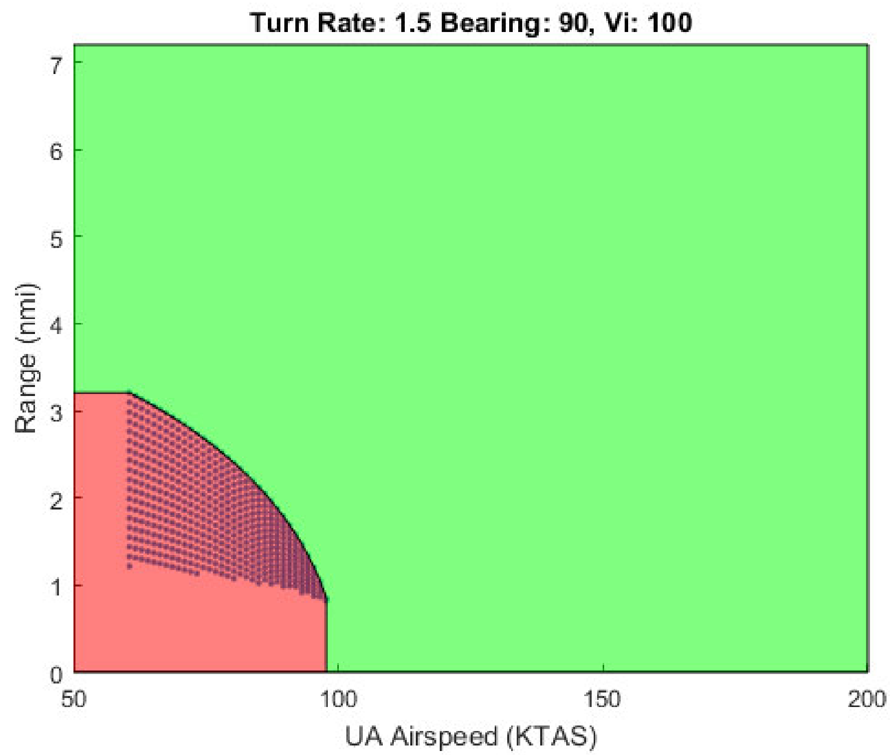


Figure B-38 **RDR – Turn Rate: 1.5 deg/s, Bearing: 90 deg, Intruder Airspeed: 100 KTAS**

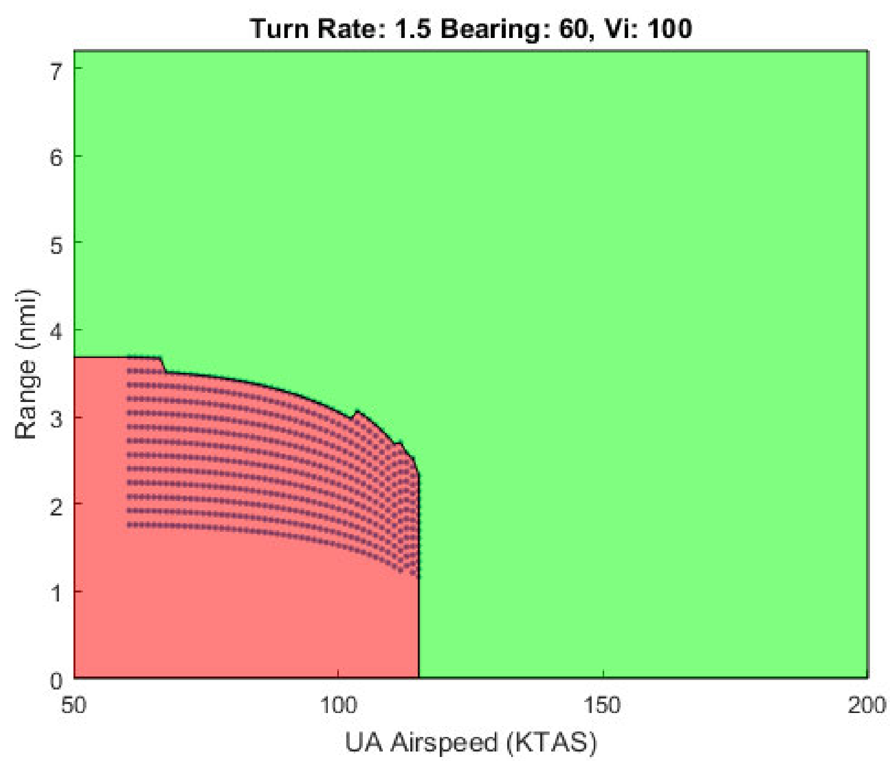


Figure B-39 **RDR – Turn Rate: 1.5 deg/s, Bearing: 60 deg, Intruder Airspeed: 100 KTAS**

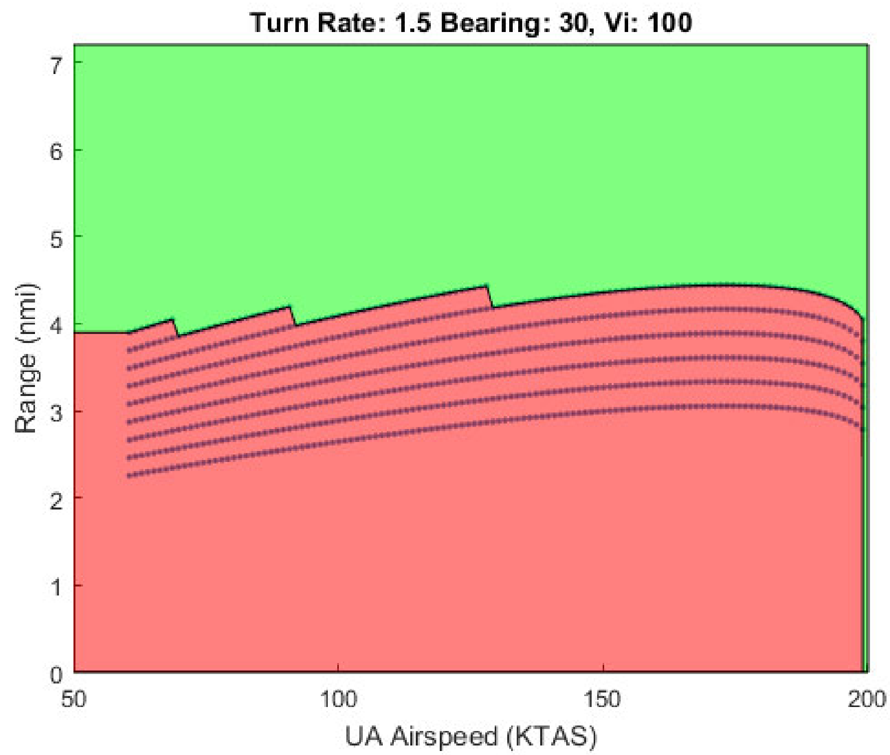


Figure B-40 **RDR – Turn Rate: 1.5 deg/s, Bearing: 30 deg, Intruder Airspeed: 100 KTAS**

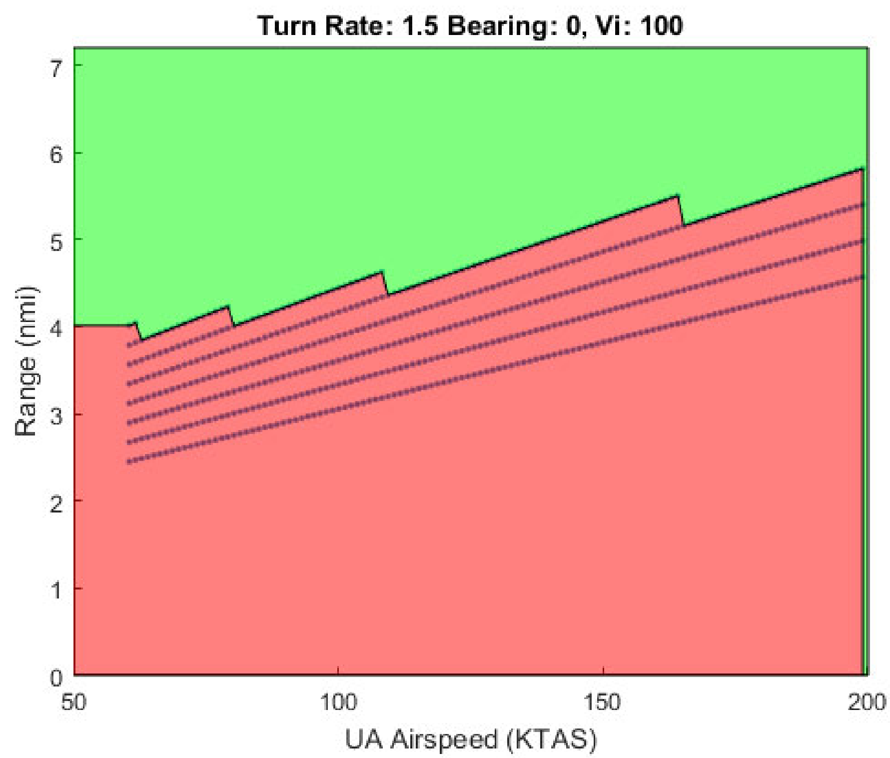
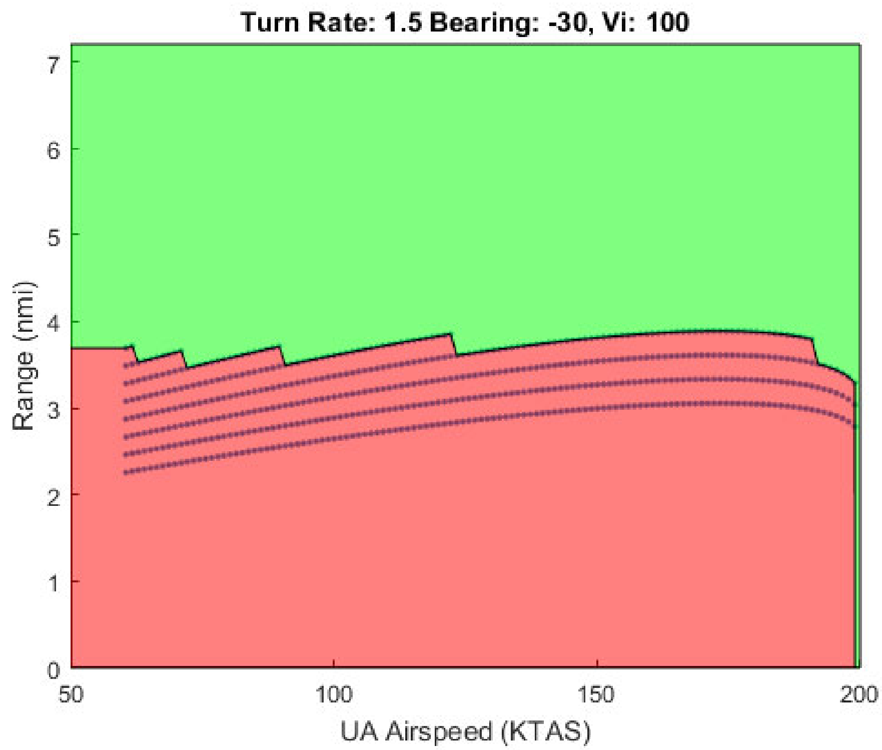
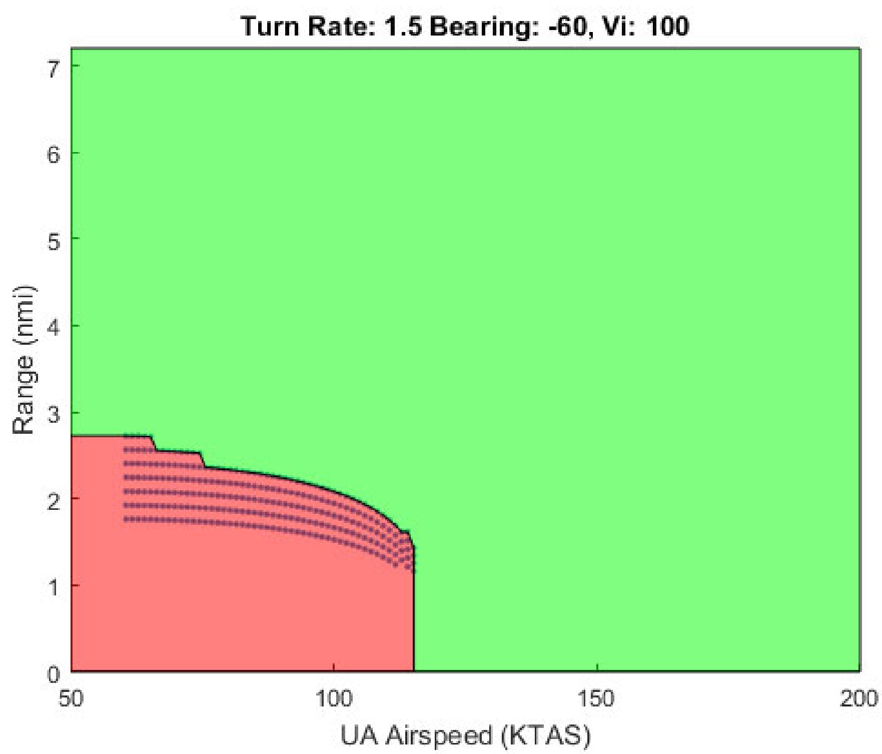


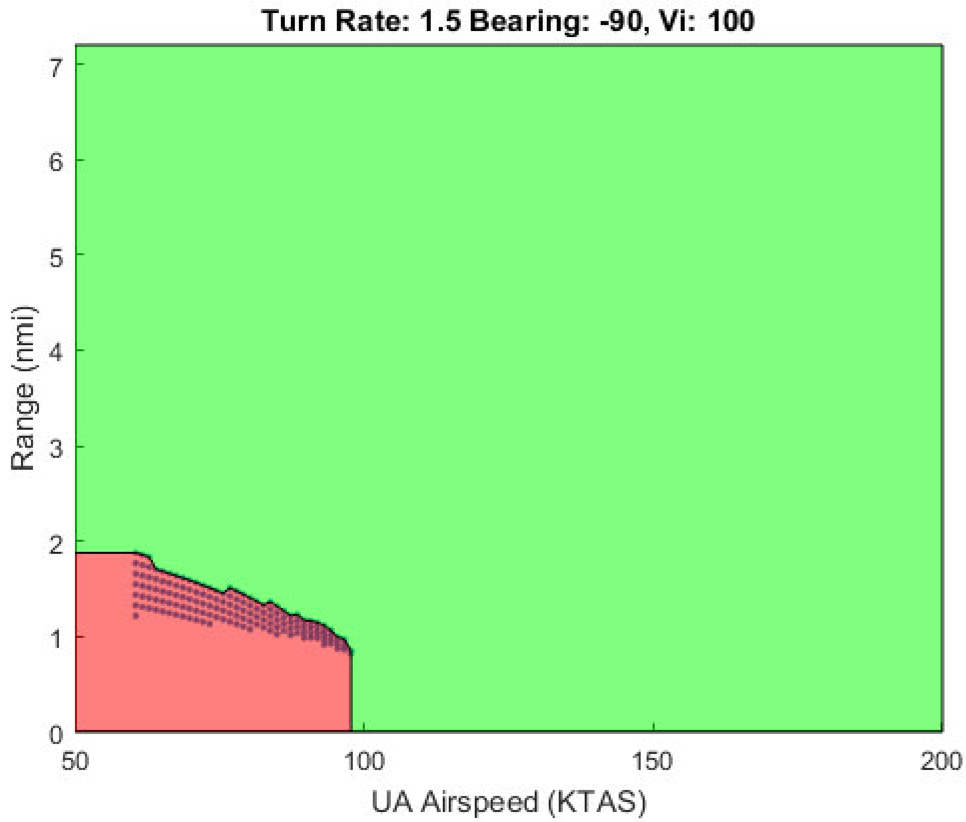
Figure B-41 **RDR – Turn Rate: 1.5 deg/s, Bearing: 0 deg, Intruder Airspeed: 100 KTAS**



<u>Figure B-42</u> **RDR – Turn Rate: 1.5 deg/s, Bearing: -30 deg, Intruder Airspeed: 100 KTAS**



<u>Figure B-43</u> **RDR – Turn Rate: 1.5 deg/s, Bearing: -60 deg, Intruder Airspeed: 100 KTAS**



<u>Figure B-44</u> **RDR – Turn Rate: 1.5 deg/s, Bearing: -90 deg, Intruder Airspeed: 100 KTAS**

C APPENDIX C PROBABILITY OF AN INTRUDER ENTERING THE RADAR FIELD OF REGARD WITHIN THE RADAR DECLARATION RANGE

C.1 INTRODUCTION

Subparagraph 2.2.7-22 of these Minimum Operational Performance Standards (MOPS) covers the cases where the intruder enters the Field of Regard (FOR) within the Radar Declaration Range (RDR) (e.g., ownship maneuver or intruder overtake) A concern was raised regarding the likelihood of these events, and their geometries. This section describes the Modeling and Simulation (M&S) effort to estimate the probability of the previously undetected intruder entering the FOR within the RDR and those potentially affected by the 15-second delay for the radar to establish a track.

C.2 ENCOUNTER MODEL & PRE-CONDITIONING

Approximately one million encounters from the Uncorrelated Encounter Model were sampled for this analysis (see Subsection C.7). This dataset represents encounters against non-cooperative Visual Flight Rules (VFR) intruders with and without Loss of Well Clear (LoWC).

When necessary, both trajectories for the Unmanned Aircraft (UA) ownship and the intruder were linearly back propagated to ensure sufficient time margin so that there is at least 180 seconds before LoWC and the resultant encounter does not initialize with the intruder situated within the radar FOR and within the RDR. Furthermore, encounters with the UA ownship traveling less than 40 knots at LoWC were rejected from consideration.

C.3 EVENT FILTERING & ADDITIONAL ASSUMPTIONS

A series of event filtering was employed as shown in Figure C-1 to extract encounters with an intruder entering the radar FOR within the RDR that are potentially affected by the 15-second delay for radar to establish a track.

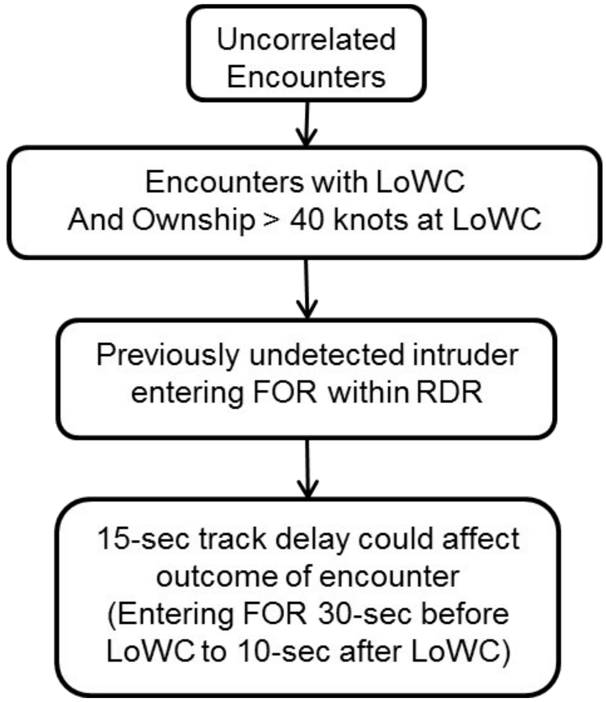


Figure C-1 Event Filtering Process Flow Diagram

After selecting only encounters that resulted in LoWC, the UA ownship trajectory was used to estimate its bank- and pitch-angle propagation. The effect of angle of attack was assumed to be negligible. The UA's attitude in conjunction with relative position to the intruder was used to determine if the intruder is within the radar's Field of Regard per Paragraph 2.2.6. Evaluated at 1-second intervals, if the previously undetected intruder first appeared within the FOR with a range less than 95% of RDR, the encounter was then selected for further analysis. The first time instance of the intruder entering the radar FOR is marked and compared with the encounter time instance corresponding to first LoWC to determine the time margin remaining as illustrated in Figure C-2. A positive time margin represents that the intruder entered the radar FOR within the RDR before LoWC while a negative time margin indicates LoWC occurred before the intruder could be detected.

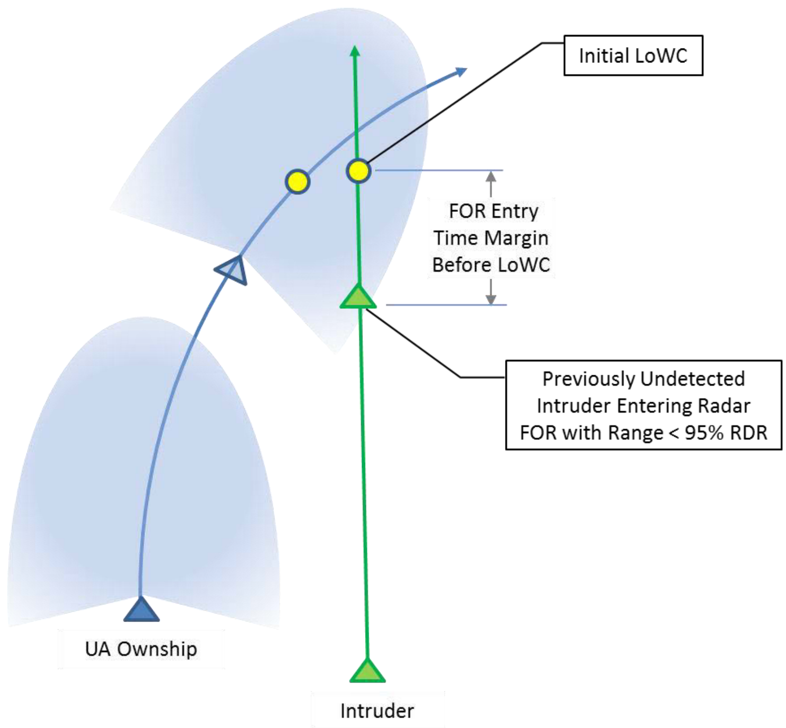


Figure C-2 Capturing the FOR Entry Time Margin

To further isolate the encounters that are potentially affected by the 15-second delay for the radar to establish a track, only encounters with FOR entry time margin between -10 to +30 seconds were selected. It is assumed for encounters with FOR entry time margin more positive than +30 seconds, even if the radar takes 15 seconds to establish a track, there is at least 15 seconds remaining before LoWC, approximately corresponding to the late threshold for the warning alert (see Table 2-21 in the MOPS for Detect and Avoid (DAA) Systems). For encounters with a FOR entry time margin more negative than -10 seconds, the intruder only becomes detectable well after LoWC has already occurred, and is thus unlikely to be affected by how long it takes for the radar to establish a track.

C.4 RESULTS

As illustrated in Figure C-3, out of 106,319 LoWC encounters, 7,611 (7.2%) involved an intruder entering the FOR within the RDR. Approximately half of these (3,527 encounters, 3.3%) could be affected by the 15-second delay for radar to establish a track.

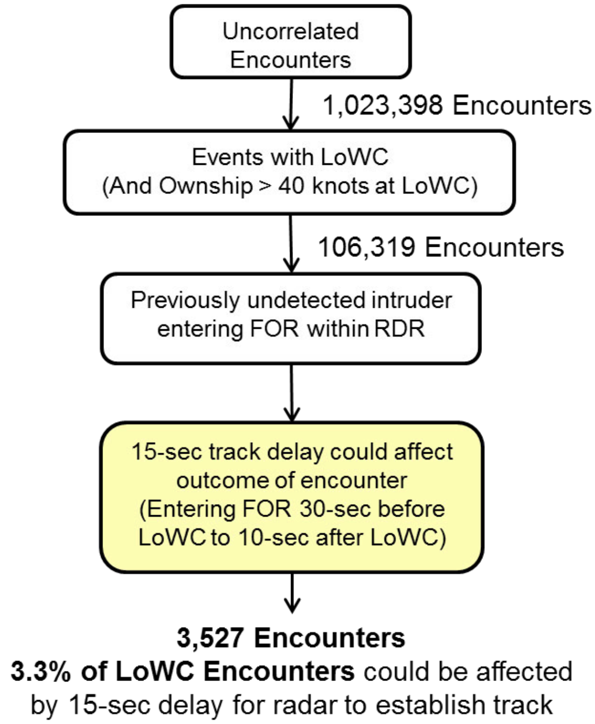


Figure C-3 **Encounter Counts and the Associated Probability w/r LoWC**

A histogram of the distribution of LoWC encounters based on the time margin from intruders entering the radar FOR to the initial LoWC is shown in Figure C-4.

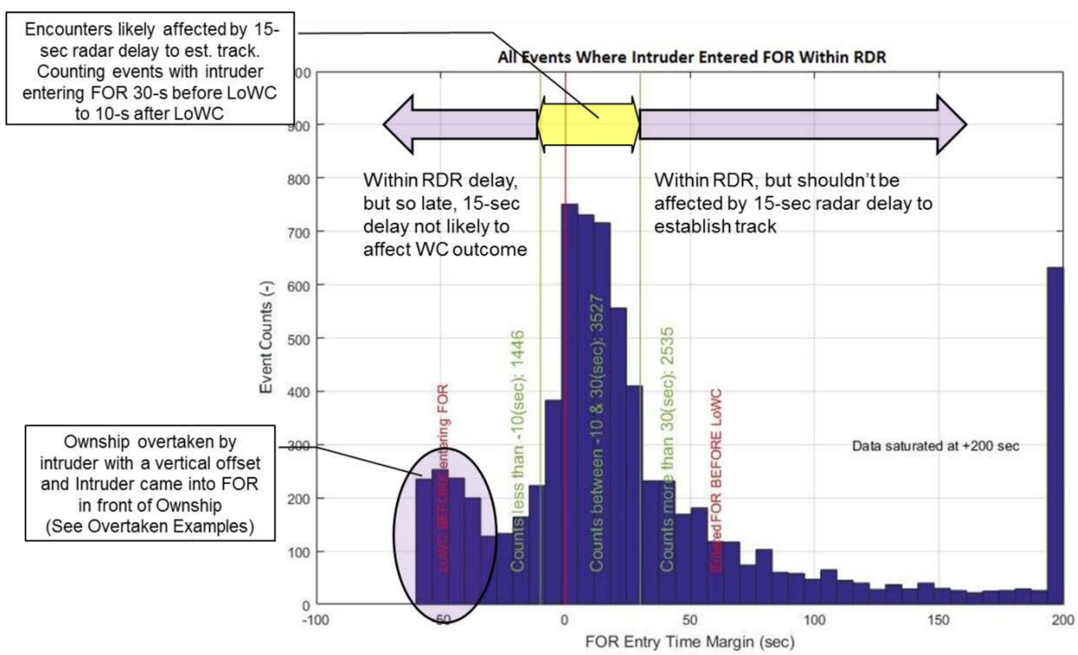


Figure C-4 **Encounter Distribution Based on Intruder FOR Entry Time Margin**

Encounters with high positive FOR entry time margin are not expected to be adversely affected by the 15-second delay for the radar to establish a track and should be able to declare/display the intruder track before the DAA late warning alert. Additionally, encounters with LoWC occurring significantly before the intruder entering FOR (negative FOR entry time margin) are not likely to be affected by the 15-second delay for the radar to establish a track since LoWC has already occurred. These are predominantly geometries where the UA ownship is overtaken by the intruder with some vertical offset, and the intruder enters the radar FOR in front of the ownship well after LoWC has already occurred. An example of these overtaken encounters causing very late FOR entry is shown in Paragraph C.5.4.

3,527 encounters (3.3% of LoWC encounters) are potentially affected by the 15-second delay for the radar to establish a track. Further breakdown by the UA ownship maneuvering history (if >200’ Altitude (Alt) change or >20° Heading (HDG) change) within the 20 seconds prior to intruder entering FOR within the RDR is provided in Figure C-5, below. Clearly these critical encounters are mostly composed of the ownship turning. Note the uncorrelated encounter set’s weighting was also applied to compute the weighted probability.

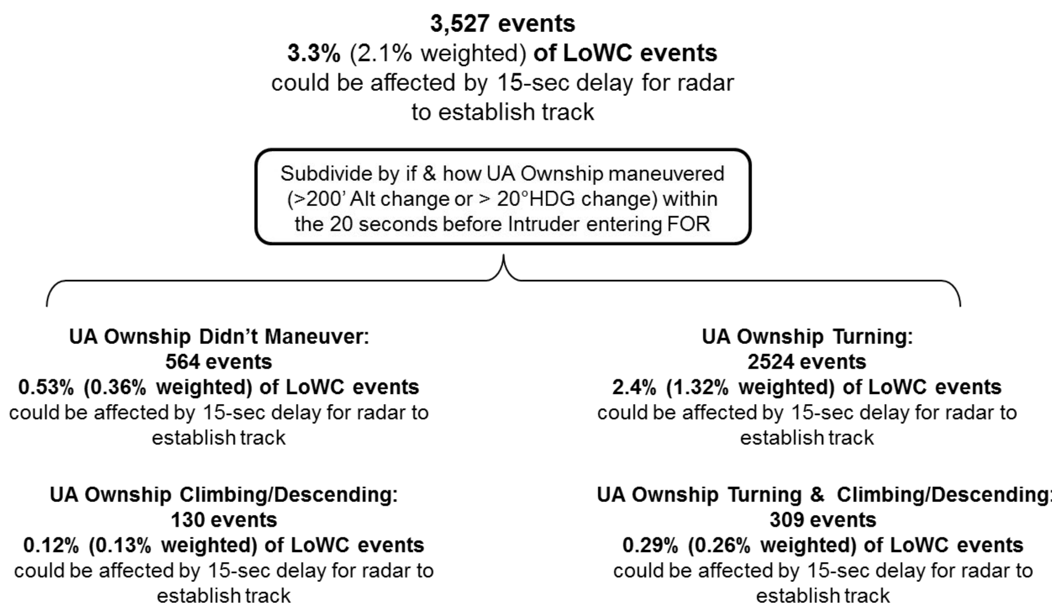


Figure C-5 Ownship Maneuvers within 20 Seconds Before the Intruder Enters the FOR

C.5 EXAMPLE ENCOUNTER GEOMETRIES

Several example encounter geometries that are potentially affected by the 15-second delay for the radar to establish a track are discussed in this section. Additionally an overtaken geometry, representing the very late FOR entry time margin encounters, is also provided in this section.

C.5.1 UA Ownship Turning Into Intruder

A co-planar LoWC encounter where the UA ownship turned into the intruder is illustrated in Figure C-6. In this geometry, well after the ownship commenced turning, the intruder entered the UA’s FOR 3 seconds prior to LoWC. Compounding the time required for the radar to establish a track with the low probability of the intruder visually detecting the UA ownship, this non-cooperative encounter would likely have resulted in late or no alert and a LoWC.

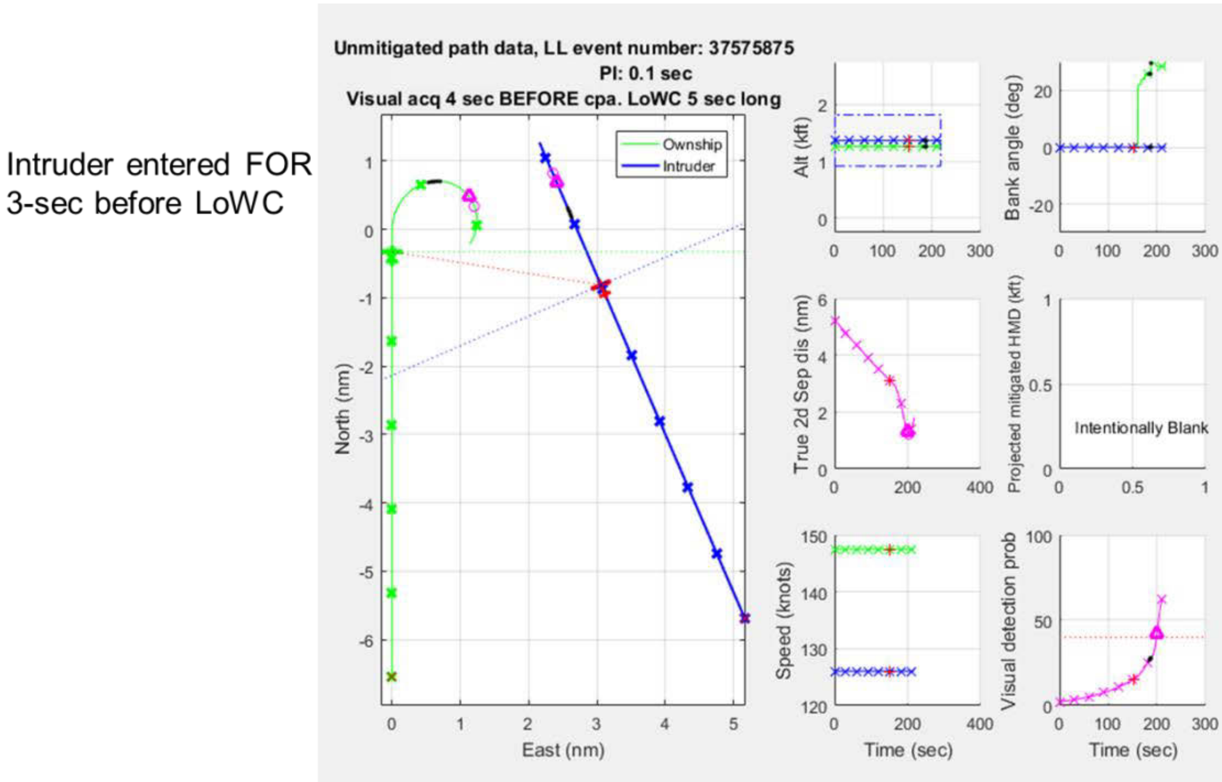


Figure C-6 **Sample Encounter with the UA Turning Into an Intruder**

C.5.2 Intruder Approaching from beyond 110° Azimuth Limit

A nearly co-altitude, non-maneuvering geometry that resulted in the intruder entering FOR within the RDR is shown in Figure C-7. In this example, the faster intruder approached from beyond the steady UA ownship's 110° azimuth limit. By the time the intruder entered the radar FOR, there is only a 7-second margin before LoWC. However, it should be noted in this geometry, the intruder would likely have visually detected the slower UA and maneuvered to maintain separation.

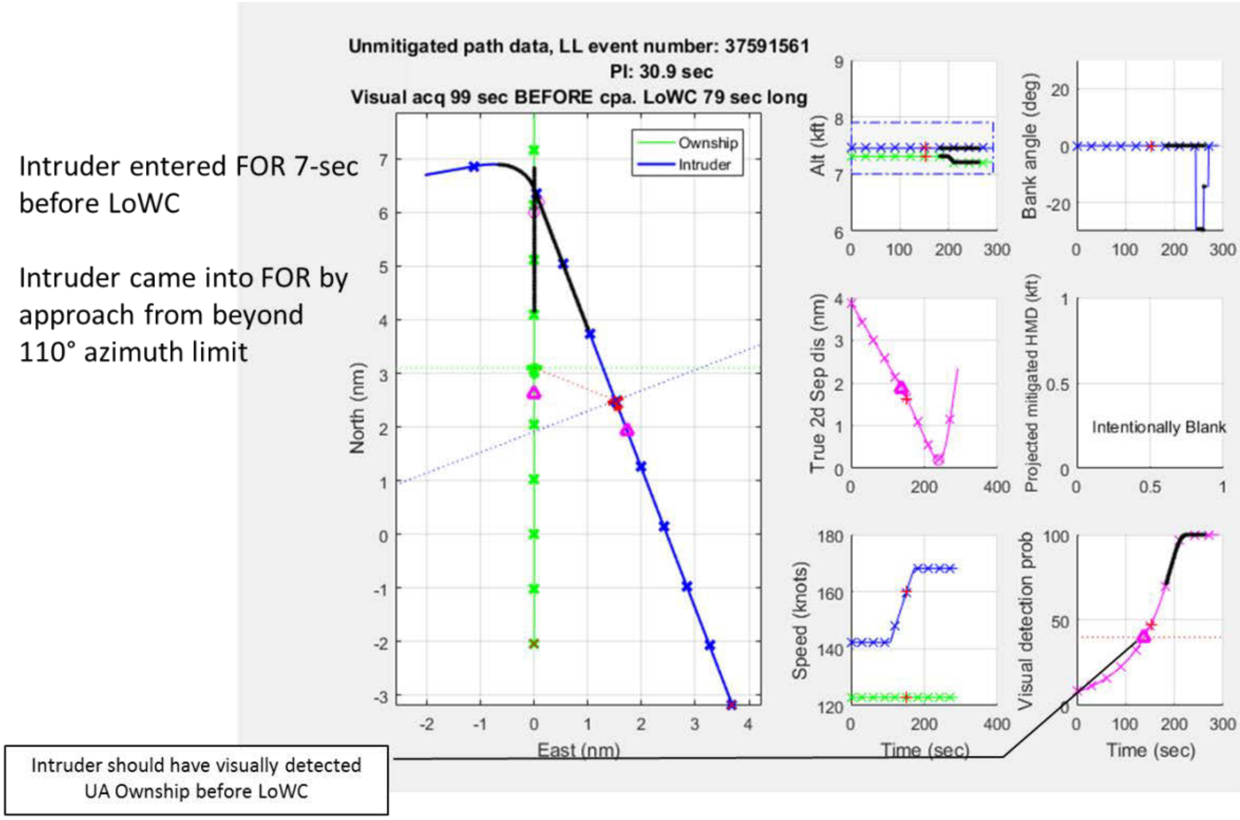


Figure C-7 **Sample Encounter with an Intruder Approaching from Beyond 110°**

C.5.3 Vertically Converging and Approaching from Beyond 15° Elevation Limits

A vertically closing geometry potentially causing late or no-detection hazard is shown in Figure C-8. In this shallow aspect, low-horizontal closure rate encounter, even though the slower intruder was located in the front hemisphere of the UA ownship, it was vertically positioned outside of the radar elevation limits. At 6 seconds before LoWC, the intruder finally came within the 15° elevation FOR limit of the UA radar. In this case, the intruder was very unlikely to have visual detection on the UA ownship.

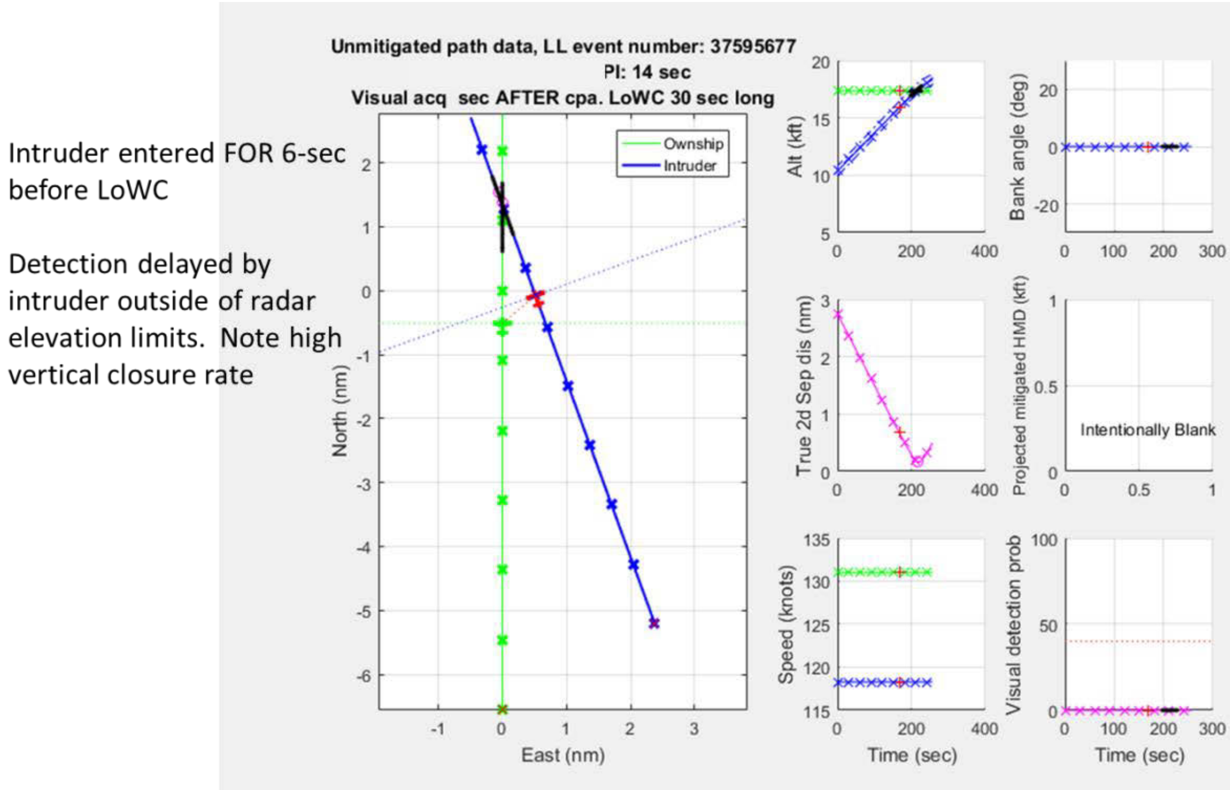


Figure C-8 **Sample Encounter with an Intruder Vertically Converging from beyond 15°**

C.5.4 Overtaken

An overtaken encounter geometry is shown in Figure C-9. In this example, the faster intruder persisted just beyond the 110° azimuth limit before LoWC. The vertical offset further keeps the intruder beyond the 15° elevation limit as the range decreased between the two aircraft. It is not until 33 seconds after LoWC that the intruder appears in the UA's FOR. Fortunately the intruder should have visually detected the UA well before LoWC and have mitigated to maintain separation.

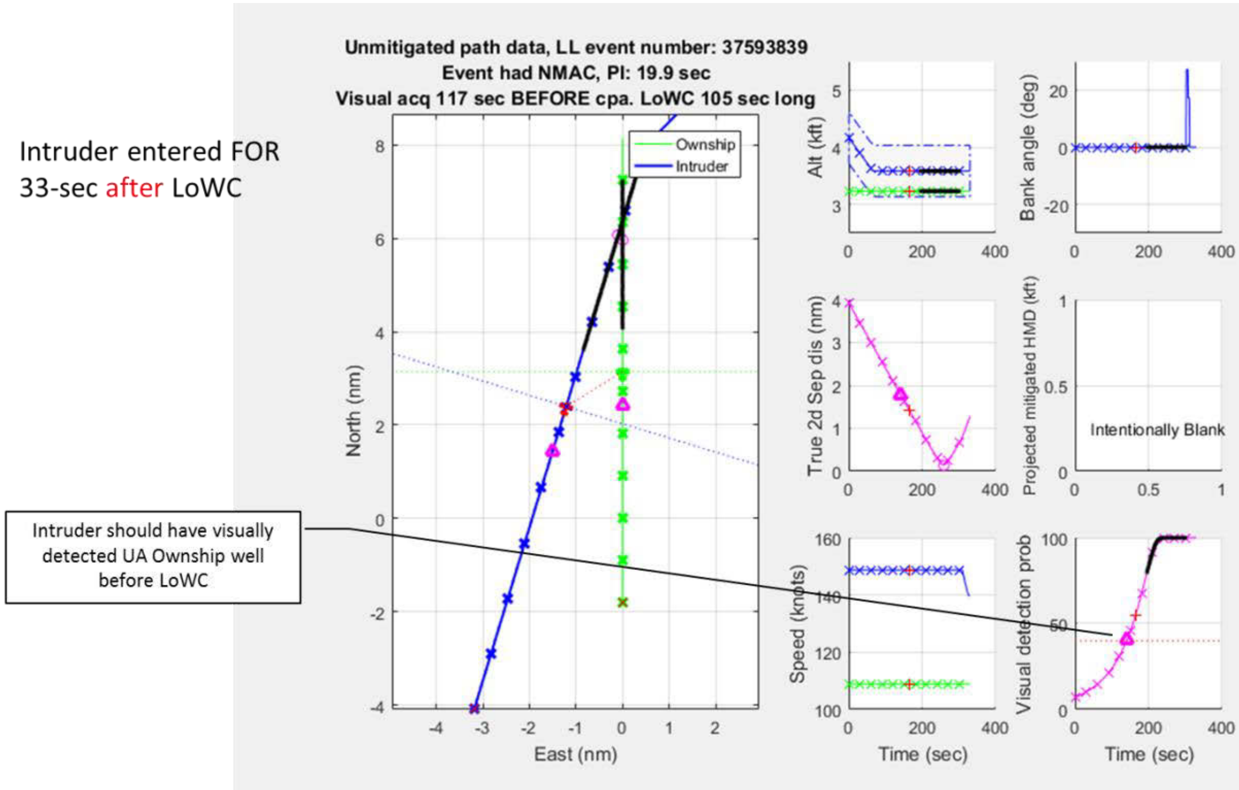


Figure C-9 **Example Encounter with an Intruder Overtaking the UA with a Vertical Offset**

C.6 CONCLUSIONS

An M&S effort was carried out to estimate the probability of non-cooperative LoWC encounters where the intruder enters the UA ownship's FOR within the RDR using uncorrelated encounters. More specifically, those encounters that are potentially affected by the 15-second delay for the DAA radar to establish a track are counted and examined.

These encounter geometries involved initially low-aspect approaches (small HDG difference) including variations and combinations of:

- The UA ownship turning into an intruder
- Vertically converging from beyond the radar's 15° elevation limit
- Horizontally converging from beyond the radar's 110° azimuth limit
- An intruder overtaking the UA ownship.

For some encounters, the intruder would likely have visual detection of the UA ownship well before LoWC and is expected to have maneuvered to maintain separation. It was estimated that 3.3% (2.1% weighted) of LoWC encounters are potentially affected by the 15-second delay for the radar to establish a track, and most of these involve the UA maneuvering and turning toward the intruder.

Given the low probability of LoWC encounters involving non-cooperative intruders that enter the radar FOR within the RDR and are affected by the 15-second delay to establish a track resulting in late or no detection and LoWC, it is doubtful if additional resources and requirements need to be specified in the Phase 1 MOPS to address such cases. Furthermore, requirements to shorten this 15-second delay to establish a track will only provide marginal improvement. Operations involving more ownship maneuvering such as surveying or flights in the terminal area and those identified in Phase 2 Terms of Reference are expected to generate higher probability of such conditions. Radar manufacturers and UA system integrators are encouraged to examine the cost and options to address these concerns. Mitigations might include but are not limited to:

- Shifting the radar scan pattern to allocate more frequent scans to look into the turn thus shortening the time to establish a track
- Limiting the UA ownship's bank angle and/or turn rate.

C.7 REFERENCES

The UAS Executive Committee Science and Research Panel (SARP) based the DAA Well Clear (DWC) definition partly on their analysis of five million uncorrelated airborne encounters. These files are stored on a secured web directory maintained by the Massachusetts Institute of Technology Lincoln Laboratory (MIT LL) at https://topa.atc.ll.mit.edu/lldata/EncounterData/, and access is available upon request. A detailed guide to using the files, Guide_to_the_Well_Clear _encounter_files.docx, is also available. For access to these files, please contact the RTCA Special Committee 228 (SC-228) Work Group 1 Document Manager.

D APPENDIX D VALIDATION OF RDR AGAINST DAA ALERTING REQUIREMENTS

The Detect and Avoid (DAA) Radar Declaration Range (RDR) specifications as outlined in Paragraph 2.2.7 were based on a 40-second allocation for pilot reaction (coordination with air traffic control plus maneuver command input) and the subsequent 3 degree-per-second (°/s) Unmanned Aircraft (UA) turn to maintain DAA Well Clear (DWC). These requirements are expressed as range values and specified for head-on intruders of three different sizes, along with their corresponding speeds. For intruders approaching from other bearing angles, RDR correction factors are applied to the head-on RDR requirements (see Table 2-4). As a result, the RDR requirements are a function of intruder speed (size) and bearing angle to the intruder. This appendix examines whether the RDR requirements subject to radar Field of Regard (FOR) limitations allow sufficient time for DAA alerting prior to a Loss of Well Clear (LoWC).

D.1 EXTRACTION OF RDR TIME MARGIN (RTM) BEFORE LOSS OF WELL CLEAR

To validate the RDR requirements, the time elapsed after crossing the RDR threshold while within the radar angular FOR limitations until the initial LoWC was extracted for 25,000 uncorrelated encounters. These encounters included linear (non-accelerating and nearly co-altitude) trajectories as well as accelerating (turning and vertically converging) flight paths. As illustrated in Figure D-1 for each encounter, the time index corresponding to the initial LoWC was first recorded as t_{LoWC}. The simulation then searches from t_0 to t_{LoWC} for the first instance in the encounter when RDR and FOR as specified in these Minimum Operational Performance Standards (MOPS) for DAA Air-to-Air Radar for Traffic Surveillance are both satisfied according to the intruder speed and bearing angle from the UA ownship to the intruder. As such, the RTM before LoWC can be extracted and recorded for each encounter resulting in unmitigated LoWC. The RTM before LoWC for each encounter can then be plotted against the corrective alerting metrics outlined in Appendix L of the DAA MOPS.[8] It should be noted that this does not specifically account for the time required to establish intruder tracks, nor does it check if the intruder remains within the FOR and RDR before reaching LoWC. Thus, the extracted RTM should represent the optimistic assessment of the Radar MOPS performance against the corrective DAA alerting timeline.

[8] Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems (RTCA Paper No. 261-15/PMC 1400)

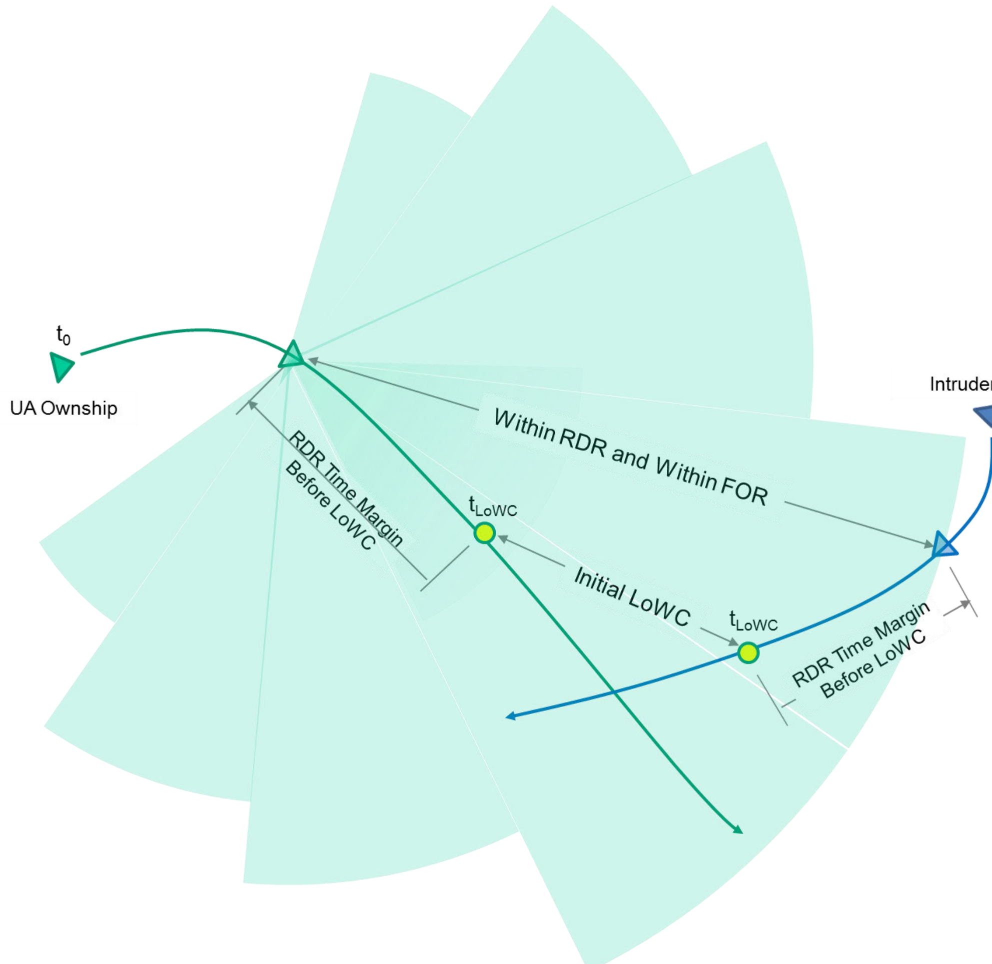


Figure D-1 **RDR Time before LoWC against Corrective Alerting Requirements**

The resultant RTM before LoWC for each encounter is binned according to intruder speed range and bearing to the intruder and plotted against the Minimum Average Corrective Alert Time at 50 seconds before the Hazard (HAZ) and corrective late alert threshold at 20 seconds before HAZ (see Appendix L of the DAA MOPS).

As shown in Figure D-2, below, the RTM before LoWC for each encounter is compared against the minimum average corrective alert time and late corrective alert threshold (20 seconds before HAZ violation) as functions of UA ownship speed.

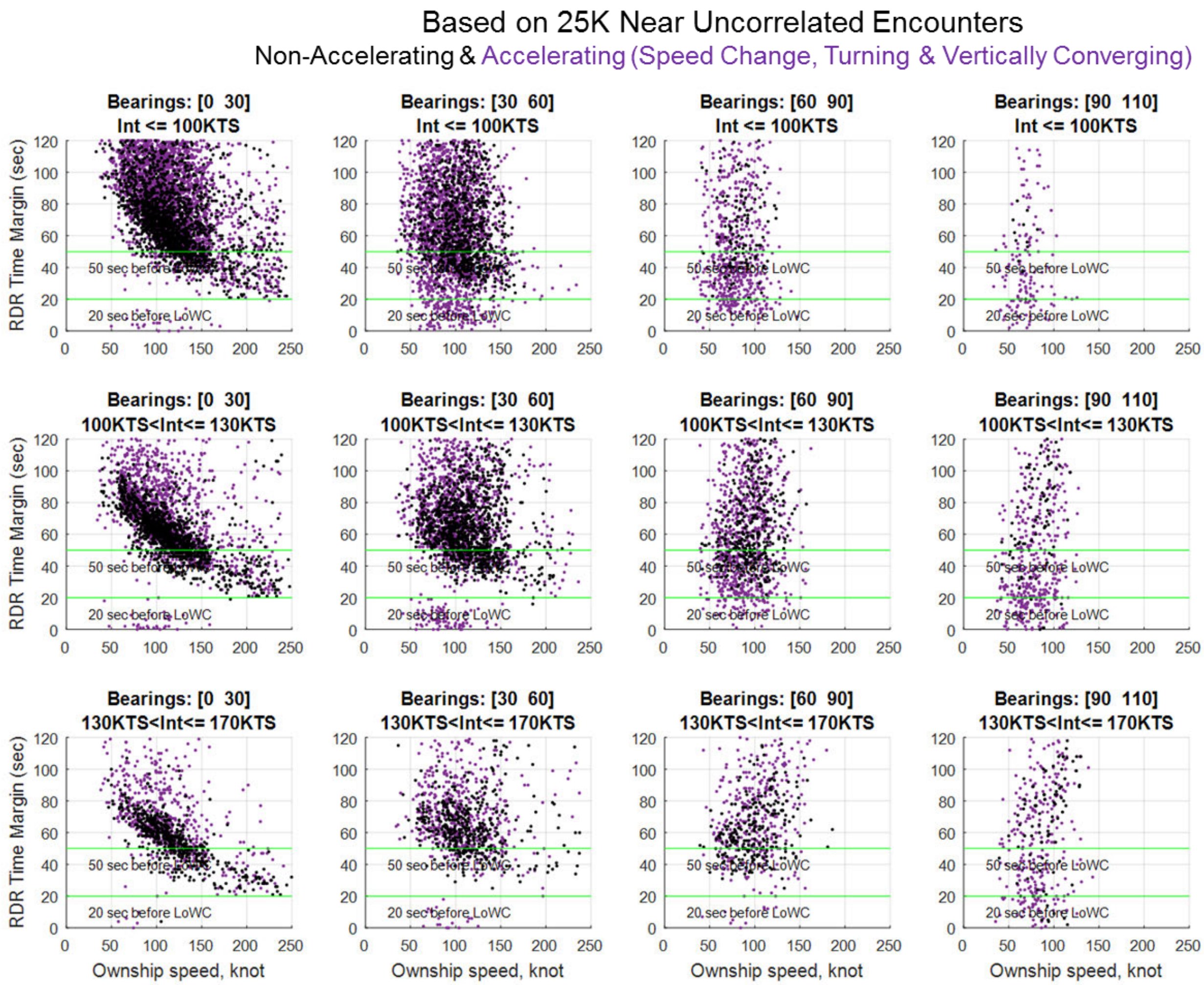


Figure D-2 **RTM vs. Corrective Alerting Thresholds (Radar MOPS vs. DAA MOPS)**

For non-accelerating encounters, the RDR requirements, as specified in Paragraph 2.2.7, appear to easily meet the late corrective alerting threshold requirement of 20 seconds before LoWC. Even if considering accelerating (turning and/or vertically converging) trajectories, the RDR requirements are only stressed in outlier cases that result in insufficient time margin leading to late corrective alerts. Furthermore, visual inspection of the scatter of RTM against the average corrective alert time of 50 seconds prior to LoWC indicates that the RDR performance should provide sufficient margin for the average corrective alerting timeline.

Expanding to sampling over 100,000 (100K) uncorrelated encounters involving LoWC, over 77% of the intruders came within the radar's FOR and RDR limits before the minimum average corrective alert time. Additionally, the radar compliant with these MOPS would have detected 94% of intruders before crossing the corrective late alert threshold. Only in 1.1% of encounters was the intruder never detected. Further investigation into the late- and no-detect cases indicated these scenarios were often a result of "overtaken" geometry with the faster intruder approaching from astern remaining undetected by the radar due to the ±110° azimuth limitation. These intruders may be subsequently detected by radar at other bearing angle sectors and sometimes in the separating phase of the encounter. These observations indicate the effects of no FOR for intruders approaching from astern.

Figure D-3 below compares the percent of encounters having the intruder currently within the radar's FOR and RDR thresholds at different stages of the encounter versus the probability that the intruder had previously met radar detection conditions. Prior to 30 seconds before LoWC, RDR is the dominant limiting factor over the FOR limitations. By 15 seconds prior to LoWC, the radar compliant with these MOPS would have detected the intruder for over 95% of intruders sometime in the encounter.

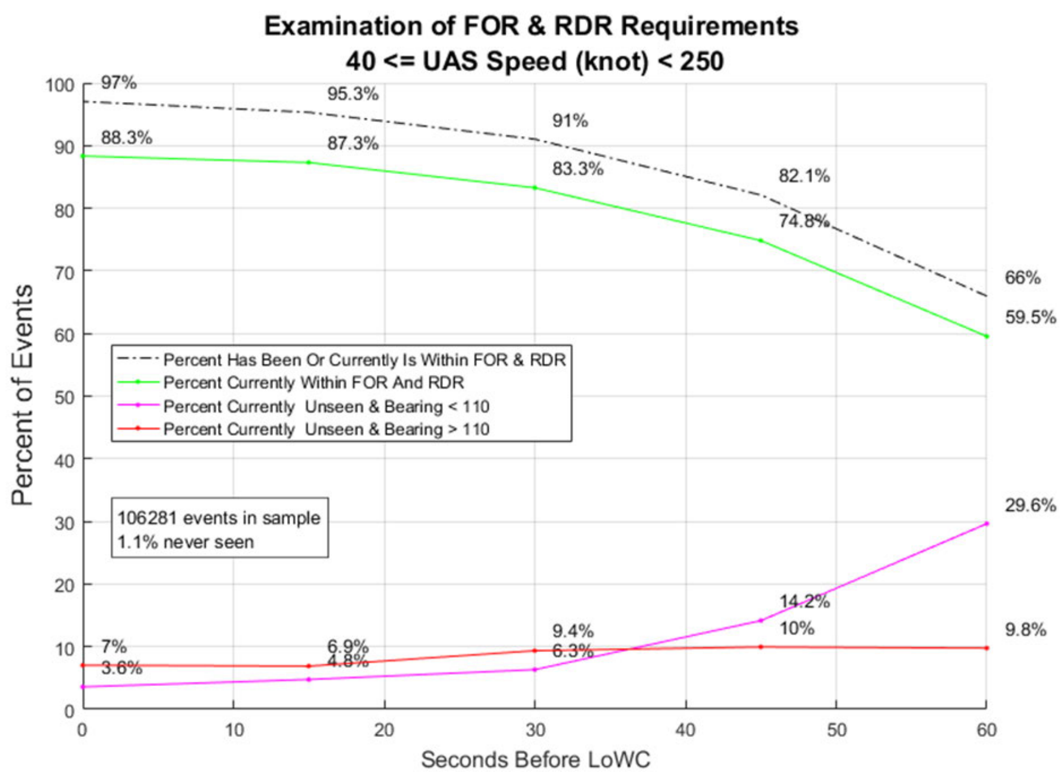


Figure D-3 **P(Meeting RDR and FOR Thresholds at Different Stages of LoWC Encounter)**

However, the detection performance of the radar compliant with these MOPS with respect to the DAA corrective late alert threshold (20 seconds before LoWC) is not uniform across the UA ownship speed range (40 to 250 Knots (Kts)). Aggregating the encounters by UA ownship speed, the effects of radar FOR causing late- or no-detection events becomes more apparent for slower UAs. In Figure D-4 below, for slow UAs operating in the 40-60-Knot range, a higher probability of late- or no-detect events is expected than UAs operating in the higher speed range. This observation is traceable to the slower UAs having a higher probability of encountering fast intruders approaching from astern beyond the radar's FOR as mentioned earlier.

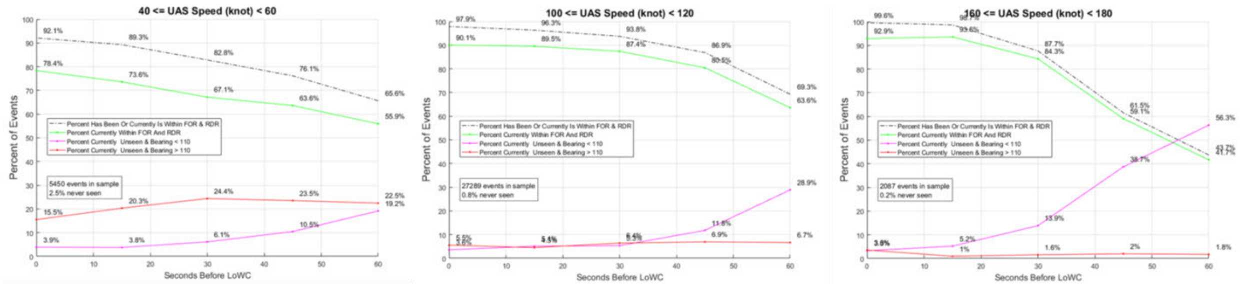


Figure D-4 **Comparison of Probability of Detection for Different UA Ownship Speeds**

In lieu of these observations, slower UAs will have higher rates of late alerts and no alerts than faster UAs given radar FOR limitations.

D.2 POSSIBLE EXCESSIVE FRONTAL RDR PERFORMANCE REQUIREMENT FOR SLOWER UAS

It is understood that the development of the RDR requirements had consolidated the effects of UA speed by adopting the highest RDR requirement across the UA speed range analyzed (50 to 200 Kts). Consequently, for frontal encounters (intruder approaching from bearing 0° to 30°), the high-speed (200 Kts) UA RDR requirements are carried over to slower UA applications (see Figures B-6, B-13, and B-20). While conservative in approach, the resultant RDR requirements appear to impose excessive frontal radar performance for slower UA operating in the 50 to 100-Knot range. As shown in Figure D-5 below, this is evident in the distribution of RTM for UA flying below 100 Kts across the range of intruder speeds analyzed. Transformed to the range domain, there appears to be 1 to 1.5 NM of unnecessary frontal RDR requirements corresponding to the rounding-up of RDR requirements across all UA speeds seen in Figures B-6, B-13, and B-20.

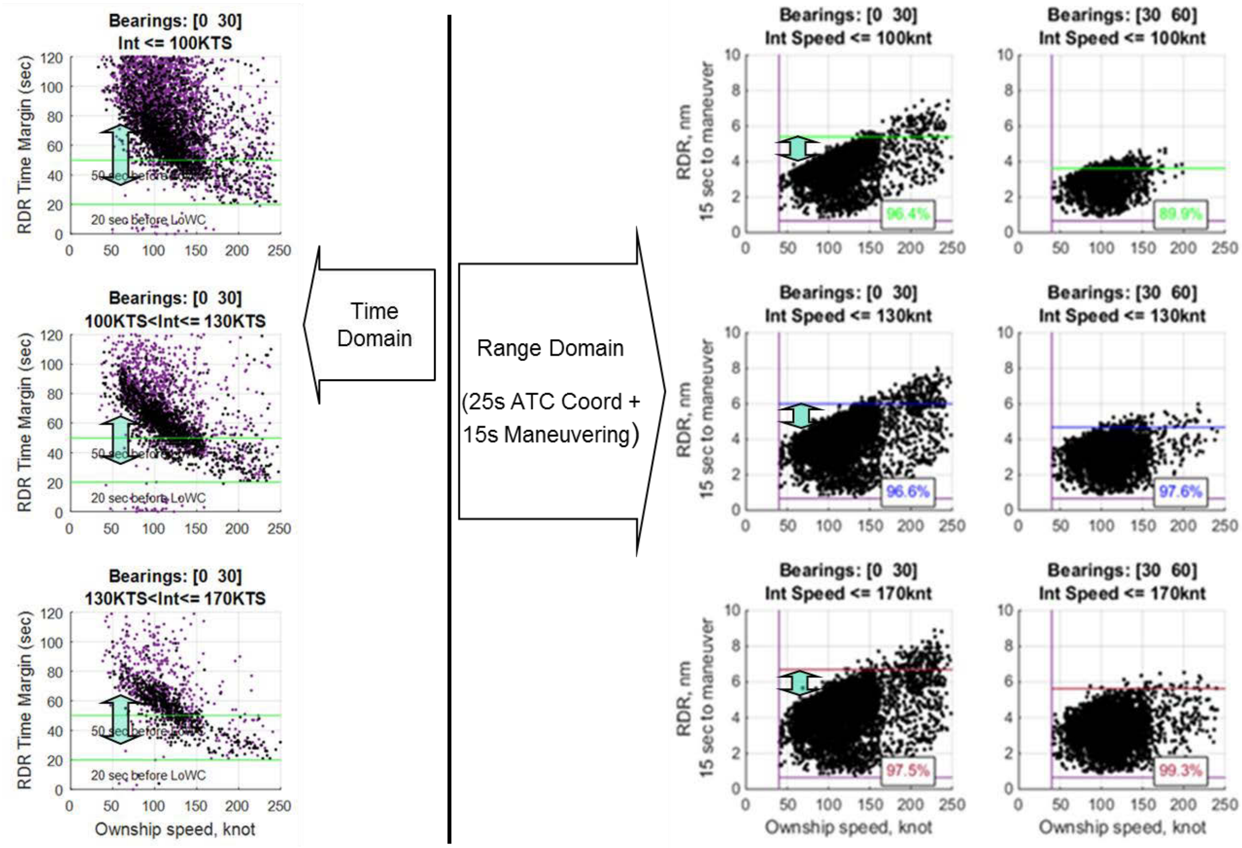


Figure D-5 **Excessive Frontal RDR Performance Requirements for Slow UAs**

E APPENDIX E AIRCRAFT RADAR CROSS-SECTION SIMULATION IN SUPPORT OF THESE MINIMUM OPERATIONAL PERFORMANCE STANDARDS

E.1 INTRODUCTION

The purpose of this appendix is to provide guidance to the radar manufacturer about the Radar Cross-Section (RCS) values for Detect and Avoid (DAA) air-to-air radar design. The Minimum Operational Performance Standards (MOPS) for DAA Systems categorizes intruders as follows:[9]

1. Small, which includes gliders, balloons, etc., and a representative true airspeed up to 100 knots
2. Medium, which includes single-engine aircraft, and a representative true airspeed up to 130 knots
3. Large, which includes dual-engine and larger aircraft, and a representative true airspeed up to 170 knots.

Subsection E.4 provides some public references for RCS measurements and evaluations. In Subsection E.2 and E.3, results from two simulations are presented to support the development of these MOPS.

E.2 FIRST SIMULATION STUDY

Below are the approach and results of the RCS simulation of a representative sample for the aircraft categories listed above. The analysis was performed to support the development of these MOPS and provide the DAA radar manufacturers with design references.

E.2.1 Approach

A commercial Computer Simulation Technology (CST) Microwave Studio was used to simulate the RCS of the Computer-Assisted Design (CAD) airplane models acquired from 3dcadbrowser (http://www.3dcadbrowser.com). First, the CST simulation accuracy was validated by comparing it with the rigorous diffraction theory that calculates the scattered electromagnetic field generated by a bullet-like shape (E.F. Knott, et.al., *Radar Cross Section*, 2nd edition, Artech House, 1993, p.564). A good agreement was found, as seen in Figure E-1.

[9] Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems (RTCA Paper No. 261-15/PMC 1400)

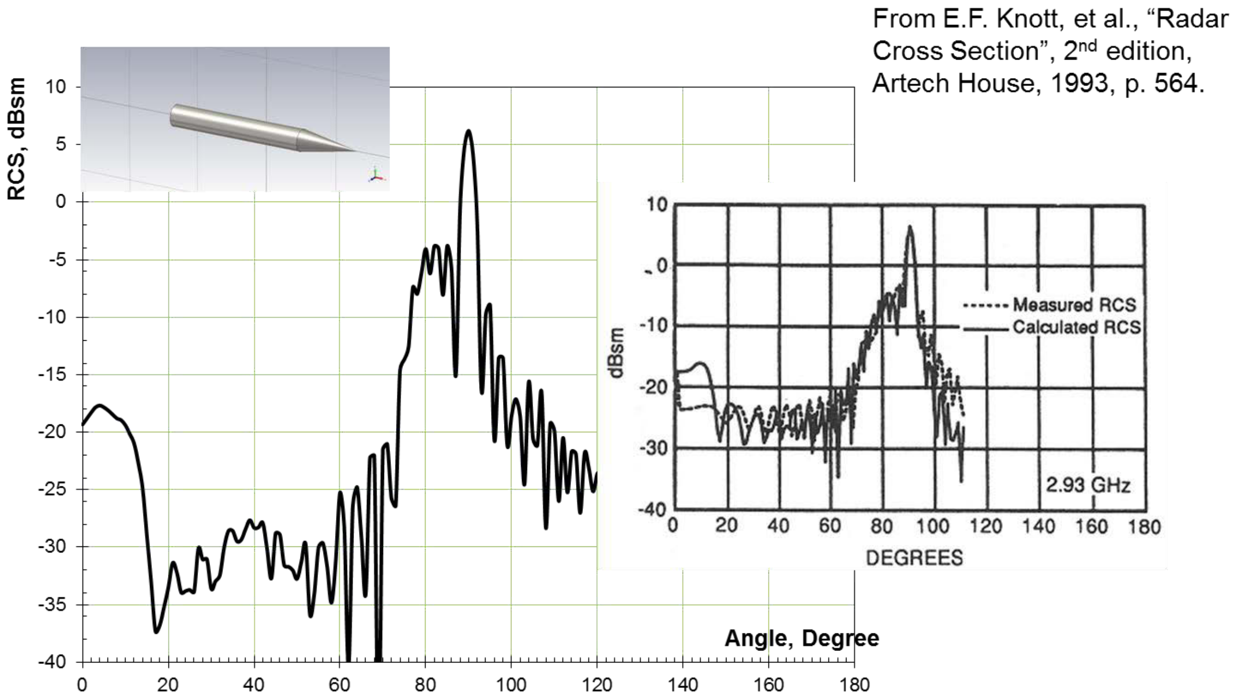
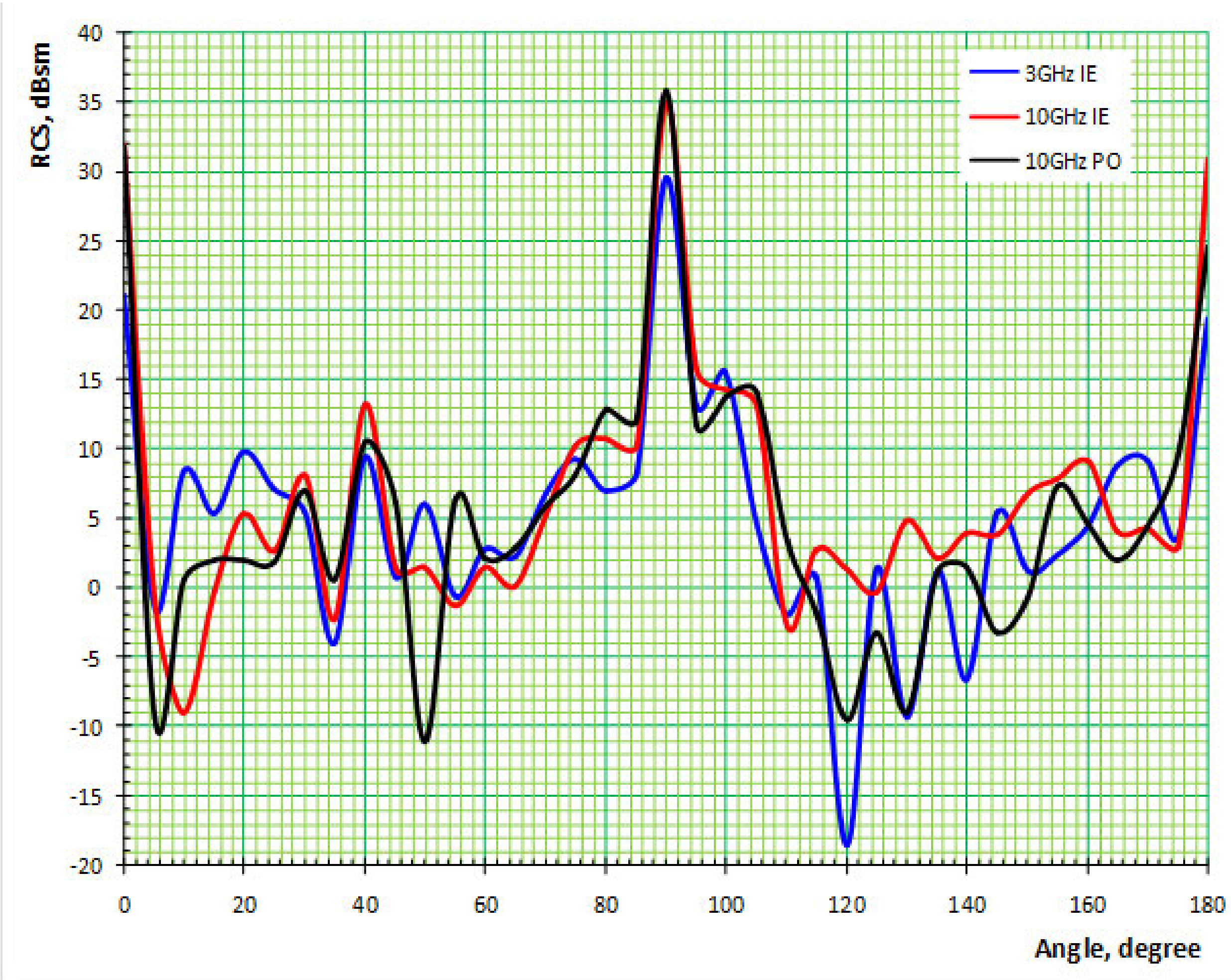


Figure E-1 RCS Simulation of a Bullet-like Shape (Upper Left) vs. Literature Data (Right)

In addition, two simulation approaches were compared: Integral Equations (EI) and Physical Optics (PO). A model of an Airbus 320 was used for the analysis. As seen from Figure E-2, IE and PO are in a good agreement, and PO was chosen as being significantly faster computationally. RCS at 3 Gigahertz (GHz) is also shown as a baseline.



<u>Figure E-2</u> **Comparison of IE and PO Computational Methods at 10 GHz**

The simulations were performed at three frequencies, 5 GHz, 10 GHz and 13 GHz, corresponding to the frequency bands specified in these MOPS.

The RCS simulation was performed in the horizontal plane due to the limited resources available. The aircraft RCS was simulated as a function of a horizontal look angle using a one-degree step, which is equal to or smaller than the angular sampling steps typically found in the open literature. The choice of horizontal plane (zero pitch and banking angles) defined by the aircraft axis is considered the most representative for the practical cases of DAA encounters. Nevertheless, for the "Medium" class aircraft simulation, a vertical plane was chosen. The choice was supported by the availability of some limited experimental data that provided further validation of the simulated data.

It is understood that while the RCS of any given intruder aircraft varies in a wide range for any given encounter, the variation is taken into account by the radar detection statistics (detectability factor), and the RCS average value can be chosen to represent a given class of aircraft. Notice that for the intruder aircraft on a collision course, the detected RCS remains nearly constant, corresponding to a Swerling 1 case.

To further validate the use of average RCS, the simulation data is presented in Figure E-3 according to relative frequency, and the resulting distribution (Gaussian best fit, as it happened to be for this case, is used to determine average RCS (see inset, upper left).

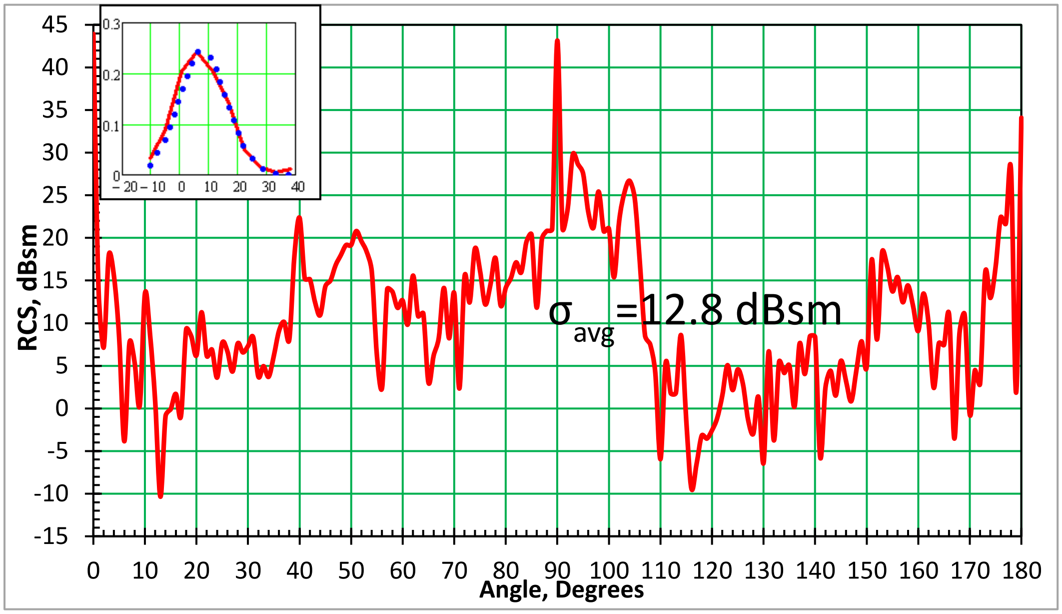


Figure E-3 **Distribution of RCS Simulation of Airbus 320 and the Best Fit Gaussian Curve**

E.2.2 Results

E.2.2.1 Small Intruder

A full-size glider model was chosen to represent "Small" class intruders, as shown in Figure E-4. The model parameters are shown in Table E-1.

Table E-1 **Small Intruder Model Parameters**

Length	14.6 Meters (m)
Wingspan	13.75 m
Average Fuselage Diameter	1.5 m
Cockpit Height	2 m
Material	Fiberglass-reinforced Epoxy

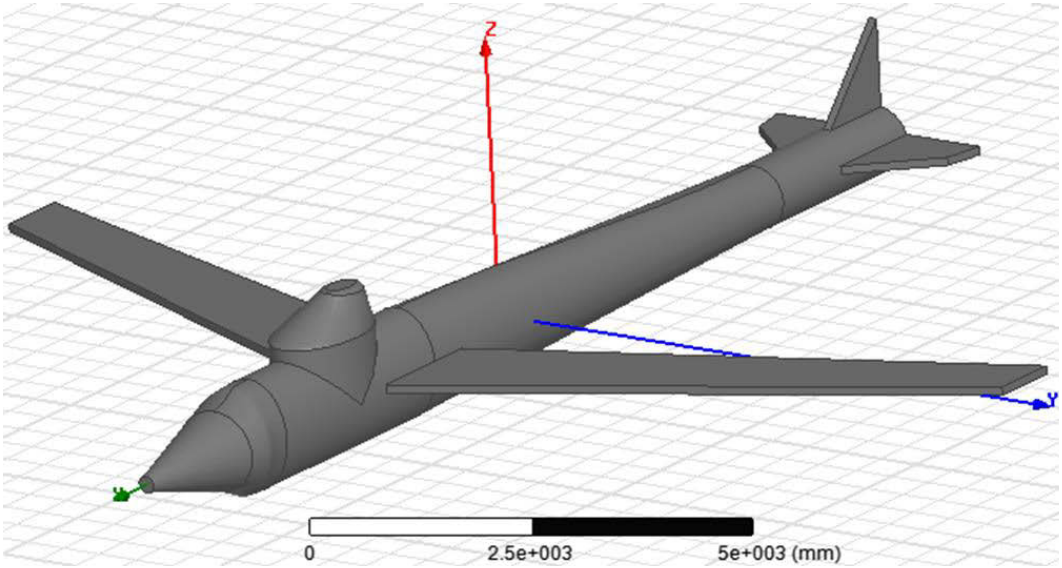


Figure E-4 **Full-size Glider Model used for Small RCS Simulation**

The results can be seen in Figure E-5; zero degrees is the radar look toward the aircraft nose. The average RCS for the three selected frequencies are shown in Table E-2. The probability distribution and inverse cumulative probability for 13 GHz can be seen in Figure E-6. The other two frequencies exhibited similar distributions.

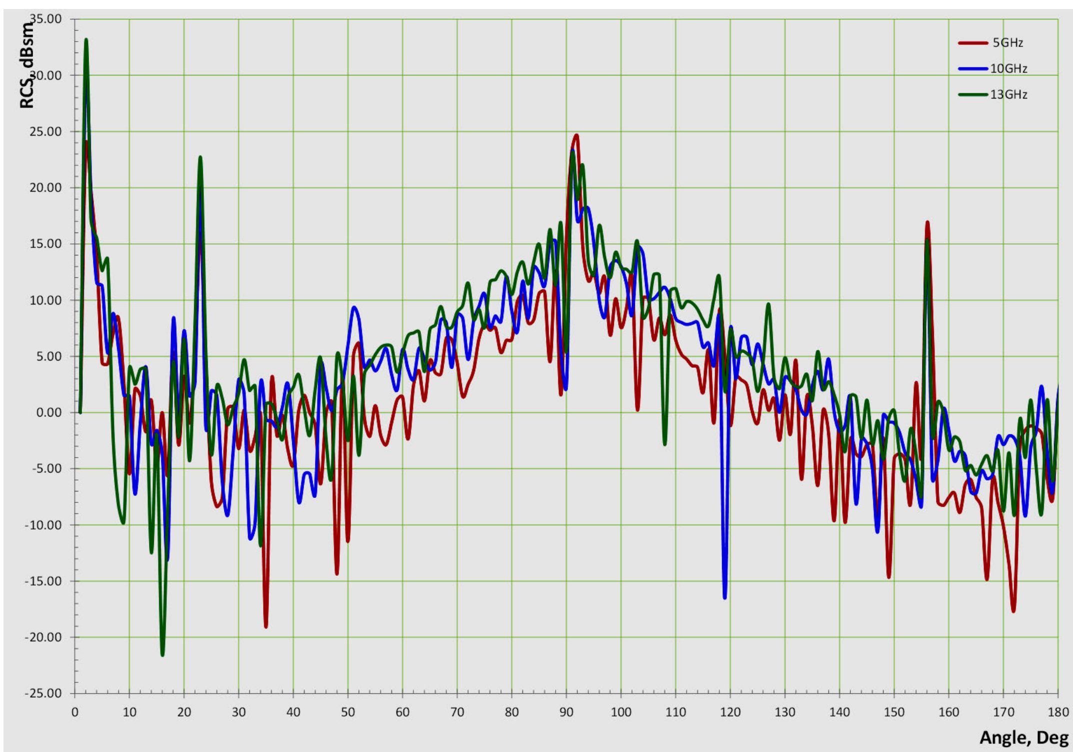
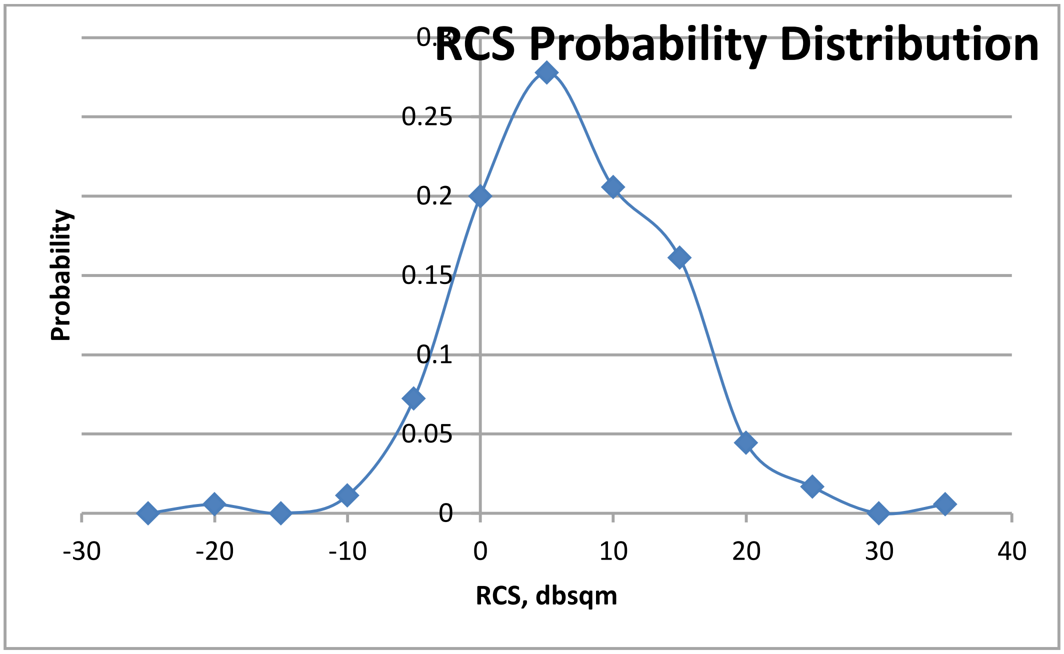


Figure E-5 **Small Intruder RCS Simulation Results for 5, 10, and 13 GHz**



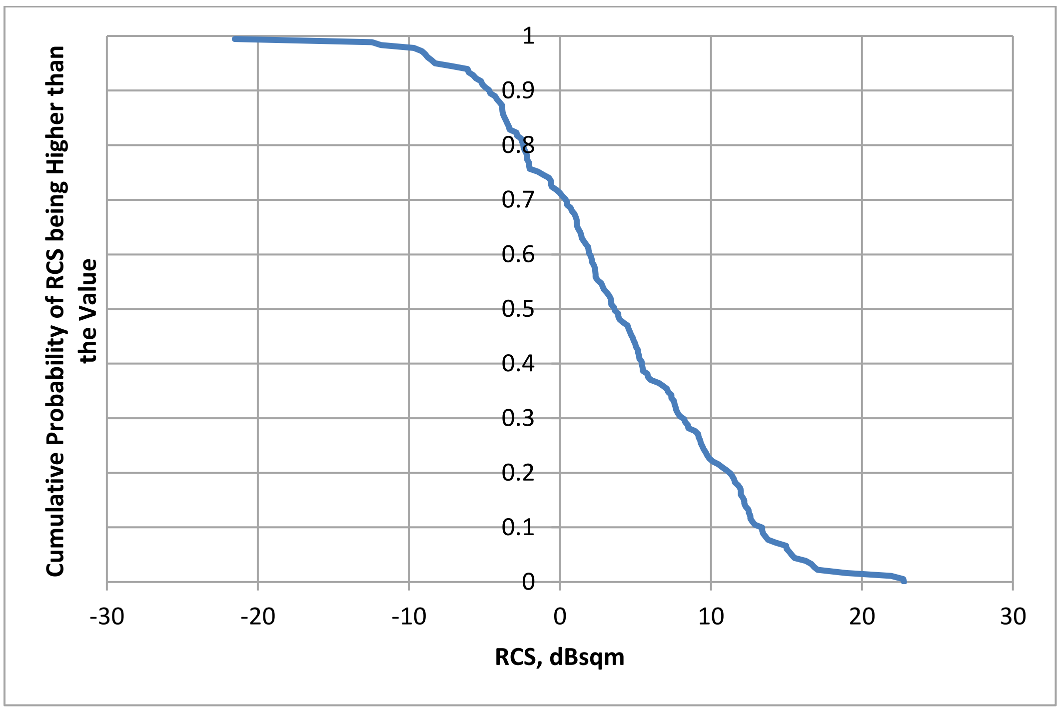


Figure E-6 Small Intruder RCS and Inverse Cumulative Probability Distributions (13 GHz)

Table E-2 Simulated Average Small Intruder RCS for 5, 10, and 13 GHz

Frequency	5 GHz	10 GHz	13 GHz
RCS, dBsm	0.9	2.8	4.0

E.2.2.2 Medium Intruder

A full-size model of a Boeing MD 530F helicopter was chosen to represent "Medium" class intruders, as depicted in Figure E-7. Table E-3 lists the model's parameters.

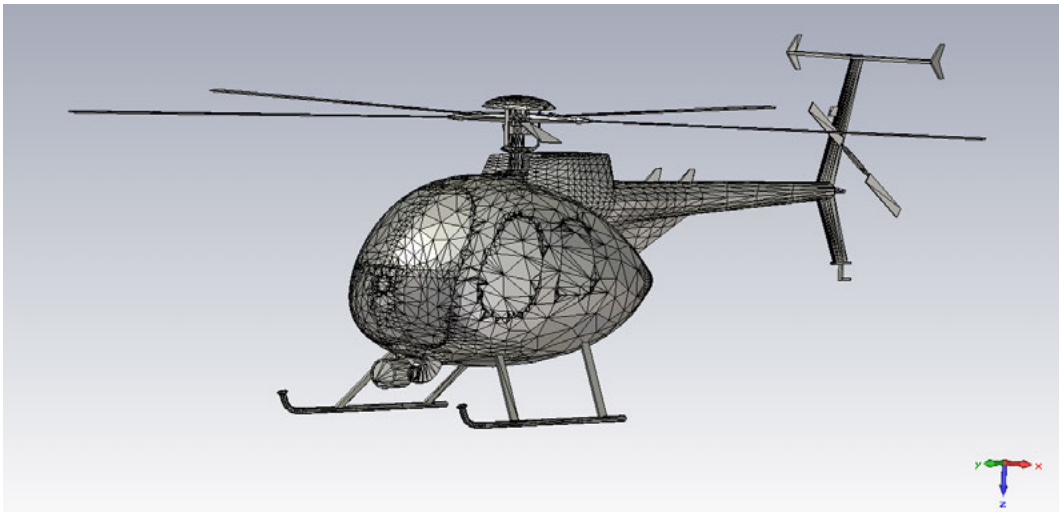


Figure E-7 Full-size Boeing 530F Helicopter Model used for Medium RCS Simulation

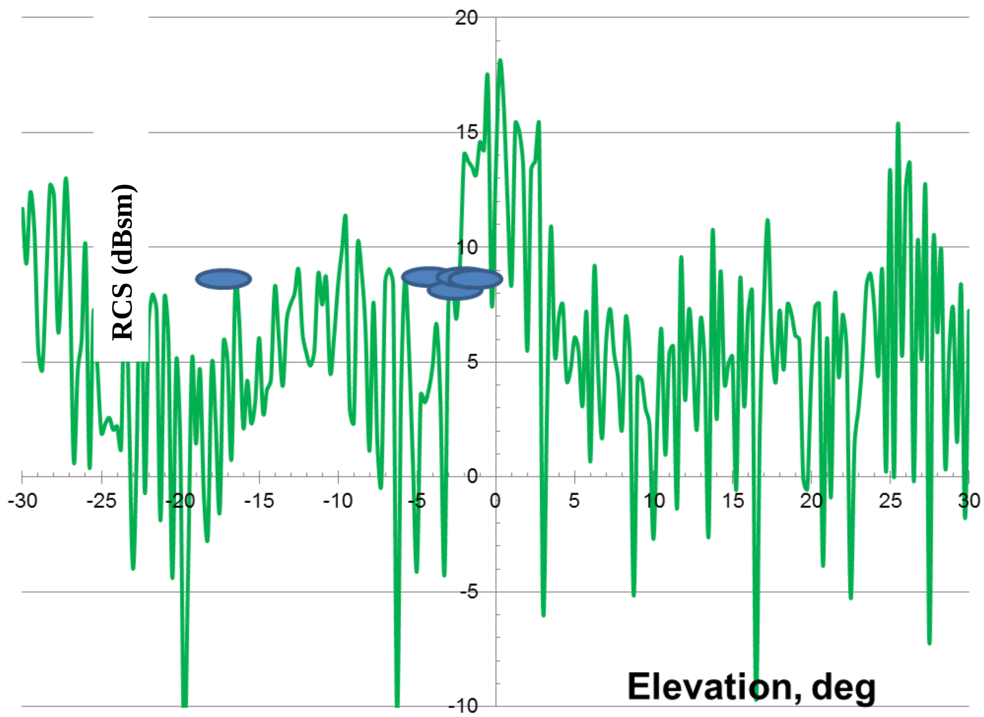
Table E-3 Medium Intruder Model Parameters

Length	**9.94m**
Height	**2.67m**
Fuselage Length	**7.49m**
Tail Plane Span	**1.65m**
Main Rotor Diameter	**8.33m**
Tail Rotor Diameter	**1.42m**

The simulation results can be seen in Figure E-8. The average RCS for 10 GHz is shown in Table E-4. The data for the other frequencies is not available, but expected to be similar. The probability distribution and cumulative distribution can be seen in Figure E-9.

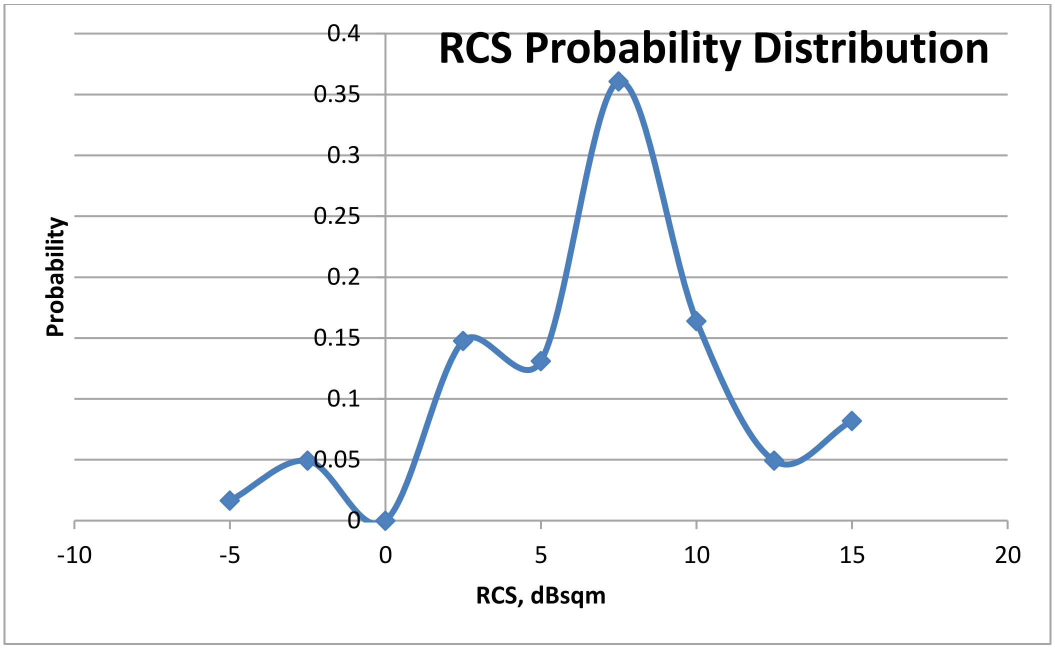
Table E-4 Simulated Average Medium Intruder RCS for 10 GHz

Frequency	5 GHz	10 GHz	13 GHz
RCS, dBsm	--	5.1	--



<u>Figure E-8</u> **Medium Intruder RCS Simulation Results**

Zero degrees is the radar's orientation, toward the aircraft nose. Blue ovals represent measured data points obtained by using ground based X-band radar. The intruder RCS probability distribution and inverse cumulative distribution are shown below.



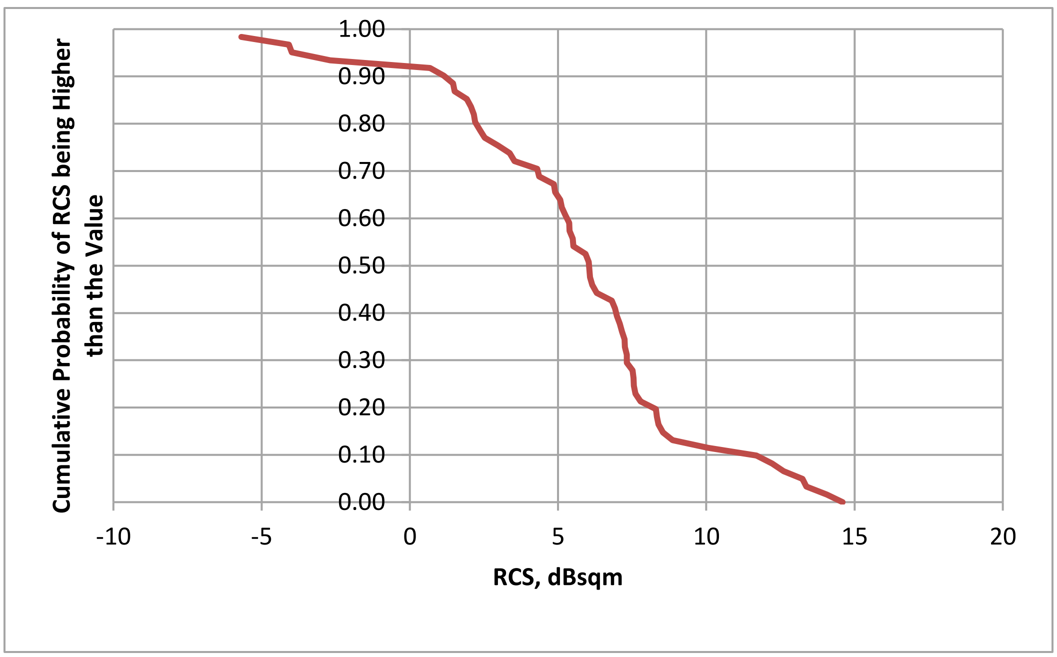


Figure E-9 **Medium Intruder RCS Probability and Inverse Cumulative Probability Distributions**

E.2.2.3 Large Intruder

A model of a full-size Cessna Citation was chosen to represent large class intruders, as shown in Figure E-10. The model's parameters are listed in Table E-5.

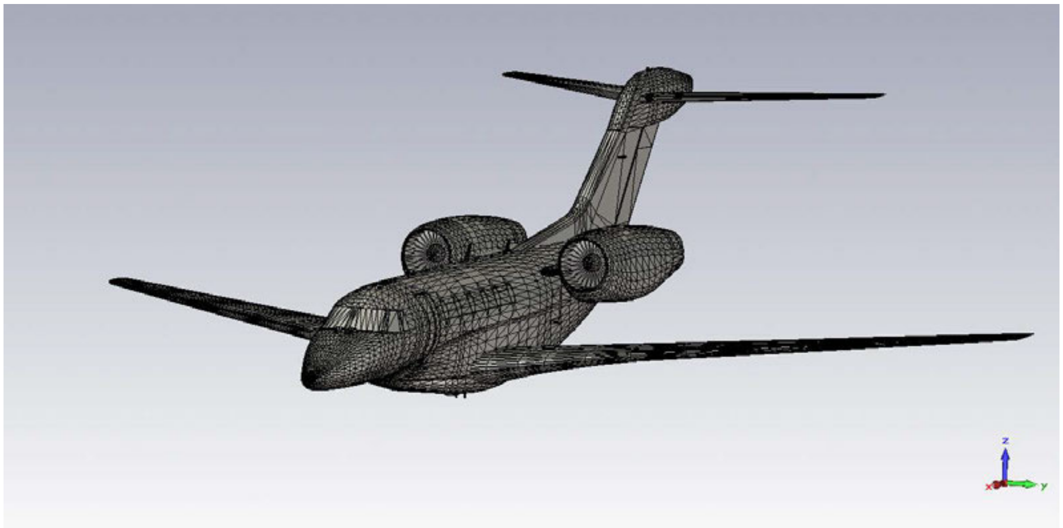


Figure E-10 Full-size Cessna Citation Model used for Large RCS Simulation

Table E-5 Large Intruder Model Parameters

Length	~18 m
Wingspan	~20 m
Compressor Diameter	~1 m

The simulation results can be seen in Figure E-11. Zero degrees is the radar's orientation, toward the aircraft nose. The average RCS for the three selected frequencies are shown in Table E-6, and the probability distribution is shown in Figure E-12.

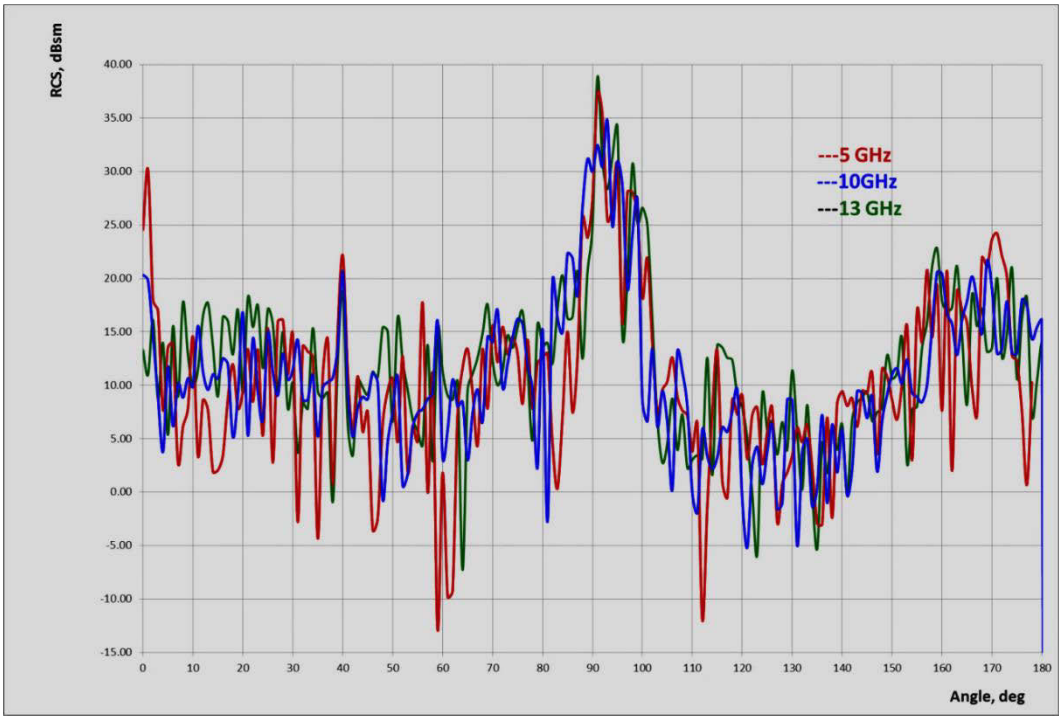
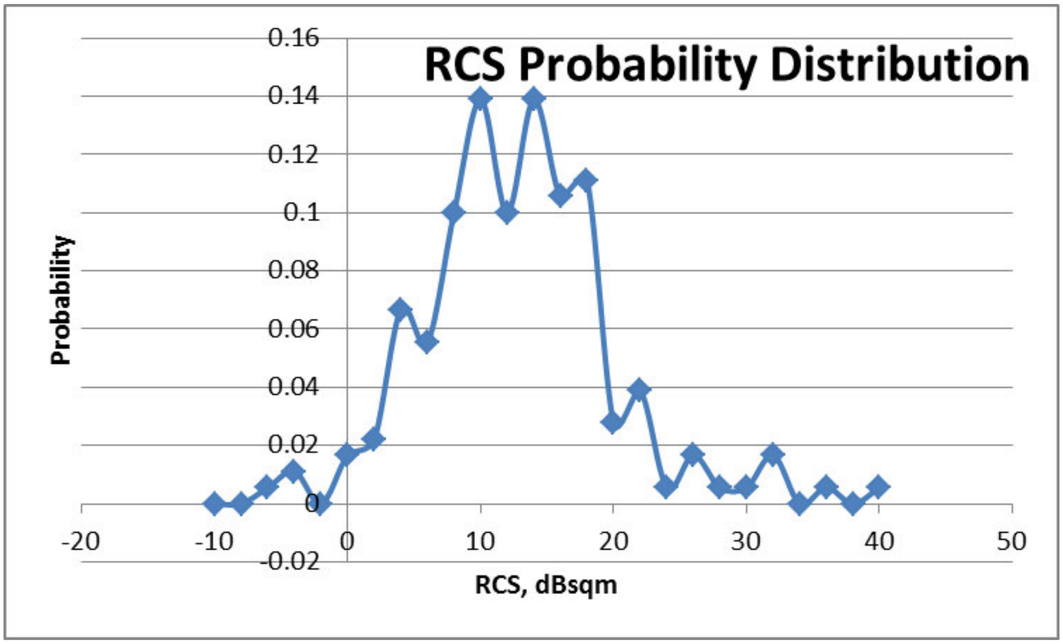


Figure E-11 **Large Intruder RCS Simulation for 5, 10, and 13 GHz**

Table E-6 **Simulated Average Large Intruder RCS for 5, 10, and 13 GHz**

Frequency	5 GHz	10 GHz	13 GHz
RCS, dBsm	9.1	10.0	11.9

Figure E-12 shows the RCS probability distribution and inverse cumulative distribution for 13 GHz simulation using large intruders.



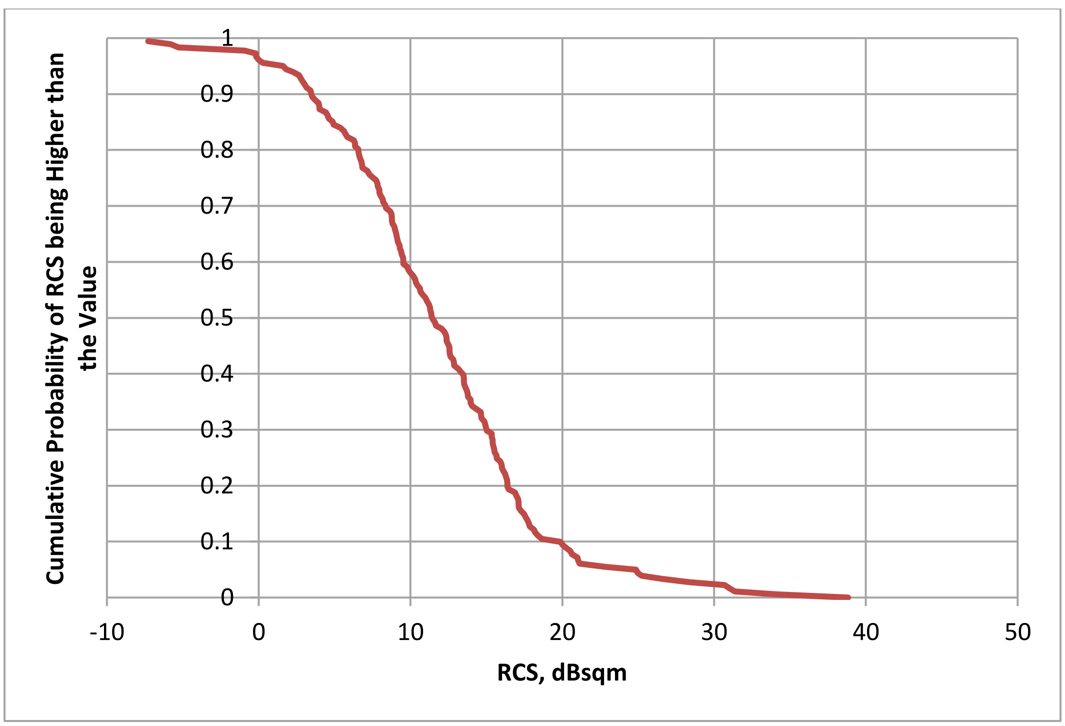


Figure E-12 **13 GHz Large Intruder RCS Probability and Inverse Cumulative Distributions**

E.3 SECOND SIMULATION STUDY

E.3.1 Introduction and Objective

Computational Electromagnetic Models (CEM) modeling and statistical analysis over numerous representative aircraft samples is the best way to obtain the representative RCS values used in support of performance analysis, safety assessments, and development of radar system requirements. In this study, RCS values were computed for large and medium representative aircraft.

The median RCS value is an appropriate value used by radar designers for performance estimation during design as it is aligned with Swerling statistical detection models. In contrast, when compared to raw radar measurements, the 90th percentile is usually selected from visual inspection.

E.3.2 Computational Electromagnetic Model

The Signa radar signature prediction and analysis tool (with a Graphical User Interface (GUI)) developed by Delcross Technologies generated the aircraft RCS values presented in this simulation. Signa is an asymptotic ray-tracing solver. Benchmark validation of Signa has been completed for a variety of canonical shapes (analytical comparison), and comparisons with scale model aircraft chamber measurements have been completed.

The RCS values were evaluated using both C and Ku bands. The results were generated over the following set of parameters:

- Angular sweeps: Azimuth from 0.0 to 180.0 degrees, Elevation from -60.0 to 60.0 degrees, every 0.25 degree.
- Frequency sweeps:
    - C-band – 16 frequency samples, linear sweeps from 5.25 to 5.55 GHz
    - Ku-band – 8 frequency samples, linear sweeps from 13.25 to 13.4 GHz.

Windowed data was processed with the following parameters:

- A Median RCS (in dBsm) was first selected from the frequency each sweep for each 0.25-degree step.
- A Median RCS (in dBsm) was then selected over angular sectors to produce the final RCS data:
- A moving window of 1.0-degree azimuth by 1.0-degree elevation, with a 0.5-degree step size.

E.3.3 Results

E.3.3.1 Small Intruder

No data is available.

E.3.3.2 Medium Intruder

A common single-engine aircraft were selected for the medium category, with radar cross-sections as presented in Figure E-13. Observations include:

- Nose Region (0 to 10 degrees): The statistical analysis of the nose region shows a median value of around -0.2 dBsm and a 90% value of 3 dBsm.

- Front Quartering Region (0 to 60 degrees with a median value of around -0.6 dBsm and a 90% value of 2.3 dBsm.
- All Regions (0 to 180 degrees): This includes the large side region with a median value of around -0.3 dBsm and a 90% value of 5 dBsm.

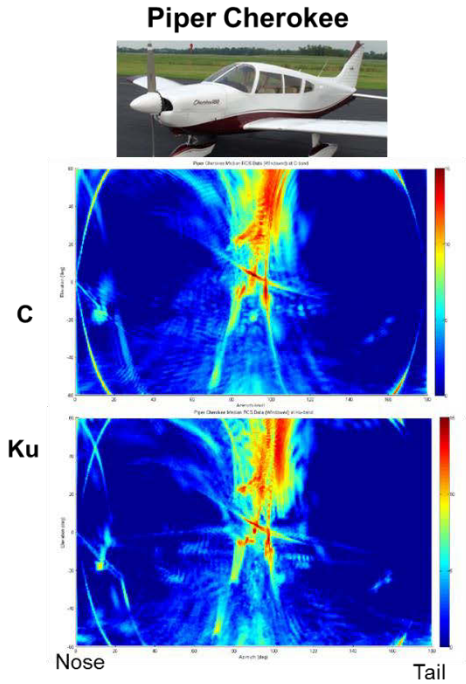


Figure E-13 Single-Engine RCS Values (All Aspects)

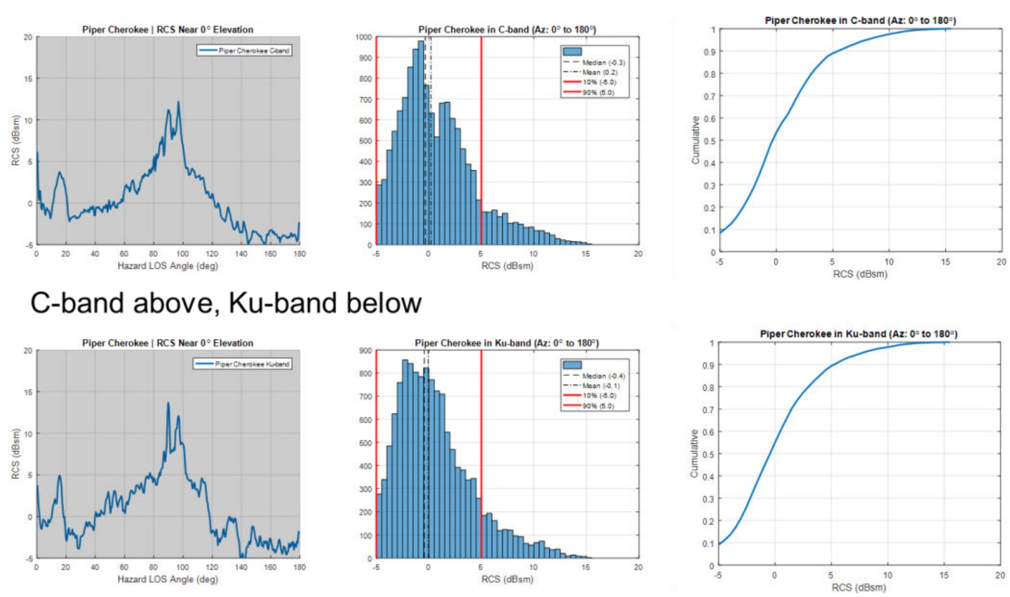


Figure E-14 Single-Engine RCS Distributions (Azimuth 0 to 180°/Elevation -10° to 10°)

The RCS statistical analysis for medium intruders is summarized in Table E-7, from which representative RCS values can be selected.

Table E-7 Results of Statistical Analysis for Medium Intruders

		C-Band				Ku-Band			
	Angle Span	10%	90%	Mean	Median	10%	90%	Mean	Median
Singles	0 to 180	-5.0	5.0	0.2	-0.3	-5.0	5.0	-0.1	-0.4

E.3.3.3 Large Intruder

Three business jets and three turbo twins were selected for the large and fast category. These were first analyzed separately and then together. The radar cross-sections for business jets are presented in Figure E-15. The engines with the fan blades are clearly visible in the nose and tail region, and symmetric at the elevation waterline. The Learjet has the smallest RCS due to the smaller engines. The statistics across all angles and specific angles are given below:

- Nose Region (0 to 10 degrees): Dominated by engines because aerodynamically very smooth with almost no flat surfaces perpendicular to the pose angle. The statistical analysis of the nose region gave a median value of around 3.5 to 4.8 dBsm and a 90% value of 6 dBsm.
- Front Quartering Region (0 to 60 degrees): Engine fans blades span out into this region but it remains aerodynamically very smooth with almost no flat surfaces perpendicular to the pose angle. The statistical analysis of the nose region gave a median value of around 2 dBsm and a 90% value of 5 dBsm.
- All Regions (0 to 180 degrees): This includes the large side region. The statistical analysis of the nose region is shown in Figure E-16, with a median value of around 3 dBsm and a 90% value of 8 dBsm.

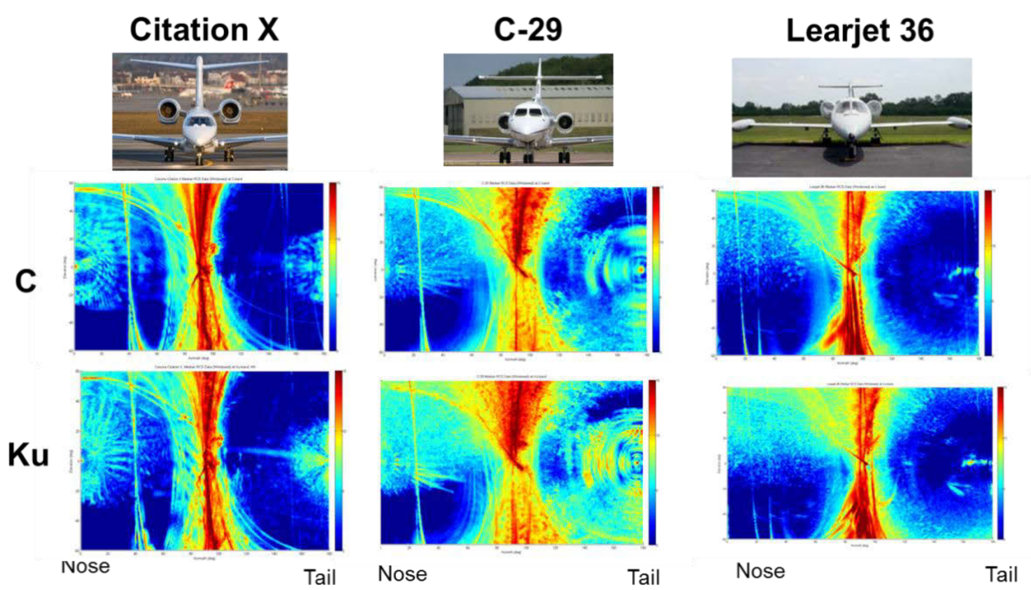


Figure E-15 Business Jet RCS Value (All Aspects)

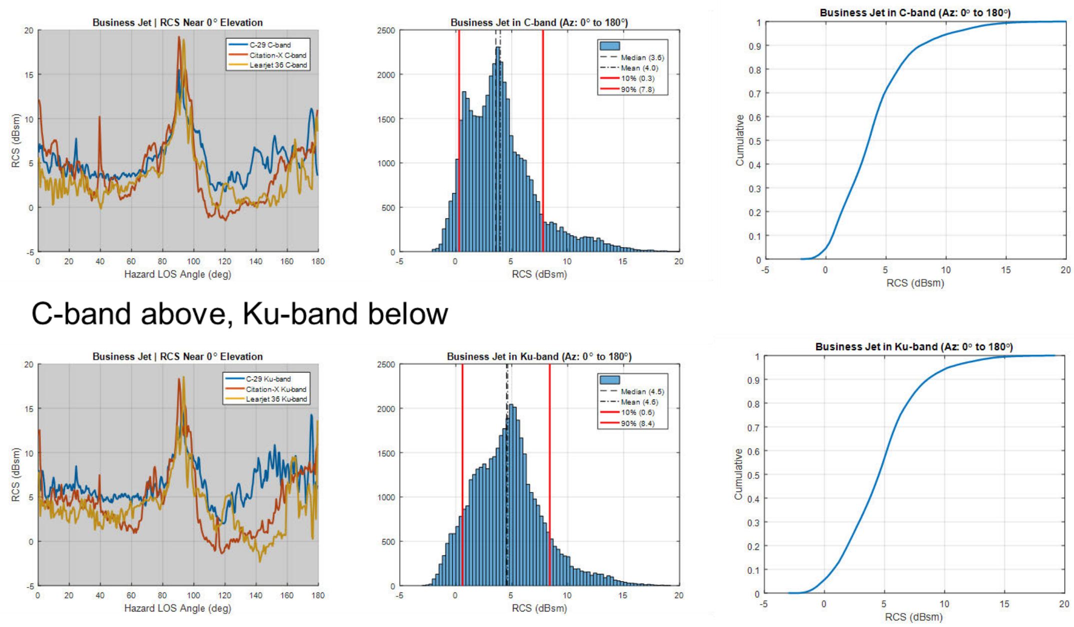


Figure E-16 **Business Jet RCS Distributions (Azimuth 0° to 180°/Elevation -10° to 10°)**

The turbo twin RCSs are presented in Figure E-17 and are very complex due to complex surfaces. The statistics across all angles and specific angles is given below.

- Nose Region (0 to 10 degrees): The statistical analysis of the nose region shows a median value of around 5 dBsm and a 90% value of 8 dBsm.
- Front Quartering Region (0 to 60 degrees): Engine fan blades span out into this region but it remains aerodynamically very smooth with almost no flat surfaces perpendicular to the pose angle. The statistical analysis of the nose region provided a median value of around 1.5 dBsm and a 90% value of 5 dBsm.
- All Regions (0 to 180 degrees): This includes the large side region. The statistical analysis of the nose region is shown in Figure E-18, with a median value of around 3 dBsm and a 90% value of 8 dBsm.

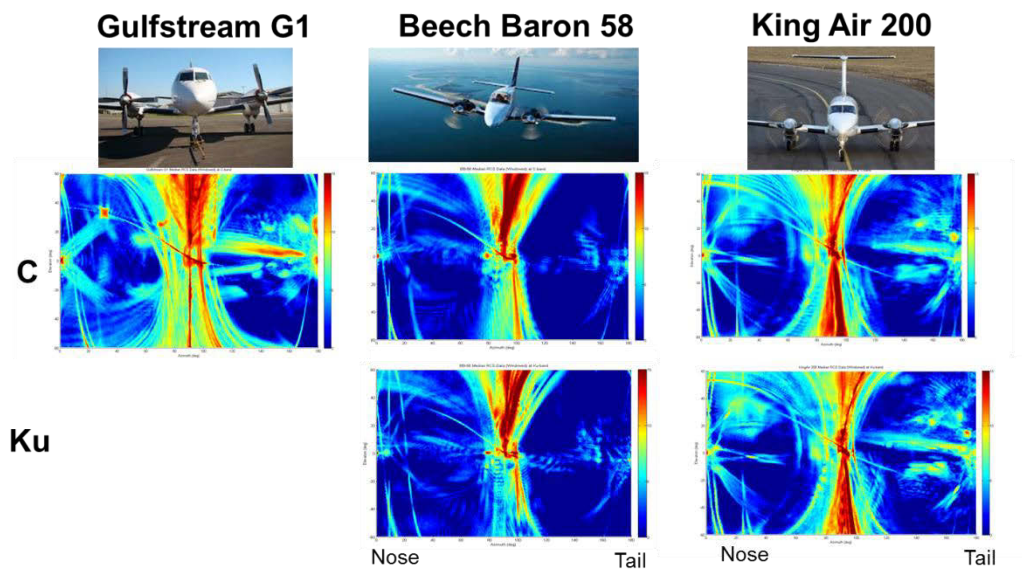


Figure E-17 **Twin RCS Values (All Aspects)**

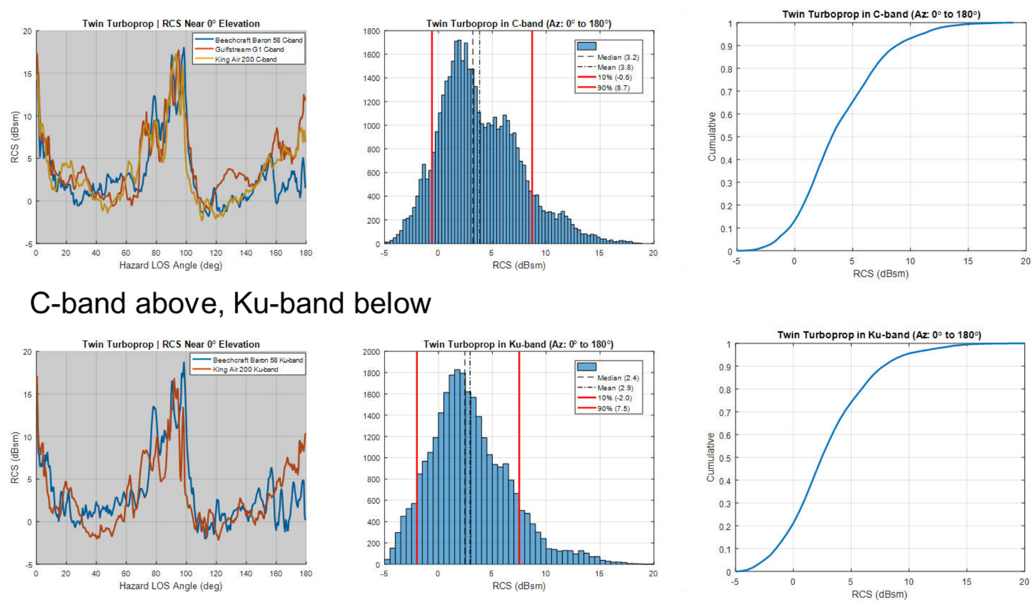


Figure E-18 **Twin RCS Distributions (Azimuth 0 to 180°/Elevation -10° to 10°)**

Figure E-19, below, shows the C and Ku band RCS distributions for a large jet.

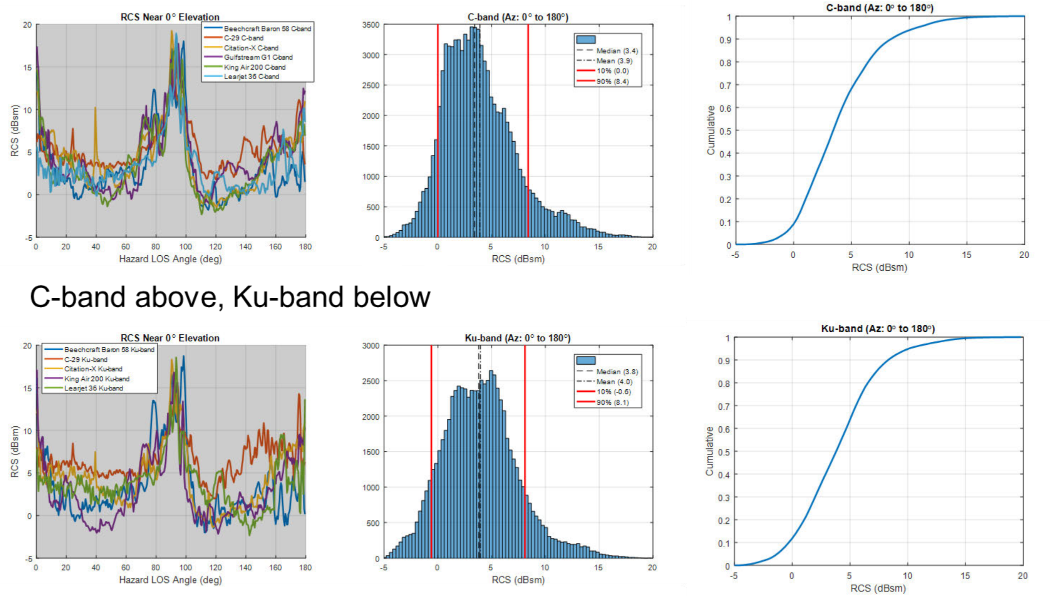


Figure E-19 **Large Jet RCS Distributions (Azimuth 0° to 180°/Elevation -10° to 10°)**

The RCS statistical analysis for large intruders is summarized in Table E-8, from which representative RCS values can be selected.

Table E-8 **Results of Statistical Analysis for Large Intruders**

		C-Band				Ku-Band			
	Angle Span	10%	90%	Mean	Median	10%	90%	Mean	Median
Biz Jets	0 to 180	0.3	7.8	4.0	3.6	0.6	8.4	4.6	4.6
Twins	0 to 180	-0.6	8.7	3.8	3.2	-2.0	7.5	2.9	2.4
Large	0 to 180	0.0	8.4	3.9	3.4	-0.6	8.1	4.0	3.8

E.4 REFERENCES

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F APPENDIX F ACRONYMS AND ABBREVIATIONS

.atc	Air Traffic Control filename extension
.com	Commercial URL Identifier
.docx	Windows Document filename extension
.edu	Educational Institution URL Identifier
.mit	Massachusetts Institute of Technology filename extension
.org	Organization URL identifier
2D	Two-Dimensional
3D	Three-Dimensional
a.k.a	Also known as
AC	Alternating Current
acq	Acquisition
ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	Above Ground Level
AIA	Aerospace Industries Association of America
Alt.	Altitude
AOA	Angle of Attack
ARNS	Aeronautical Radio Navigation Service
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
Avg.	Average
Az	Azimuth
Biz	Business
C	Celsius
CAD	Computer-Aided Design
CAS	Collision Avoidance System
CB	Constant Bearing
CEM	Computational Electromagnetic Model(s)
CFR	Code of Federal Regulations
Ch.	Chapter
CNPC	Control and Non Payload Communication
Comm.	Communications
CONUS	Continental United States
CPA	Closest Point of Approach
cpa	Closest Point of Approach
CS	Control Station
CST	Computer Simulation Technology
DAA	Detect and Avoid
DAL	Design Assurance Level
dB	Decibel
dBsm	Decibels per square meter
dBsqm	Decibels per square meter
DC	District of Columbia
deg	Degree(s)
deg/s	Degrees per second

DET	DAA Execution Threshold
dis	Distance
DME	Distance Measuring Equipment
DMOD	Distance Modification of Modified Tau
DO	Document
DoT	Department of Transportation
DWC	DAA Well Clear
e	Exponent
ed.	Edition
e.g.	Exempli Gratia, For example
Est.	Estimated
et al.	Et alia, And others
etc.	Et Cetera, And so forth
EUROCAE	European Organization for Civil Aviation Equipment
F	Fahrenheit
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FOR	Field of Regard
ft	Feet/foot
g	Acceleration of Gravity
GHz	Gigahertz =1 million Cps
GMT	Ground Moving Track(s)
GNSS	Global Navigation Satellite System
GUI	Graphical User Interface
HAZ	Hazard Zone for DAA Systems
HDG	Heading
HMD	Horizontal Miss Distance
HMI	Hazardous and Misleading Information
hr	Hour
Hz	Hertz = Cycles per Second
i.e.	Id Est, That is
ICAO	International Civil Aviation Organization
ID	Identification
IE	Integral Equations
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
Inc.	Incorporated
INS	Instrument Navigation System
Int.	Intruder
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radiocommunications Sector
JPDO	Joint Planning & Development Office
K	One thousand
kft	One thousand feet
KIAS	Knots-Indicated Airspeed

KTAS	Knots True Air Speed
kts	Knots
LLC	Limited Liability Corporation
LoWC	Loss of DAA Well Clear
m	Meter(s)
M&S	Monitoring and Simulation
m2	Square meter(s)
Max.	Maximum
MHz	MegaHertz
MIT LL	Massachusetts Institute of Technology/Lincoln Laboratory
MITRE	MIT-Based Aviation Research Organization; (Not an acronym)
mm	Millimeters
Mode S	Mode Select
MOPS	Minimum Operational Performance Standards
MSL	Mean Sea Level
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NATCA	National Air Traffic Controllers Association
NM	Nautical Mile (1.15 Statute Miles = 1.852 km)
nm	Nautical Mile(s)
NMAC	Near-Mid-Air Collision
nmi	Nautical Mile(s)
No.	Number
NTIA	National Telecommunications and Information Administration
NUAIR	Northeast UAS Airspace Integration Research Alliance
NW	Northwest
ODL	Optical Delay Line
p	Page
PC	Personal Computer
PIC	Pilot In Command
PMC	Program Management Committee
PO	Physical Optics
Prob.	Probability
PVT	Position, Velocity and Time
R	Range
r	Intruder Range
ŕ	Intruder Range Rate
RA	Resolution Advisory
RCPR	Radar Closest Performance Range
RCS	Radar Cross-Section
RDR	Radar Declaration Range
Rev.	Revision
RF	Radio Frequency
RMSE	Root Mean Square Error
RUT	Radar Under Test
s	Second(s)

SAIC	Science Applications International Corporation
SC	Special Committee
sec	Second(s)
sin	Sine
SUA	Special Use Airspace
t	Time
TCAS	Traffic Alert and Collision Avoidance System
TCAS II	Traffic Alert and Collision Avoidance System Model 2
U.S.	United States
U.S.C.	United States Code
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System(s)
UK	United Kingdom
USA	United States of America
USAF	United States Air Force
V	Version
VFR	Visual Flight Rules
Vi	Intruder Airspeed
Vol.	Volume
VOR	VHF Omnidirectional Range Radar
VUA	Maximum Velocity of the UA Under Test
WAAS	Wide-Area Augmentation System
WGS-84	World Geodetic System – 1984
Wi-Fi	Wireless Fidelity
WRC	World Radiocommunication Conference
x	X Horizontal Axis
y	Y Horizontal Axis
z	Z Vertical Axis
φ	Rho – Symbol representing relative bearing
τ_{mod}	Modified Tau