A54-Propose UAS Right of Way (RoW) Rules for Unmanned Aircraft Systems (UAS) Operations and Safety

Task 3 and 4

Preliminary/Draft Results and Interpretation

Sep 30, 2024

NOTICE

LEGAL DISCLAIMER

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.
A11L.UAS.97_A54</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
A54-Propose UAS Right of Way (RoW) Rules for Unmanned Aircraft Systems (UAS) Operations and Safety
Task 3 and 4: Preliminary/Draft Results and Interpretation</td><td colspan="2">5. Report Date
31 July 2024</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
University of North Dakota
Embry Riddle Aeronautical University
University of Kansas</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
U.S. Department of Transportation
Federal Aviation Administration
Washington, DC 20591</td><td colspan="2">13. Type of Report and Period Covered
Interim Report</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code
5401</td></tr>
<tr><td colspan="4">15. Supplementary Notes
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration, ASSURE UAS Center of Excellence.</td></tr>
<tr><td colspan="4">16. Abstract</td></tr>
<tr><td colspan="2">17. Key Words</td><td colspan="2">18. Distribution Statement</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages
348</td><td>22. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

1 SIMULATIONS 2

1.1 CONFIGURATION ... 2

1.1.1 University of North Dakota ... 2

1.1.2 University of Kansas ... 4

1.1.3 Embry-Riddle Aeronautical University ... 8

1.2 GENERAL INTERACTIONS (ROUND 1) ... 9

1.2.1 Introduction ... 9

1.2.2 sUAS vs. sUAS (UND) ... 9

1.2.3 sUAS vs Crewed (UND) ... 20

1.2.4 Single and Multiple sUAS vs Crewed (KU) ... 25

1.2.5 Intruder Maneuvering (i.e., Following Right of Way Rules (ERAU) ... 36

1.2.6 Intruder Maintaining Course (i.e., Not Following Right of Way Rules ... 38

1.2.7 General Interactions - Summary ... 43

1.2.8 General Interaction Conclusions and Recommendations ... ***Error! Bookmark not defined.***

1.3 RESERVED AIRSPACE CONCEPT (ROUND 2) ... 44

1.3.1 Scenarios ... 44

1.3.2 sUAS vs sUAS (UND) ... 44

1.3.3 Reserved Airspace Simulations for Flight in a Corridor (KU) ... 57

1.3.4 Reserved Airspace Simulations for a Grid Survey Mission (KU) ... 65

1.3.5 Helicopter vs sUAS (ERAU) ... 72

1.3.6 General Interactions – Summary ... ***Error! Bookmark not defined.***

1.3.7 Estimated Saturation point for sUAS with non-cooperative crewed aircraft ... 77

1.4 REMOTE ID (ROUND 3) ... 78

1.4.1 sUAS vs sUAS (UND) ... 78

1.4.2 sUAS vs Crewed (UND) ... 87

1.4.3 Remote ID Conclusions and Recommendations ... 96

2 FLIGHT TEST PLANS 96

2.1 FLIGHT TEST OBJECTIVES ... 96

2.1.1 Primary Objective(s) ... 96

2.1.2 Round 1 (Head-on, Converging, and Overtaking) Objectives ... 97

2.1.3 Round 2 (Reserved Airspace Concepts) Objectives ... 97

2.1.4 Round 3 (RID) Objectives ... 97

2.2 UND ... 98

2.2.1 Location ... 98

2.2.2 Date/Schedule ... 99

2.2.3 Test plan overview ... 101

2.2.4 Sample test cards ... 101

2.2.5 Data Analysis ... *104*
2.3 UNIVERSITY OF KANSAS ... 108
2.3.1 Location ... *108*
2.3.2 Flight Test Aircraft and Ground Station ... *109*
2.3.3 Nominal Flight Test Operations ... *110*
2.3.4 Test Plan Overview ... *111*
2.4 EMBRY-RIDDLE AERONAUTICAL UNIVERSITY ... 116
2.4.1 Location ... *116*
2.4.2 Date/Schedule ... *117*
2.4.3 Sample test cards ... *120*
3 FLIGHT TESTS 124
3.1 GENERAL INTERACTIONS ... 124
3.1.1 sUAS vs sUAS and CA vs sUAS (UND) ... *124*
3.1.2 Assessment of Flight Test Objectives (UND) ... *137*
3.1.3 Single and Multiple sUAS vs Crewed (KU) ... *140*
3.1.4 Helicopter vs sUAS (ERAU) ... *140*
3.2 RESERVED AIRSPACE CONCEPT ... 156
3.2.1 sUAS vs sUAS Maneuevring Criteria (UND) ... *156*
3.2.2 sUAS vs Crewed (KU) ... *163*
3.2.3 Helicopter vs sUAS (ERAU) ... *164*
3.3 REMOTE ID – ROUND 3 ... 189
3.3.1 sUAS vs sUAS (UND) ... *189*
3.3.2 Flight test Observation (ERAU) ... *191*
4 CONCLUSION/INTERPRETATION OF SIMULATION AND FLIGHT TESTING DATA 196
4.1 KEY INTERPRETATIONS IDENTIFIED TO INFORM ROW RECOMMENDATIONS ... 196
4.2 CONCLUSION ... 197
BIBLIOGRAPHY 199
UND ... 199
KU 199
A. APPENDIX A – GENERAL INTERACTIONS – ROUND 1 200
A.1. sUAS VS sUAS (UND) ... 200
A.1.1 FOLLOWING RIGHT-OF-WAY RULES ... 200
A.1.2. Not Following Right-of-Way Rules ... *202*
A.2. sUAS VS CREWED (UND) ... 205
A.2.1. Following Right-of-Way Rules ... *205*
A.3. GENERAL INTERACTIONS (KU) ... 209
A.3.1. Single vs Crewed (KU) ... *209*
A.3.2. Mutiple sUAS vs Crewed (KU) ... *215*

APPENDIX B – RESERVED AIRSPACE – ROUND 2 221

A.3.3. sUAS vs sUAS (UND) 221

A.3.4. Following Right-of-Way Rules 221

A.3.5. Not Following Right-of-Way Rules 222

A.4. Single and Multiple sUAS vs Crewed (KU) 224

A.4.1. Moving Corridor Single sUAS 224

A.4.2. Moving Corridor Multiple sUAS 227

A.4.3. Moving Corridor Single sUAS Loiter Guidance 229

A.4.4. Survey Pattern Single sUAS 239

A.4.5. Survey Pattern Multiple sUAS 245

A.5. Saturation Point Results 251

APPENDIX C – REMOTE ID – ROUND 3 254

A.6. sUAS vs sUAS (UND) 254

A.6.1. Following Right-of-Way Rules 254

A.7. sUAS vs Crewed (UND) 264

A.7.1. Following Right-of-Way Rules 264

APPENDIX D – SMALL NMAC 279

A.8. Head-on 280

A.9. Converging 282

A.10. Overtaking 284

APPENDIX E – FIXED AIRCRAFT AVOIDANCE MANEUVER 287

A.11. Single heading change 287

A.12. Relative heading change (Overtaking) 289

APPENDIX F - GPS ACCURACY AND HORIZONTAL VS. VERTICAL MANEUVER PRIORITY 291

A.13. Following Right-of-Way Rules 292

A.14. Not Following Right-of-Way Rules 292

APPENDIX G – FLIGHT TEST ANALYSIS 293

A.15. Round-1 : sUAS-sUAS 293

G.2. Round-1 : CA-UAS 302

G.3 Round-2 : sUAS vs sUAS (RAC) 311

TABLE OF FIGURES

Figure 1. Stationary Potential Field and a Morphing Potential Field. 7
Figure 2. Morphing Potential Field Geometry. 8
Figure 3. ERAU well-clear definition. 9
Figure 4. sUAS vs sUAS Following ROW Rules, Converging from Right, Horizontal-only, and with WAAS GPS. 11
Figure 5. Depicted colors for best restricted maneuver type. 11
Figure 6. sUAS vs sUAS Following Rules, Head-on, Horizontal-only, SPS GPS. 12
Figure 7. sUAS vs sUAS Following Rules, Converging from Right, Horizontal-only, RTK GPS. 13
Figure 8. sUAS vs sUAS Following Rules, Overtaking, Horizontal Only, WAAS GPS. 15
Figure 9. Non-cooperative Aircraft Heading Angle Definition 26
Figure 10. Large Detection Range with Successful Avoidance 26
Figure 11. Intermediate Detection Range with Successful Avoidance 27
Figure 12. Low Detection Range with ROW Violation 27
Figure 13. General Interactions 170ft/s Overtaking Single sUAS. 28
Figure 14. General Interactions 170 ft/s Head-On Converging Single sUAS. 28
Figure 15. General Interactions 195 ft/s Head-On Converging Single sUAS. 29
Figure 16. Maximum attained Roll Rates 195 ft/s Head-On Converging Single sUAS. 30
Figure 17. Maximum attained Yaw Rates 195 ft/s Head-On Converging Single sUAS. 31
Figure 18. Two sUAS Flying in Formation with Successful Maneuver. 31
Figure 19. General Interactions Overtaking Multiple sUAS. 32
Figure 20. General Interactions Head-On Converging Multiple sUAS. 32
Figure 21. 195 ft/s Overtaking Multi sUAS. 33
Figure 22. Maximum attained Roll Rates 145 ft/s Head-On Converging Multiple sUAS. 34
Figure 23. Maximum attained Yaw Rates 145 ft/s Head-On Converging Multiple sUAS. 35
Figure 24. Reserved Airspace Corridor sUAS vs sUAS following rules maneuver. 46
Figure 25. Reserved Airspace Corridor sUAS vs sUAS not following rules maneuver. 47
Figure 26. Reserved Airspace Concept Corridor Turn Limit. 48
Figure 27. RAC corridor fixed heading change for head-on geometry without GPS uncertainty. 48
Figure 28. RAC corridor fixed heading change for head-on geometry with SPS GPS uncertainty. 49
Figure 29. RAC corridor fixed heading change for overtaking geometry without GPS uncertainty. 49
Figure 30. RAC corridor fixed heading change for overtaking geometry with SPS GPS uncertainty. 50
Figure 31. sUAS Encounter with a Crewed Aircraft While Flying in a Reserved Airspace Corridor. 57
Figure 32. Single sUAS Maneuver Width for 145 ft/s Cessna. 58
Figure 33. Single sUAS Required Corridor Width for 270° Encounter with Crewed Aircraft Flying at 145 ft/s (l) and 170 ft/s (r). 59
Figure 34. Sucessful Loiter Manuever. 59

Figure 35. Maneuver Width at Varying Cessna Speeds. 60
Figure 36. 170 ft/s Cessna Head-on All Angles. 60
Figure 37. 170 ft/s Cessna Head-On. 61
Figure 38. Loiter Maneuver Exit. 61
Figure 39. Maneuver Width for 170 ft/s Cessna Overtaking Angles. 62
Figure 40. Multiple sUAS Maneuver Width for 145 ft/s Cessna. 63
Figure 41**.** Required Corridor Width for sUAS Flying at 45 ft/s Encountering Crewed Aircraft. 63
Figure 42. Survey Grid Encounter Point Definitions. 66
Figure 43. Large Detection Range with Extended Loiter. 67
Figure 44. Medium Detection Range with sUAS Returning. 67
Figure 45. Low Detection Range with ROW violation. 67
Figure 46. Successful multiple sUAS Avoidance Maneuver. 68
Figure 47**.** Point 4 Single sUAS Encountering 195 ft/s Crewed Aircraft at Point 4. 70
Figure 48. 195 ft/s Point 4 Multiple sUAS. 70
Figure 49. ERAU RAC Configurations. 73
Figure 50. ERAU RAC Helicopter Paths. 73
Figure 51. RAC Safe Zones. 74
Figure 52. Use Case #2 before course correction (L) and after course correction (R). 77
Figure 53. Remote ID transmitter range reference. 80
Figure 54. Gorman Field; 47.847794° -97.347316°. 99
Figure 55. Crewed launch & recovery airfield layout; Grand Forks International Airport (KGFK). 99
Figure 56. Sample test card of Round-1, sUAS-sUAS showing Head-On aspect. 102
Figure 57. Sample test card of Round-1, CA -sUAS showing converging aspect. 102
Figure 58. Sample test card of Round-2 (RAC) sUAS-sUAS showing Overtaking aspect. The RAC and RAC buffuer boundaries are displayed in the figure. 103
Figure 59. Sample test card of Round-3, sUAS-sUAS showing Symmetric and Parallel aspect. 103
Figure 60. Round 1 Encounter - General Interaction. 104
Figure 61. Round 2 Encounter- Reserved Airspace Concept. 105
Figure 62. Round 3 Encounter- Remote ID. 105
Figure 63. Virtual trajectory extension. 106
Figure 64. Rate of turn calculations. 107
Figure 65. Air Chart showing LWC (upper right) and the AMA field (star at lower left). 108
Figure 66. Clinton International AMA Airport. 109
Figure 67. SkyHunter sUAS. 109
Figure 68. Dipole antenna attached to Cessna 172 strut. 110
Figure 69**.** Sample Flight Test Card: Head-on Encounter, Crewed Aircraft Doesn’t Maneuver. 112

Figure 70. Round 1/2.1 Supporting Flight In a Corridor Analysis. 113
Figure 71. Sample Round 2.1 Flight Test Card (for a Head-on Maneuver). 113
Figure 72. Head-on Encounter over Clinton Lake. 114
Figure 73. Sample Flight Test Card for Head-on Encounter over Clinton Lake. 115
Figure 74. Encounter Scenario During a Grid Survey Mission. 115
Figure 75. Sample Flight Test Card for Encounter During a Grid Survey Mission over Clinton Lake. 116
Figure 76. Round-1, sUAS-sUAS overall analysis. 129
Figure 77. Round-1, sUAS vs CA. 130
Figure 78. Round-1, sUAS vs sUAS. 130
Figure 79. Round-1, sUAS-sUAS, Altitude data. 131
Figure 80. Ground Speed, Round-1, sUAS-sUAS. 131
Figure 81. Round-1, sUAS-sUAS, Ground speed data. 132
Figure 82. Round-1, CA-sUAS. 134
Figure 83. Round-1, CA-sUAS. 134
Figure 84. Round-1, CA-sUAS. 135
Figure 85. Round-1, CA-sUAS, Altitude data. 135
Figure 86. Ground Speed, Round-1, CA-sUAS. 136
Figure 87. Round-1, CA-sUAS, Ground speed data. 136
Figure 88. Frequency of CA sighting UAS sightings during Round 1 for CA-sUAS. 137
Figure 89. Flight Test Area. 142
Figure 90. AAGS Pilot GUI for Avoidance Maneuvering. 144
Figure 91. Collision Avoidance Distance Rings (CADR). 147
Figure 92. UAS DAA equipment graphic interface with CADR, ADS-B. 151
Figure 93. Head-On Encounter. 153
Figure 94. Converging Encounter. 154
Figure 95. Overtaking Encounter. 155
Figure 96. Round 2, sUAS-sUAS in RAC. 158
Figure 97. Round-2, sUAS-sUAS,RAC. 159
Figure 98. Round-2, sUAS-sUAS, RAC. 159
Figure 99. Round-2, sUAS-sUAS, RAC. 160
Figure 100. Ground Speed, Round-2 sUAS-sUAS. 160
Figure 101. Round-2, sUAS-sUAS, RAC, Ground speed data. 161
Figure 102. Round-2, sUAS-sUAS, RAC, Altitude data. 162
Figure 103. Round-2, sUAS-sUAS, RAC, Operator Reaction Times. 162
Figure 104. Head-on Encounter with Virtual Cessna 172 (17 July 2024). 163
Figure 105. Head-on Encounter with Cessna 172 (18 July 2024). 164

Figure 106. Flight Test Area. 166
Figure 107. Applied Aeronautics Ground Station RAC and Buffer Zone GUI. 166
Figure 108. Encounter Disance Results between Ownship and Intruder. 167
Figure 109. Run 2-5 Head On Encounter with Successful Avoidance. 168
Figure 110. Run 2-9 Head On Encounter with Unsuccessful Avoidance. 169
Figure 111. Run 2-11 Converging Encounter with Successful Avoidance. 169
Figure 112. Applied Aeronautics Ground Station GUI. 171
Figure 113. Intruder Avoidance Concept. 173
Figure 114. Actual sUAS Linear RAC Avoidance Maneuver Linear RAC avoidance maneuver. 174
Figure 115. Actual sUAS Area RAC Avoidance Maneuver. 175
Figure 116. Avoidance Maneuver Initiated. 177
Figure 117. Best Avoidance under Given Interactions. 177
Figure 118. Round 2 Area RAC, Head-On Encounter. 180
Figure 119. Round 2 Linear RAC, Head-On Encounter. 181
Figure 120. Round 2 Area RAC 182
Figure 121. Round 2, Run 2-1, Area RAC, Head On Encounter. 183
Figure 122. Round 2, Run 2-2, Area RAC, Head On Encounter. 183
Figure 123. Round 2, Run 2-3, Area RAC, Head On Encounter. 184
Figure 124. Round 2, Run 2-4, Linear RAC, Head On Encounter. 184
Figure 125. Round 2, Run 2-5, Linear RAC, Head On Encounter. 185
Figure 126. Round 2, Run 2-6, Linear RAC, Head On Encounter. 185
Figure 127. Round 2, Run 2-7, Linear RAC, Head On Encounter. 186
Figure 128. Round 2, Run 2-9, Linear RAC, Head On Encounter. 186
Figure 129. Round 2, Run 2-10, Area RAC, Converging Encounter. 187
Figure 130. Round 2, Run 2-11, Area RAC, Converging Encounter. 187
Figure 131. Round 2, Run 2-12, Area RAC, Converging Encounter. 188
Figure 132. Round 2, Run 2-13, Area RAC, Converging Encounter. 188
Figure 133. Round-3, RID:1 Data receiving rate (counts/sec) for different encounter criteria. 190
Figure 134. Round-3, RID:2 Data receiving rate (counts/sec) for different encounter criteria. 190
Figure 135. Round-3, RID:3 Data receiving rate (counts/sec) for different encounter criteria. 190
Figure 136. Flight Test Area. 192
Figure 137. Test Run Configurations In this round of flight, the head-on and perpendicular aspects are tested. 193
Figure 138. Flight test stations iPod Touch. 194
Figure 139. GCS monitor layout shows simultaneous aircraft locations in two different programs. 195
Figure 140. AAGS Albatross Telemetry (left) and DroneTag Mini Telemetry of test flight run 3-1. 195
Figure 141. 145 ft/s Overtaking Single sUAS. 209

Figure 142. 170 ft/s Overtaking Single sUAS. 209
Figure 143. 195 ft/s Overtaking Single sUAS. 210
Figure 144. 145 ft/s Head-On Converging Single sUAS. 210
Figure 145. 170 ft/s Head-On Converging Single sUAS. 211
Figure 146. 195 ft/s Head-On Converging Single sUAS. 211
Figure 147. Roll Rates 145 ft/s. 212
Figure 148. Yaw Rates 145 ft/s. 212
Figure 149. Roll Rates 170 ft/s. 213
Figure 150. Yaw Rates 170 ft/s. 213
Figure 151. Roll Rates 195 ft/s. 214
Figure 152. Yaw Rates 195 ft/s. 214
Figure 153. 145 ft/s Overtaking Multi sUAS. 215
Figure 154. 170 ft/s Overtaking Multi sUAS. 215
Figure 155. 195 ft/s Overtaking Multi sUAS. 216
Figure 156. 145 ft/s Head On Converging Multi sUAS. 216
Figure 157. 170 ft/s Head On Converging Multi sUAS. 217
Figure 158. 195 ft/s Head On Converging Multi sUAS. 217
Figure 159. Roll Rates 145 ft/s. 218
Figure 160. Yaw Rates 145 ft/s. 218
Figure 161. Roll Rates 170 ft/s. 219
Figure 162. Yaw Rates 170 ft/s. 219
Figure 163. Roll Rates 195 ft/s. 220
Figure 164. Yaw Rates 195 ft/s. 220
Figure 165. 145 ft/s Overtaking single sUAS. 224
Figure 166. 145 ft/s Head On Converging Single sUAS. 224
Figure 167. 170 ft/s Overtaking single sUAS. 225
Figure 168. 170 ft/s Head On Converging Single sUAS. 225
Figure 169. 195 ft/s Overtaking single sUAS. 226
Figure 170. 195 ft/s Head On Converging Single sUAS. 226
Figure 171. 145 ft/s Overtaking Multi sUAS. 227
Figure 172. 145 ft/s Head On Converging Multi sUAS. 227
Figure 173. 170 ft/s Overtaking Multi sUAS. 228
Figure 174. 170 ft/s Head On Converging Multi sUAS. 228
Figure 175. 195 ft/s Overtaking Multi sUAS. 229
Figure 176. 195 ft/s Head On Converging Multi sUAS. 229
Figure 177. 145 ft/s Overtaking. 230

Figure 178. 145 ft/s Head On Converging. 230
Figure 179. 170 ft/s Overtaking. 231
Figure 180. 170 ft/s Head On Converging. 231
Figure 181. 195 ft/s Overtaking. 232
Figure 182. 195 ft/s Head On Converging. 232
Figure 183. 145 ft/s Overtaking Loiter Guidance. 233
Figure 184. 145 ft/s Overtaking Loiter Guidance with MPF. 233
Figure 185. 170 ft/s Overtaking Loiter Guidance. 234
Figure 186. 170 ft/s Overtaking Loiter Guidance with MPF. 234
Figure 187. 195 ft/s Overtaking Loiter Guidance. 235
Figure 188. 195 ft/s Overtaking Loiter Guidance with MPF. 235
Figure 189. 145 ft/s Head On Converging Loiter Guidance. 236
Figure 190. 145 ft/s Head On Converging Loiter Guidance With MPF. 236
Figure 191. 170 ft/s Head On Converging Loiter Guidance. 237
Figure 192. 170 ft/s Head On Converging Loiter Guidance With MPF. 237
Figure 193. 195 ft/s Head On Converging Loiter Guidance. 238
Figure 194. 195 ft/s Head On Converging Loiter Guidance With MPF. 238
Figure 195. 145 ft/s Survey Single sUAS Point 1. 239
Figure 196. 145 ft/s Survey Single sUAS Point 2. 239
Figure 197. 145 ft/s Survey Single sUAS Point 3. 240
Figure 198. 145 ft/s Survey Single sUAS Point 4. 240
Figure 199. 170 ft/s Survey Single sUAS Point 1. 241
Figure 200. 170 ft/s Survey Single sUAS Point 2. 241
Figure 201. 170 ft/s Survey Single sUAS Point 3. 242
Figure 202. 170 ft/s Survey Single sUAS Point 4. 242
Figure 203. 195 ft/s Survey Single sUAS Point 1. 243
Figure 204. 195 ft/s Survey Single sUAS Point 2. 243
Figure 205. 195 ft/s Survey Single sUAS Point 3. 244
Figure 206. 195 ft/s Survey Single sUAS Point 4. 244
Figure 207. 145 ft/s Survey Multiple sUAS Point 1. 245
Figure 208. 145 ft/s Survey Multiple sUAS Point 2. 245
Figure 209. 145 ft/s Survey Multiple sUAS Point 3. 246
Figure 210. 145 ft/s Survey Multiple sUAS Point 4. 246
Figure 211. 170 ft/s Survey Multiple sUAS Point 1. 247
Figure 212. 170 ft/s Survey Multiple sUAS Point 2. 247
Figure 213. 170 ft/s Survey Multiple sUAS Point 3. 248

Figure 214. 170 ft/s Survey Multiple sUAS Point 4. 248

Figure 215. 195 ft/s Survey Multiple sUAS Point 1. 249

Figure 216. 195 ft/s Survey Multiple sUAS Point 2. 249

Figure 217. 195 ft/s Survey Multiple sUAS Point 3. 250

Figure 218. 195 ft/s Survey Multiple sUAS Point 4. 250

Figure 219. Volume bounds tested for best sNMAC between small UAS. 279

Figure 220. sNMAC volume test for head-on geometries, with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left). 281

Figure 221**.** Zero probability plot for sNMAC volume test for head-on geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left). 282

Figure 222**.** sNMAC volume test for converging geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left). 283

Figure 223. Zero probability plot for sNMAC volume test for converging geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left). 284

Figure 224. sNMAC volume test for overtaking geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left). 285

Figure 225. Zero probability plots for sNMAC volume test for overtaking geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left). 286

Figure 226. Fixed heading change relative to Ownships heading for head-on geometries. 287

Figure 227. Fixed heading change relative to Ownships heading for converging from left geometries. 288

Figure 228. Fixed heading change relative to Ownships heading for converging from right geometries. 288

Figure 229. Fixed heading change relative to Ownships heading for overtaking geometries. 289

Figure 230. Fixed heading change relative to intruder relative bearing for overtaking geometries with 7,500m detection range. 290

TABLE OF TABLES

Table 1. Super Hauler performance. 2
Table 2. Cessna 182T performance. 3
Table 3. GPS Uncertainty. 4
Table 4. Number of encounters simulated for General Interactions. 4
Table 5. Number of encounters simulated for Remote ID Interactions 4
Table 6. Parameters for sUAS vs sUAS following right of way rule simulations. 10
Table 7. General interactions, sUAS vs sUAS following RoW rules, head-on. 13
Table 8. General interactions, sUAS vs sUAS following RoW rules, converging from right. 14
Table 9. General interactions, sUAS vs sUAS following RoW rules, overtaking. 15
Table 10. Maximum required detection ranges for sUAS vs sUAS following right-of-way rules. 16
Table 11. General interactions, sUAS vs sUAS not following RoW rules, head-on. 17
Table 12. General interactions, sUAS vs sUAS not following RoW rules, converging from left. 18
Table 13. General interactions, sUAS vs sUAS not following RoW rules, overtaking. 19
Table 14. Maximum required detection ranges for sUAS vs sUAS not following right-of-way rules. 20
Table 15. Parameters for sUAS vs Crewed following right-of-way rule simulations. 21
Table 16. General interactions, sUAS vs Crewed following RoW rules, head-on. 21
Table 17. General interactions, sUAS vs Crewed following RoW rules, converging from left. 22
Table 18. General interactions, sUAS vs Crewed following RoW rules, converging from right. 23
Table 19. General interactions, sUAS vs Crewed following RoW rules, overtaking. 23
Table 20. Maximum required detection ranges for sUAS vs Crewed following right-of-way rules. 24
Table 21. Worst Case Roll and Yaw and Roll Rates for General Interaction Simulations. 29
Table 22. Worst Case Roll and Yaw and Roll Rates for General Interaction Simulations. 33
Table 23. Scaling Factors for a Linear Equation Relating Relative Velocity to Required Detection Distance. 36
Table 24. Head On Parameter Manifest. 37
Table 25. Overtaking Parameter Manifest. 37
Table 26. Converging Left. 37
Table 27. Converging Right. 38
Table 28.Head On Horizontal Manifest. 38
Table 29. Head On Vertical Manifest. 39
Table 30. Overtaking Horizontal Manifest. 39
Table 31. Overtaking Vertical Manifest. 39
Table 32. Converging Left Horizontal Manifest. 40
Table 33. Converging Left Vertical Manifest. 40
Table 34. Converging Right Horizontal Manifest. 40
Table 35. Converging Right Vertical Manifest. 41

Table 36. Round 1 ROW Results. 41
Table 37. ROW Risk over Response Distance. 42
Table 38. ERAU Round 1 Results. 42
Table 39: Non-ROW Risk over Response Distance 43
Table 40. RAC corridor, sUAS vs sUAS following RoW rules, head-on. 51
Table 41. RAC corridor, sUAS vs sUAS following RoW rules, overtaking. 52
Table 42. Maximum required detection ranges for sUAS vs sUAS following RoW rules in a RAC corridor. 53
Table 43. RAC corridor, sUAS vs sUAS not following RoW rules, head-on. 54
Table 44. RAC corridor, sUAS vs sUAS not following RoW rules, overtaking. 55
Table 45. Maximum required detection ranges for sUAS vs sUAS not following RoW rules in a RAC corridor. 56
Table 46. Non-dimensional scaling factor. 64
Table 47. Minimum Safe Detection Distance. 69
Table 48. Scaling Factors for Single and Multiple sUAS Flying in a Grid Survey Reserved Airspace 71
Table 49. Round 2 Rectangular RAC Results. 74
Table 50. Round 2 Narrow RAC Results. 75
Table 51. Remote ID transmitters. 79
Table 52. Remote ID, sUAS vs sUAS following RoW rules, head-on, Horizontal-only. 80
Table 53. Remote ID, sUAS vs sUAS following RoW rules, head-on, Vertical-only. 81
Table 54. Remote ID, sUAS vs sUAS following RoW rules, head-on, Unrestricted. 81
Table 55. Remote ID, sUAS vs sUAS following RoW rules, Converging from Right, Horizontal-only. 82
Table 56. Remote ID, sUAS vs sUAS following RoW rules, Converging from Right, Vertical-only. 83
Table 57. Remote ID, sUAS vs sUAS following RoW rules, Converging from Right, Unrestricted. 84
Table 58. Remote ID, sUAS vs sUAS following RoW rules, Overtaking, Horizontal-only. 85
Table 59. Remote ID, sUAS vs sUAS following RoW rules, Overtaking, Vertical-only. 85
Table 60. Remote ID, sUAS vs sUAS following RoW rules, Overtaking, Unrestricted. 86
Table 61. Remote ID, sUAS vs Crewed following RoW rules, head-on, Horizontal-only. 87
Table 62. Remote ID, sUAS vs Crewed following RoW rules, head-on, Vertical-only. 88
Table 63. Remote ID, sUAS vs Crewed following RoW rules, head-on, Unrestricted. 89
Table 64. Remote ID, sUAS vs Crewed following RoW rules, Converging from Left, Horizontal-only. 90
Table 65. Remote ID, sUAS vs Crewed following RoW rules, Converging from Left, Vertical-only. 90
Table 66. Remote ID, sUAS vs Crewed following RoW rules, Converging from Left, Unrestricted. 91
Table 67. Remote ID, sUAS vs Crewed following RoW rules, Converging from Right, Horizontal-only. 91
Table 68. Remote ID, sUAS vs Crewed following RoW rules, Converging from Right, Vertical-only. 92
Table 69. Remote ID, sUAS vs Crewed following RoW rules, Converging from Right, Unrestricted. 93
Table 70. Remote ID, sUAS vs Crewed following RoW rules, Overtaking, Horizontal-only. 94
Table 71. Remote ID, sUAS vs Crewed following RoW rules, Overtaking, Vertical-only. 94

Table 72. Remote ID, sUAS vs Crewed following RoW rules, Overtaking, Unrestricted. 95
Table 73. Round-1 schedule. 100
Table 74. Round-2 schedule. 100
Table 75. Round-3 schedule. 101
Table 76. Round 1 Test Matrix. 111
Table 77. General Interactions Round 1 Timeline. 117
Table 78. RAC Round 2 and RID Round 3 Timeline. 118
Table 79. Data Collection Plan. 123
Table 80. Summary of flight test encounters. Detailed analysis of all rounds are given in Appendix G. 125
Table 81.Abbreviations and maneuver initiation distances for Round-1, sUAS-sUAS encounters. 126
Table 82. Abbreviations and maneuver initiation distances for Round-1, sUAS-sUAS encounters. 127
Table 83. Flight Test Results. 139
Table 84. Avoidance Distances to Maintain Well Clear. 143
Table 85. Abbreviations and maneuver initiation distances for Round-2, sUAS vs sUAS in RAC. 156
Table 86. Round 3 (RID) Encounter Criteria and Objectives. 189
Table 87**.** General Interactions sUAS vs sUAS Following Rules, Head-on, Required Detection Range in Feet. 200
Table 88. General Interactions sUAS vs sUAS Following Rules, Converging from Right, Required Detection Range in Feet. 201
Table 89. General Interactions sUAS vs sUAS Following Rules, Overtaking, Required Detection Range in Feet. 202
Table 90. General Interactions sUAS vs sUAS Not Following Rules, Head-on, Required Detection Range in Feet. 203
Table 91. General Interactions sUAS vs sUAS Not Following Rules, Converging from Left, Required Detection Range in Feet 203
Table 92. General Interactions sUAS vs sUAS Not Following Rules, Overtaking, Required Detection Range in Feet. 204
Table 93. General Interactions sUAS vs Crewed Following Rules, Head-on, Required Detection Range in Feet. 205
Table 94. General Interactions sUAS vs Crewed Following Rules, Converging from Left, Required Detection Range in Feet. 206
Table 95. General Interactions sUAS vs Crewed Following Rules, Converging from Right, Required Detection Range in Feet. 207
Table 96. General Interactions sUAS vs Crewed Following Rules, Overtaking, Required Detection Range in Feet. 208
Table 97. RAC corridor sUAS vs sUAS Following Rules, Head-on, Required Detection Range in Feet. 221
Table 98. RAC corridor sUAS vs sUAS Following Rules, Overtaking, Required Detection Range in Feet. 221
Table 99. RAC corridor sUAS vs sUAS Not Following Rules, Head-on, Required Detection Range in Feet. 222
Table 100. RAC corridor sUAS vs sUAS Not Following Rules, Overtaking, Required Detection Range in Feet. 223
Table 101. RAC Saturation Point Results. 251
Table 102. Additional RAC Saturation Point Results. 252

Table 103. Remote ID sUAS vs sUAS Following Rules, Head-on, 0.2s Update Rate, Required Detection Range in Feet. 254

Table 104. Remote ID sUAS vs sUAS Following Rules, Converging from Right, 0.2s Update Rate, Required Detection Range in Feet. 255

Table 105. Remote ID sUAS vs sUAS Following Rules, Overtaking, 0.2s Update Rate, Required Detection Range in Feet. 256

Table 106. Remote ID sUAS vs sUAS Following Rules, Head-on, 1s Update Rate, Required Detection Range in Feet. 257

Table 107. Remote ID sUAS vs sUAS Following Rules, Converging from Right, 1s Update Rate, Required Detection Range in Feet. 258

Table 108. Remote ID sUAS vs sUAS Following Rules, Overtaking, 1s Update Rate, Required Detection Range in Feet. 258

Table 109. Remote ID sUAS vs sUAS Following Rules, Head-on, 3s Update Rate, Required Detection Range in Feet. 259

Table 110. Remote ID sUAS vs sUAS Following Rules, Converging from Right, 3s Update Rate, Required Detection Range in Feet. 260

Table 111. Remote ID sUAS vs sUAS Following Rules, Overtaking, 3s Update Rate, Required Detection Range in Feet. 261

Table 112. Remote ID sUAS vs sUAS Following Rules, Head-on, 5s Update Rate, Required Detection Range in Feet. 262

Table 113. Remote ID sUAS vs sUAS Following Rules, Converging from Right, 5s Update Rate, Required Detection Range in Feet. 263

Table 114. Remote ID sUAS vs sUAS Following Rules, Overtaking, 5s Update Rate, Required Detection Range in Feet. 264

Table 115. Remote ID sUAS vs Crewed Following Rules, Head-on, 0.2s Update Rate, Required Detection Range in Feet. 265

Table 116. Remote ID sUAS vs Crewed Following Rules, Converging from Left, 0.2s Update Rate, Required Detection Range in Feet. 266

Table 117. Remote ID sUAS vs Crewed Following Rules, Converging from Right, 0.2s Update Rate, Required Detection Range in Feet. 267

Table 118. Remote ID sUAS vs Crewed Following Rules, Overtaking, 0.2s Update Rate, Required Detection Range in Feet. 267

Table 119. Remote ID sUAS vs Crewed Following Rules, Head-on, 1s Update Rate, Required Detection Range in Feet. 268

Table 120. Remote ID sUAS vs Crewed Following Rules, Converging from Left, 1s Update Rate, Required Detection Range in Feet. 269

Table 121. Remote ID sUAS vs Crewed Following Rules, Converging from Right, 1s Update Rate, Required Detection Range in Feet. 270

Table 122. Remote ID sUAS vs Crewed Following Rules, Overtaking, 1s Update Rate, Required Detection Range in Feet. 271

Table 123. Remote ID sUAS vs Crewed Following Rules, Head-on, 3s Update Rate, Required Detection Range in Feet. 272

Table 124. Remote ID sUAS vs Crewed Following Rules, Converging from Left, 3s Update Rate, Required Detection Range in Feet. 273

Table 125. Remote ID sUAS vs Crewed Following Rules, Converging from Right, 3s Update Rate, Required Detection Range in Feet. 273

Table 126. Remote ID sUAS vs Crewed Following Rules, Overtaking, 3s Update Rate, Required Detection Range in Feet. 274

Table 127. Remote ID sUAS vs Crewed Following Rules, Head-on, 5s Update Rate, Required Detection Range in Feet. 275

Table 128. Remote ID sUAS vs Crewed Following Rules, Converging from Left, 5s Update Rate, Required Detection Range in Feet. 276

Table 129. Remote ID sUAS vs Crewed Following Rules, Converging from Right, 5s Update Rate, Required Detection Range in Feet. 277

Table 130. Remote ID sUAS vs Crewed Following Rules, Overtaking, 5s Update Rate, Required Detection Range in Feet. 278

Table 131. Parameters for all sNMAC volume configuration simulations. 280

Table 132. Relative Size of GPS Uncertainty vs initial sNMAC volume. 291

Table 133. Relative Size of GPS Uncertainty vs sNMAC volume used for testing. 291

TABLE OF ACRONYMS

Acronym	Meaning
AAA	Advanced Aircraft Analysis
ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	Above Ground Level
AM	Avoidance Maneuvers
AMA	Academy of Model Aeronautics
ARC	Aviation Rulemaking Committee
ASSURE	Alliance for System Safety of UAS Through Research Excellence
AVL	Athena Vortex Lattice
BVLOS	Beyond Visual Line Of Sight
CA	Crewed Aircraft
CADR	Collision Avoidance Distance Rings
CFR	Code of Federal Regulations
CPA	Closest Point of Approach
CVSS	Computer Vision Sensor System
DAA	Detect and Avoid
ERAU	Embry Riddle Aeronautical University
FAA	Federal Aviation Administration
FW	Fixed Wing
GA	General Aviation
GPS	Global Positioning System
KU	University of Kansas
MPF	Morphing Potential Field
NMAC	Near Mid Air Collision
PIC	Pilot in Command
QGC	QGroundControl
RA	Reserved Airspace
RAC	Reserved Airspace Concept
RAV	Reserved Airspace Violation
RID	Remote Identification
ROT	Rate of Turn
RoW	Right of Way

RoWV	Right of Way Violation
RPIC	Remote Pilot in Command
RTCA	Radio Technical Commission for Aeronautics
RTK	Real Time Kinematics
SA	Situational Awareness
sNMAC	Small Near Mid Air Collision
SPS	Standard Positioning Service
sUAS	Small Uncrewed Aircraft System
UA	Uncrewed Aircraft
UAS	Uncrewed Aircraft System
UND	University of North Dakota
US	United States
WAAS	Wide Area Augmentation
WC	Well Clear

TABLE OF DEFINITIONS

Adequate Separation	This proposed concept (FAA, 2022), as a replacement of the term ‘well clear,’ is intended to address the context of a broader range of sensing capabilities available in aviation more specifically. The word ‘see’ is contextually incorrect regarding Uncrewed Aircraft (UA). Available avionics provide the same core intent to identify other aircraft and avoid collisions.
Collision Avoidance	Collision avoidance involves preventing an intruder from penetrating a volume of airspace centered on the aircraft within which avoidance of a collision can only be considered a matter of chance (FAA, 2016; DoD, 2011). Collision avoidance is distinct from well clear, in that well clear provides greater separation than collision avoidance. Collision avoidance can rely on both human and automated systems. The pilot uses proper scanning techniques, sounds (for Uncrewed Aircraft System (UAS) pilots), and vigilance. Automated systems include a sense and avoid system function where the Pilot in Command (PIC) is alerted to a conflict and manually takes action, or the UAS diverts to prevent a collision.
Cooperative intruders	Cooperative intruders carry equipment that allows the ownship to receive state information about the intruder, Electronic transmission of position information to include Mode C or Automatic Dependent Surveillance-Broadcast (ADS-B) are examples of cooperative technology. It’s important to note that not all cooperative intruders are ADS-B equipped. ADS-B equipage is a subset of the larger set of cooperative aircraft. (Ramasamy, 2015)
Non-cooperate Intruders	Non-cooperative intruders are "silent" and all state data must be determined by sensors supporting the UAS operation, which include both onboard and ground-based systems. (Ramasamy, 2015)
Detect and Avoid (DAA)	The capability of a UAS to remain well clear from and avoid collisions with other aircraft. (Federal Aviation Administration, 2009).
Mid-sized uncrewed aircraft	There is no standard definition of mid-sized UA. However, for purposes of this research, a mid-sized UA is one that is greater than 55 pounds but smaller than an aircraft capable of carrying a person. This can include aircraft such as the RMAX uncrewed helicopter, a ScanEagle, or the RQ-7 Shadow fixed wing drone. The distinction for this research is not necessarily based on weight or size however, but on conspicuity.
Reserved Airspace Concept (RAC)	A volume of airspace with defined boundaries and times within which particular rules apply, and which particular aircraft might be operating within. This supports operations in controlled or uncontrolled airspace and conceptually exists as two types; First, a 3D polygon-shaped block of airspace second, a 3D corridor defined by specified height, width, and

length that can support Beyond Visual Line of Sight (BVLOS) operations The intent of the RAC is to segregate aircraft that cannot reasonably detect each other, specifically, to segregate crewed aircraft that are not equipped with ADS-B out, from uncrewed aircraft that cannot detect aircraft that are not equipped with ADS-B out.

Right-of-way (RoW) (FAR 91.113)	The right of a vehicle to proceed with precedence over others in a particular situation. Right of way rules establish which aircraft in any encounter must give way to the other aircraft. 14 CFR § 91.113 is Right-of-way rules: Except water operations.
Right-of-Way Violation (ROWV)	A right-of-way violation occurs when an aircraft, despite having the right of way, is compelled to change its course in order to avoid a collision with another aircraft. This implies that the other aircraft failed to yield as required, thereby infringing upon the right of the first aircraft to proceed on its intended path without obstruction.
See and Avoid (FAA-H-8083-3C)	See and avoid refers to the obligation conferred on each person operating an aircraft to maintain vigilance so as to see and avoid other aircraft. See and avoid includes the requirement to give way to aircraft with the RoW, and not pass over, under, or ahead of it unless well clear. 14 Code of Federal Regulations (CFR) Part B states that when weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft. When a rule of this section gives another aircraft the RoW, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear. This concept relies on knowledge of the limitations of the human eye and the use of proper visual scanning techniques to help compensate for these limitations. Pilots should remain constantly alert to all traffic movement within their field of vision, as well as periodically scanning the entire visual field outside of their aircraft to ensure detection of conflicting traffic. A proposal in the BVLOS Aviation Rulemaking Committee (ARC) Final Report (BVLOS ARC (FAA, 2022), 2022) recommends replacing this term with ‘detect and avoid.’
See and Be Seen	Visual separation of air traffic depends on the principle of see and be seen, which requires that each person operating an aircraft maintain vigilance so as to see and avoid other aircraft and recommends that each person operating an aircraft make their own aircraft as visible as possible to other aircraft. The "See and Be Seen" concept incorporates both detection and conspicuity to enable safe interactions between aircraft. It is foundational to the principles of see and avoid, right-of-way, night lighting, and much of Part 91. The concept also underpins electronic detection and conspicuity systems, including transponders, TCAS, and ADS-B In/Out.

Sense and Avoid	Sense and Avoid is the capability of a UAS to remain well clear from and avoid collisions with other airborne traffic. Sense and avoid provides the functions of self-separation and collision avoidance to fulfill the regulatory requirement to see and avoid (DoD, 2011).
Shielded Operation	The FAA Drone Advisory Committee defines shielded operations as "flight within close proximity to existing obstacles and not to exceed the height of the obstacle" (Federal Aviation Administration, 2020c, pg. 31). Civil Aviation Authority of New Zealand defines a shielded operation as one in which the "drone remains within 100 meters of, and below the top, of a natural or man-made object" (Civil Aviation Authority (CAA) of New Zealand, 2019).
Small Uncrewed Aircraft	Small Uncrewed Aircraft are small platform and associated elements (including communication links and components that controls the craft) that are required for the safe and efficient operation of such in the National Airspace System (AIM, 2021). The actual aircraft must weigh less than 55 lbs. on takeoff including everything on board or otherwise attached (FAA, 2021).
Swarm	Swarms are biologically inspired collective robot systems, operate without centralized control, which uses local interactions with other robots and the environment as control inputs. Swarms use indirect communication from a leader robot to perform complex action or behavior. The disturbance to individual robots may not affect the overall ability or satisfy the collective goal (Leaf 2021).
Multi-Robot system	A multi-robot system consist of few agents which are assigned to do a specific task, which they cooperate to complete a goal. In a multi-robot system, each robot is able to do some sub-tasks of a given task. For such multi-robot system, it requires all the nodes (robots/drones) to reach the ultimate goal.
Well Clear	Well Clear is used in 14 CFR 91.113 to define the separation that a pilot must maintain between their aircraft and another aircraft with the RoW so as to not violate or interfere with the other aircraft's RoW. Part 91. states that when encounters occur, the aircraft that does not have the RoW shall give way to the aircraft with the RoW, and may not pass over, under, or ahead of the aircraft with the RoW unless well clear. A recommendation in the BVLOS ARC (FAA, 2022) proposes to replace this term with 'adequate separation'.

EXECUTIVE SUMMARY

Right-of-Way (RoW) rules govern the interactions between aircraft in order to coordinate aircraft encounters and preserve safety. The overall purpose of this project is to inform rulemaking and standards development regarding potential RoW concepts for manned and unmanned aircraft in the low altitude environment

This report presents documentation and analysis of the simulations efforts outlined in Task 3 Simulation Plan and the Final Task 4 Flight Test Plan.

As described in the simulation and flight test plans, there were three key areas that were addressed to answer the research questions posed: General Interactions – focusing on head-on, converging, and overtaking as outlined in FAR Part 91; Reserved Airspace Concept – which was a concept developed as a result of Task 2 when researchers provided a possible short-term solution to assist in the separation of small Unmanned Aircraft Systems (sUAS) and non-cooperative crewed aircraft when sUAS are operating Beyond Visual Line Of Sight (BVLOS); and Remote Identification (RID) – to identify if RID could be effective tool for determining RoW for encounters between UAS as well as used to assist in execution of RoW rules that are being recommended in the final report.

Initial interpretations suggest that for the Federal Aviation Administration (FAA) to proceed with RoW rules pertaining to sUAS and crewed aircraft, the following key themes will need to be addressed in rule making:

- Crewed aircraft are unable to effectively visually identify sUAS; therefore, the burden must be left to the BVLOS sUAS aircraft to detect and avoid.
- Specifications on maneuverability and handling characteristics of unmanned aircraft to ensure separation standards are met.
- Specification on the accuracy of the sUAS technology to operate BVLOS, for example maintaining a given altitude or location accuracy.
- Specifications on crew reaction times to accomplish a collision avoidance maneuver such as a descending turn to remain well clear.
- Clear separations standards for Detect And Avoid (DAA) systems to provide adequate warning of collision based on speed of two aircraft, including two sUAS or a sUAS and crewed aircraft, that will result in a Near Mid-Air Collison (NMAC) or well clear violation.
- Specifications on the reservation of certain airspace to allow for the short term commercialization of sUAS operations yet also enable fair use of the airspace to all users.
- Current minimum regulatory requirements for remote ID systems are not adequate to separate sUAS from other sUAS traffic in BVLOS scenarios.
- Well Clear (WC) and NMAC distances, vertically and horizontally, need to be identified for sUAS when passing manned aircraft and other sUAS.

The data and interpretations within this report will assist the research team to provide information needed to to assist in potential ROW policy changes for specific scenarios such as: encounters between one or more UAS and encounters between UAS operating BVLOS and cooperative or non-cooperative crewed aircraft..

As specified in Task 2, this research is focused on sUAS operating in the National Airspace System below 400ft Above Ground Level (AGL) BVLOS. The results of this report will be used in a successive final report to provide a reasoned and well-founded set of criteria to assist in potential ROW policy changes for specific scenarios.

These simulations and flight tests were also performed to analyze the competing requirements to manage risks with UAS flight and risks with crewed aircraft. While the aim is to be comprehensive, the researchers acknowledge that a feasible solution must also be practicable in nature and certain scenarios will need to be prioritized based on FAA and industry feedback.

1 SIMULATIONS

As described in the Simulation Test Plan, previously submitted by the research team, a variety of simulation platforms were used to conduct simulation testing for Right-of-Way rules. Among these platforms included was 1) Fast-time Simulation Testbed - high fidelity six-degree freedom dynamic software that performs sweeps over aircraft and sensor performance parameters to generate metric data; 2) Simlat - This commercial software platform performs real-time simulations in a simulated world with direct control of the aircraft; 3) Anylogic - This commercial software platform can be used to develop multimethod simulation modeling; and 4) High-Fidelity Multi-Agent Heterogeneous Unmanned Aircraft System (UAS) Simulation - in-house simulator developed by University of Kansas (KU) that uses high fidelity six degrees of freedom dynamic model of unmanned aerial systems instead of a point mass.

1.1 Configuration

1.1.1 University of North Dakota

Two fixed wing aircraft models, one sUAS and one crewed, are primarily used by the fast-time and real-time simulation environments for evaluating the proposed right-of-way rules. The fixed wing sUAS is modeled as a Super Hauler BTE with the general performance characteristics shown in Table 1. The crewed aircraft is a Cessna 182T with the general performance characteristics shown in Table 2.

Table 1. Super Hauler performance.

BTE Super Hauler	
Endurance (minutes)	90
Maximum Climb Rate (ft min^{-1})	670
Cruise Speed (kts)	40
Maximum Forward Speed (kts)	78
Maximum Bank Angle (°, limited via autopilot settings)	60

Table 2. Cessna 182T performance.

Cessna 182T	
Never Exceed Speed (V_{ne}, kts)	175
Maneuvering Speed (V_a, kts at max. gross weight)	110
Assigned Cruising Speed (kts)	120
Maximum Climb Rate (ft min^{-1} at 84 knots)	1,040
Assigned Climb Rate (ft min^{-1})	670

To evaluate the proposed right-of-way rules, multiple encounters were simulated covering the common types of approach geometries of head-on, converging, and overtaking as defined by Radio Technical Commission for Aeronautics (RTCA) DO-365 [1]. These encounters were set up to result in an unmitigated sUAS Near Mid-Air Collision (sNMAC) violation of under 50ft and are deterministic to allow for direct comparison of multiple runs of the encounter set. To allow for direct comparison of multiple simulations runs all of the basic parameters are held constant and a sweep is performed over the maneuver start distance to determine at which point the aircraft(s) are able to maintain a safe distance while following the right-of-way rules. This allows for changing a single parameter, like the Global Positioning System (GPS) uncertainty, to see how it affects the ability of the aircraft to maintain a safe distance. For the following scenarios, this resulted in millions of encounters being performed for each scenario tested.

Two safety volumes were used to evaluate if an encounter failed, a modified sNMAC and small well clear. A modified sNMAC of 100ft horizontal and 25ft vertical was used instead of the original proposed 50ft horizontal and 15ft vertical sNMAC volume due to its relatively small size compared to larger sUAS and GPS uncertainty. The analysis for this choice can be found in the appendix. The small well clear volume, from crewed aircraft, used is a static volume of 2000ft horizontal and 250ft vertical [2].

While performing the scenarios, the aircraft's performance and response can be restricted to limit its airspeed, vertical performance, or type of maneuver performance. The aircraft's airspeed was limited to 38-58 knots and the climb/descent rate was 250fpm, 500fpm, 750fpm, or 1000fpm. The aircraft's type of response was also limited to horizontal-only, vertical-only, or unrestricted maneuvers to evaluate whether vertical or horizontal performance is best for a given approach geometry and performance configuration. To allow for direct comparison of the results, the response maneuver horizontally was restricted to a fixed maneuver of 110 degrees with the reasoning behind this response explained in the appendix.

The response time of the maneuvering aircraft was also tested for a quick response time of 1s and a nominal pilot response time of 5s to evaluate the rules in a nominal and quick response scenario. The latter represents the time a pilot of average skill may require shifting from being confronted or surprised by a problem to moving through recognition of it and formulating a response to take action. For remote ID scenarios, the update rate of the intruder was also tested for the following update rates: 0.2s, 1s, 3s, and 5s.

Four primary categories of GPS devices that provide different uncertainties [3] were used in the simulations. These are: Real Time Kinematics (RTK) [4], Wide Area Augmentation (WAAS) enabled GPS [5], Standard Positioning Service (SPS) GPS [6], and a reasonable upper bound of unaided GPS uncertainty [6], as shown in Table 3.

Table 3**.** GPS Uncertainty.

GPS Receiver	Horizontal Uncertainty	Vertical Uncertainty
RTK	0.1ft (0.03m)	0.33ft (0.1m)
WAAS	3.28ft (1m)	7.22ft (2.2m)
SPS	5.64ft (1.72m)	11.22ft (3.42m)
MAX	26.25ft (8m)	42.65ft (13m)

To facilitate testing the proposed right-of-way rules in Task 2, numerous encounters were performed using the above variations in performance, uncertainty, and test scenarios. Table 4 and Table 5 show the total number of encounters performed for each of the scenarios for the general interactions and Remote ID sections of the report.

Table 4. Number of encounters simulated for General Interactions.

Geometry	sUAS vs sUAS Following Rules	sUAS vs sUAS Not Following Rules	sUAS vs Crewed Following Rules
Head on	806,400	806,400	806,400
Converging	844,800	844,800	1,689,600
Overtaking	1,958,400	1,958,400	1,958,400
Total	3,609,600	3,609,600	4,454,400

Table 5. Number of encounters simulated for Remote ID Interactions

Geometry	sUAS vs sUAS Following Rules	sUAS vs Crewed Following Rules
Head on	3,225,600	3,225,600
Converging	3,379,200	6,758,400
Overtaking	7,833,600	7,833,600
Total	14,438,400	17,817,600

1.1.2 University of Kansas

The focus of simulations by KU is the simulation of *autonomous* UAS flight control to avoid right of way violations with regards to other aircraft. Further, the simulations are intended to simulate avoidance maneuvers one might expect for UAS operated in missions during which the UAS would *return to its mission* following the successful avoidance of a crewed aircraft or another

UAS. As such, the avoidance maneuvers simulated have the additional complication of needing to return to the mission. This has the important characteristic that the many computed trajectories of encounter maneuvers *which return to mission flight lines* in the General Interaction scenarios provide an estimate of the volume of airspace within which the UAS would be expected to need for normal operations interrupted by avoidance of a Right of Way Violation (RoWV). Therefore, the *required* size of Reserved Airspace (RA), including a flight corridor, can be *derived*. Alternatively, given a *proposed* size of a RA, the probability of a Reserved Airspace Violation (RAV), P_{RAV}, can be computed. Regarding the analysis of the minimum size of a RA, the tendency to return to the UAS mission after an encounter might not result in the smallest estimate of the required size of RA. In particular, with the added constraint on the navigation and guidance algorithm to specifically avoid a RAV, the required size of a RA or the P_{RAV} for a given size of a RA could likely be reduced if the UAS turn rate is (autonomously) increased from a nominal rate to the rate needed to avoid exiting the RA.

1.1.2.1 Summary of the simulations conducted

The KU simulation can be configured for a variety of scenarios and missions. For this investigation, these missions include the same General Interactions studied by the University of North Dakota (UND) and Embry Riddle Aeronautical University (ERAU) as well as two RA scenarios: flight in a corridor of fixed width and a grid surveying mission. In all scenarios the simulation consists of either a single sUAS or multiple sUAS flying in fixed formation encountering a crewed aircraft. These encounters are:

- at the same altitude;
- for a range of encounter angles;
- for three relative speeds; or
- designed such that a mid-air collision would occur if there were no avoidance maneuvering.

Based on the assumption that the crewed aircraft will not see the sUAS or the multiple sUAS in formation, in all cases the pilot of the crewed aircraft does not maneuver. As such, the sUAS will frequently be referred to as “ownships” and the crewed aircraft as the “othership.” In all single sUAS cases, only horizontal maneuvers area used. For multiple sUAS avoidance maneuvers there are some vertical maneuvers as well.

The main parameter of interest is the required detection distance for a sUAS detect and avoid system to avoid a RoWV over all encounter angles for a given relative speed. For encounters with a crewed aircraft, a right of way violation means not maintaining the required well-clear separation of 2000 ft horizontally and 250 ft vertically. A secondary parameter of interest is the avoidance of a Near Mid-Air Collision (NMAC). In addition, the percentages of RoWV and NMAC are computed, which quantify the percentage of encounter angles at a given detection distance that result in a RoWV or NMAC.

In the flight in a corridor scenario, the sUAS or multiple sUAS are flying along the centerline of a reserved airspace corridor like what might happen when a sUAS is inspecting power lines over a long distance. The single sUAS or multiple sUAS are geographically constrained in a reserved corridor where it cannot exit the reserved airspace. Because of this restriction, the sUAS or multiple sUAS must avoid a crewed, non-cooperative aircraft while remaining inside of the reserved airspace. The recommendations and results for the moving corridor scenario are based upon the avoidance maneuvers in the General Interaction scenarios wherein the sUAS automatically returns--rather efficiently--to the intended course after the encounter. This then establishes the required width of the corridor, ensuring that the UAS does not exit the reserved corridor.

In the grid surveying scenario, the sUAS or multiple sUAS are flying in a surveying pattern to simulate a mission like agricultural spraying or ground mapping. While the sUAS or multiple sUAS are flying in this surveying pattern, an non-cooperative crewed aircraft enters into the reserved airspace. The sUAS or multiple sUAS, upon detecting the crewed aircraft maneuvers to avoid a ROW violation while still remaining inside its reserved airspace. The grid surveying scenario is the only case where changes in altitude are simulated, and only for the case of the multiple sUAS in which the sUAS must avoid each other, which is accomplished with a small vertical separation.

In all simulations using the KU simulator, the crewed intruder aircraft is modeled as a Cessna 172. The heading and location at which the intruding aircraft will collide with the sUAS or multiple sUAS can be configured at the researcher's discretion. The sUAS and multiple sUAS are modelled as SonicModell SkyHunters.

For Round 1 sUAS interactions with crewed aircraft, sUAS and a formation of two sUAS have been simulated. The studies of crewed aircraft and sUAS interactions by KU were not formally required by the FAA; however, they were conducted to co-validate the analyses by UND and KU. The basis of the comparison is the comparison of KU's autonomous sUAS simulations and UND's simulations of piloted sUAS simulations with the crewed aircraft not following right of way rules. The key take-away of the comparisons is that for the "worst case" maneuvers, that is, when the detection distance is so small that a RoWV is just barely avoided, both KU and UND maneuvers require abrupt turns: for head-on encounters a 105^{o} turn to the right used for all UND encounters is essentially the same maneuver simulated by the autonomous simulations by KU wherein mostly 90^{o} turns are computed. The data generated by the simulations in Round 1 are, as by UND, in the form of graphs of 3 items vs the detection distance: the closest approach of the sUAS to traffic with ROW; the probability of a RoWV vs a crewed aircraft, that is approaching closer than 2000 ft horizontally; and the probability of the UAS entering the NMAC volume of the crewed aircraft, that is, 500 ft horizontally. The KU simulations did not address GPS uncertainty since this effect on ROW violations was carefully studied by UND.

1.1.2.2 Description of the navigation and guidance algorithms

The fundamental basis of the navigation and guidance algorithms explored by KU is the Morphing Potential Field (MPF) or artificial potential field navigation method. This is based on Khatib's research into obstacle avoidance in robotics [1] and similar multi-agent approaches such as Reynolds' ground-breaking work on local flocking behaviors [2] and Leonard and Fiorelli's work on coordinated control of groups [3]. In these approaches, a potential field is computed which creates a repelling influence on navigation and guidance by creating a "cost" to enter an undesired volume of airspace. In particular as in (1:

$$pf = A \cdot exp\left\{-\left(\frac{\|\vec{p}^{obj} - \vec{p}^{o}\|}{\sigma}\right)^2\right\} \quad (1)$$

The numerator of the argument of the exponential is the distance norm between the object to be avoided and the avoiding aircraft. **Error! Reference source not found.** shows a plot of a stationary potential field and a *morphing* potential field.

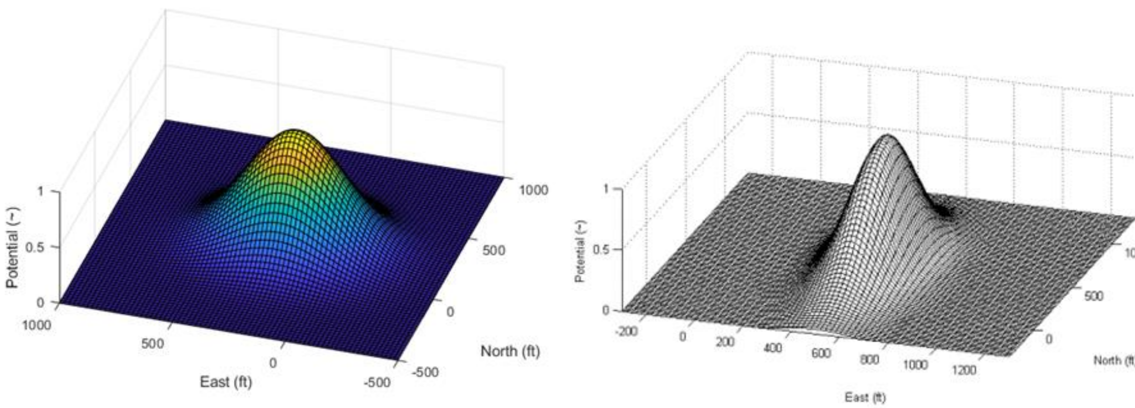


Figure 1. Stationary Potential Field and a Morphing Potential Field.

Considering kinematic and physical constraints of aircraft flying at high speeds (e.g., minimum turning radii and limited deceleration capabilities), the aircraft must begin evasion of obstacles somewhat further in advance than would be necessary for slower moving vehicles (or a stationary object). Use of the generic potential formulation from Equation 1 in such an application is possible but would require significant enlargement in amplitude and/or choice of a larger avoidance radius. The resulting evasion path would be fairly inefficient, with respect to time off the desired trajectory, and lead to unnecessary avoidance maneuvers in aircraft passing an object at a safe distance with a nonconflicting heading, inhibiting operations with tight spatial constraints or in a congested urban area. To remedy these issues, a "morphing" factor G was integrated into the potential function, based on the angle of approach, magnitude of the relative velocity between aircraft, and kinematic aircraft constraints.

This extension of the potential field (visualized in Figure 1) "repels" the avoiding aircraft from entering airspace which might cause a right of way violation without the undesirable effects of amplitude or avoidance radius enlargement seen in the generic formulation. An additional reference shifting term **S** has also been included in the distance norm as a means of further shaping the potential to avoid unnecessary levels of cost beyond the avoided obstacle by shifting the potential function origin c away from the centroid of the object. The resultant formulation is deemed a morphing potential function mpf [4]:

$$mpf = exp\left\{-\Gamma\left(\frac{\left\|\vec{p}^{obj} - \vec{p}^{o} - \vec{S}\right\|}{\sigma}\right)^2\right\} \quad (2)$$

Figure 2 shows the geometric meanings of the terms in parenthesis in (2.

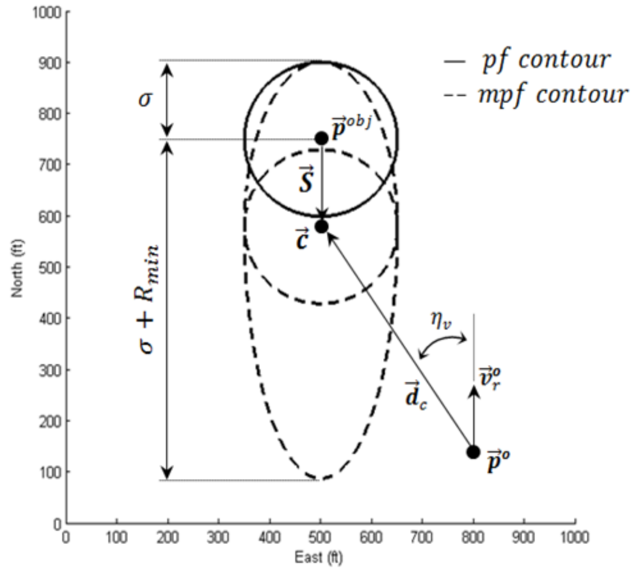


Figure 2. Morphing Potential Field Geometry.

Another approach used in this research is a modification of the MPF algorithm, utilizing the relative distance and detection range as inputs to the avoidance logic. In this simplified version, the minimum required detection range is a function of the relative velocity of two aircraft. This modified approach in the MPF algorithm is discussed in later sections.

1.1.3 Embry-Riddle Aeronautical University

The simulation was implemented in the Julia programming language (Bezanson, Julia: A fresh approach to numerical computing, 2017), using the Agents.jl package (DuBois, Agents.jl: a performant and feature-full agent-based modeling software of minimal code complexity, 2022) for the creation of the model. This simulation has the design goal of being flexible in how the scenarios are defined to allow for future exploration of how maneuvers affect violation risk. Scenarios both define and parameterize the behavior of the agents, whereas the model initialization is responsible for the setup of initial state of the space and agents. The drone and helicopter are placed within a 12,000ft long, 12,000ft wide, and 1,000ft high volume.

Upon the drone encountering the helicopter, it will execute one of three maneuvers. The first maneuver is the standard Right-of-Way (ROW) maneuver, where the drone takes a right-hand turn. The second maneuver is a non-standard Horizontal Maneuver, where the drone can turn left or right to face orthogonally away from the helicopter's path. Finally, the Vertical Maneuver allows the drone to ascend or descend to avoid a violation.

The simulations define a well-clear to be 2000 foot horizontal separation and 250 foot vertical separation between the centers of the aircraft. As visualized in Figure 3, this creates a cylindrical volume that is 2,000 feet in radius and 500 feet in height, for which the enclosed space will be referred to as the violation region. A violation will be defined as the entering of this region, breaking well-clear.

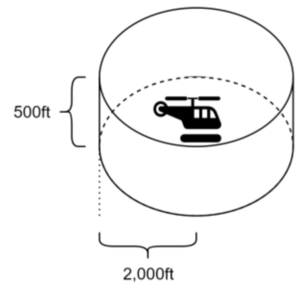


Figure 3. ERAU well-clear definition.

The output of the simulation is the minimum distance measured between each aircraft and what violation occurred. The minimum distance is used to determine the severity of the violation. Probability of a violation is estimated by the ratio of violations to total simulations. Finally, a risk metric can be derived by the product between the mean severity of the violations and the probability of a violation.

1.2 General Interactions (Round 1)

1.2.1 Introduction

General traffic interactions provide a baseline understanding to better evaluate the requirements and performance of interactions between sUAS vs sUAS and sUAS vs Crewed in scenarios where the aircraft follow or do not follow the proposed right-of-way rules. These interactions can help evaluate the required performance and detection capabilities of sUAS in these interactions, especially in the case of sUAS vs Crewed. These results will help determine the feasibility of the proposed rules by exploring if it is possible for sUAS to maintain the required distances given the requirements found during simulations and the type of maneuvers that are required to maintain said distances.

In the assumptions made in the proposed rules, one is that all UAS are operating as cooperative aircraft. One unspoken assumption that always exists is that the ownship aircraft cannot know the opposing aircraft's intentions and response whether it is an uncrewed vehicle or crewed. That aircraft may comply with right-of-way rules or not. In the simulations, two responses are tested: one is that the opposing aircraft complies with conventional right-of-way behaviors and the other one the aircraft continues its current trajectory.

1.2.2 sUAS vs. sUAS (UND)

1.2.2.1 Following Right-of-Way Rules

For this scenario, researchers simulated the outcomes of traffic interactions where both aircraft obey RoW rules, have the same aircraft priority, and give way at appropriate times, given proposed RoW priorities and sNMAC volume. For these tests, the parameters in **Error! Reference source not found.** were used for the interactions.

Table 6. Parameters for sUAS vs sUAS following right of way rule simulations.

Ownship Cruise Speed	38 kts
Intruder Cruise Speed	50 kts
Ownship Maneuvering Speed	38 kts
Vertical Speed limits	250, 500, 750, and 1000 ft/min
Horizontal maneuver	110°
Bank Angle Limit	45°
Pilot Response Delay	1s and 5s
Track Update Rate	1s
Location Uncertainty	RTK, WAAS, SPS, and MAX
Detection Range Increment	~16.4ft (5m)

The sNMAC volume used for the testing was set to 100ft horizontally and 25ft vertically instead of the initially proposed 50ft horizontal and 15ft vertical. Each of the scenarios below was broken into three or four primary categories based on the standard geometry sets, converging, head-on, and overtaking as defined by DO-365. Multiple configurations involving four GPS accuracy categories, four vertical performance limits, and three maneuvering modes consisting of horizontal-only, vertical-only, and unrestricted, were used to test the proposed rules. Restricting the maneuvering type allows for also evaluating what type of maneuver is best for a given convergence geometry while attempting to maintain a safe distance to the sNMAC volume.

Each configuration was tested for a range of detection/maneuver distance to determine what detection range is required to have 0% probability of sNMAC violation while following the proposed right-of-way rules. The overall combination of maneuver, GPS uncertainty, pilot response, and horizontal and vertical performance configurations was then used to evaluate the overall detection range requirements for a given convergence geometry to evaluate the feasibility of the proposed rules regarding the ability of a sUAS to maintain a safe distance. An example of results for one of these configurations is shown in Figure 4, where the *x*-axis represents the detection range of both aircraft in the encounter and the point at which the aircraft(s) will maneuver after a defined pilot response time, 5s in this case, for the given test set. The scatter points and left y-axis represent the distance to the sNMAC volume for each of the geometries tested within the head-on test set while the purple line and right *y*-axis represent the probability of sNMAC violation defined as the percentage of the total geometries that were unable to maintain a safe distance to the sNMAC volume.

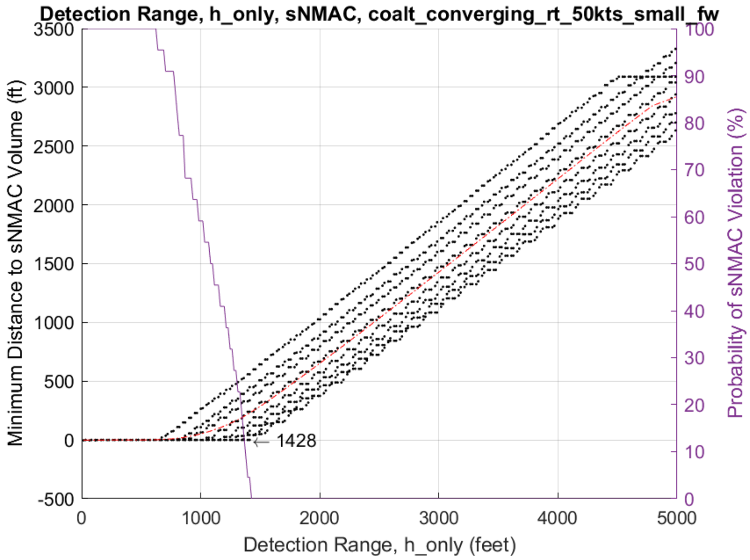


Figure 4. sUAS vs sUAS Following ROW Rules, Converging from Right, Horizontal-only, and with WAAS GPS.

The results below will investigate what type of restricted maneuver, horizontal vs vertical, is best for a given scenario and geometry set. To simply the analysis because the high numbers of data, these results are represented by a matrix that shows which type of restricted maneuver is best using the color coding shown in Figure 5, where blue fields indicate that privileging horizontal maneuvers would be more effective and green fields indicate that privileging vertical maneuvers would be more effective. Yellow fields indicate that the vertical-only maneuver is within +/-5% of the horizontal-only maneuver and either would potentially be viable. The restricted maneuvers are also compared against an unrestricted maneuver to determine if such a maneuver is better.

Horizontal only	Vertical only	Same performance

Figure 5. Depicted colors for best restricted maneuver type.

Although the simulations investigated the interactions for the range [1sec, 5sec] of the pilot response, only the results of worse case corresponding to 5s pilot response time are described below. However, the full set of results for 1s and 5s pilot response times can be found in the Appendix.

1.2.2.1.1 Head-on

In Task 2, it was assumed that UAS are of equal priority and, in the case that they are following right-of-way rules, both aircraft will deviate right for head-on geometries. In the simulations, both aircraft deviate to the right using the maneuver defined in the best turn section at the moment of detection after a specified pilot response delay of 5s. The results discussed below use the 5s pilot response time as it provides a reasonable average for a pilot. The 1s response time results can be found in the appropriate section of the appendix and usually perform better compared to the 5s results.

When the aircraft was restricted to horizontal-only maneuvering, a detection range of 1,313-1,329ft is required for a 5s pilot response time. In the case of horizontally restricted maneuvering, the GPS uncertainty does not represent a significant increase in the overall safety volume and as a result does not have a large effect on the required detection range, as shown in Table .

An example of the horizontal-only result is shown in Figure 6 for the case of a SPS GPS. Due to the small relative bearing size of head-on encounters and the fact both aircraft maneuver right, the differences between the individual head-on geometries are relatively small. Combining this with the high rate of closure and the detection/maneuver range increment of 16.4ft (5m) the results have a relatively small spread and almost stair step like clustering. This results in the transition from 100% probability of sNMAC violation to 0% probability, the purple line, occurring with only one or two distance increments.

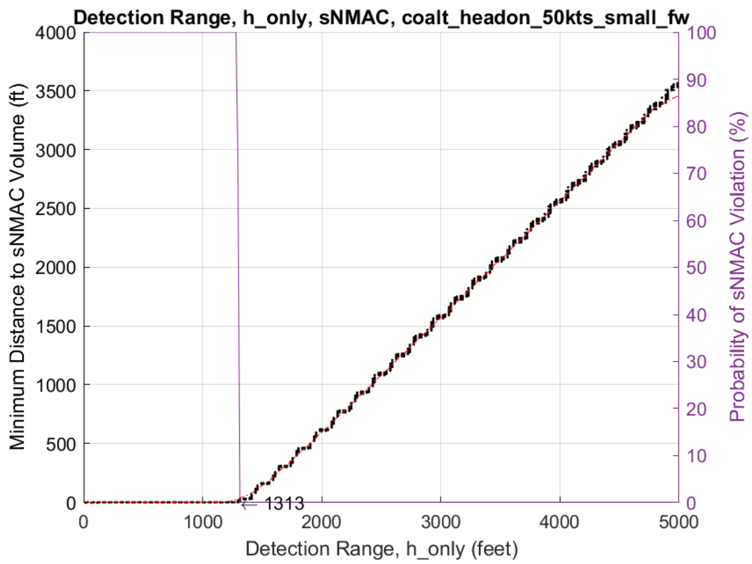


Figure 6. sUAS vs sUAS Following Rules, Head-on, Horizontal-only, SPS GPS.

In the case of vertical-only maneuvering, the GPS uncertainty and the vertical performance, as expected, had a larger effect on the required detection range with ranges varying from 1,149ft in the best configuration to 2,248 ft in the worst case. The required detection ranges for the tested vertical performances are 1,149-1,444 ft for RTK, 1,165-1,493 ft for WAAS, 1,264-1,625 ft for SPS, and 1,313-2,248 ft for MAX.

For restricted maneuvering, vertical-only represented the best maneuver when using a higher precision GPS with high vertical performance while horizontal-only was the best in low vertical performance or high GPS uncertainty configurations, as shown in Table 7. Horizontal and vertical-only were about the same for the rest of the configurations.

Table 7. General interactions, sUAS vs sUAS following RoW rules, head-on.

Head-on	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm	Both			
750fpm	Vertical			
1000fpm				

When executing an unrestricted maneuver, GPS uncertainty and the vertical performance has a significant effect on the required detection range. This is similar to vertical-only maneuvering, with ranges varying from 1,165 ft in the best configuration to 1,329 ft in the worst case. The required detection ranges for the tested vertical performances are 1,165-1,313 ft for RTK and WAAS, 1,264-1,313 ft for SPS, and 1,313-1,329 ft for MAX. This means that an unrestricted maneuver represents the best maneuver for this scenario with required detection ranges most commonly the same as or better than restricted maneuvering. These results demonstrate successful compliance with the proposed rules in Task 2.

1.2.2.1.2 Converging from Right

When two UAS of equal priority converge and the opposing aircraft is approaching from the right, according to Task 2, the ownship aircraft will deviate to the right to pass behind the intruder aircraft.

For horizontal-only restricted maneuvering, a 1,428-1,444ft detection range is required and an example of the horizontal-only results is shown in Figure 7 for the case of a RTK GPS. Compared to the head-on results, there is a larger spread between the individual geometries and there is a more gradual reduction in the probability of sNMAC violation due to the larger relative bearing range for converging geometries.

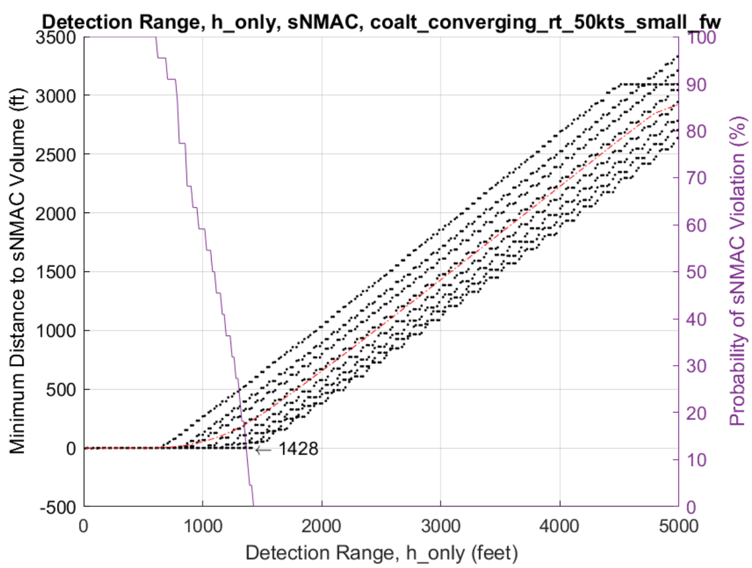


Figure 7. sUAS vs sUAS Following Rules, Converging from Right, Horizontal-only, RTK GPS.

When restricted to vertical-only maneuvers, GPS uncertainty and vertical performance had a larger effect on the required detection ranges which varied from 1,247ft in the best case to 3,216ft in the worst case. Required detection ranges for the tested vertical performances were 1,247-1,772ft for RTK, 1,280-2,051ft for WAAS, 1,296-2,100ft for SPS, and 1,608-3,216ft for MAX.

For restricted maneuvering, a similar trend to head-on scenarios is found: horizontal-only maneuvering is preferred for lower vertical performance or higher GPS uncertainty, while vertical maneuvering is preferred for higher vertical performance or low GPS uncertainty. As shown in Table 8, more of the configurations have better performance when performing horizontal-only maneuvers compared to the head-on results, especially in the case of low vertical performance, 250fpm, or high GPS uncertainty, MAX.

Table 8. General interactions, sUAS vs sUAS following RoW rules, converging from right.

Converging from right	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm	Both			
750fpm	Vertical			
1000fpm				

For these encounters, unrestricted maneuvering again represents the best maneuver. As before, GPS uncertainty and vertical performance had the largest effect on detection range. Here, ranges varied from 1,247ft in the best configuration to 1,542 ft in the worst case. The required detection ranges for the tested vertical performances are 1,247-1,395 ft for RTK, 1,264-1,428 ft for WAAS, 1,264-1,428 ft for SPS, and 1,444-1,542 ft for MAX.

1.2.2.1.3 Overtaking

Given overtaking geometries in sUAS vs sUAS encounters, in Task 2, the ownship has the right-of-way and should continue on course while the opposing aircraft passes on the right using the maneuver defined in the best turn section at the moment of detection after a specified pilot response delay of 5s. The results discussed below use the 5s pilot response time as it provides a reasonable average for a pilot.

The results show that when restricted to horizontal-only maneuvering the required detection range is 558-575ft. An example of the horizontal-only result is shown in Figure 8 for the case of a WAAS GPS restricted to horizontal-only maneuvering. Since the overtaking aircraft is passing the ownship aircraft, the aircraft diverge quickly and the results, therefore, have a relatively small spread and difference between the individual geometries in the overtaking set.

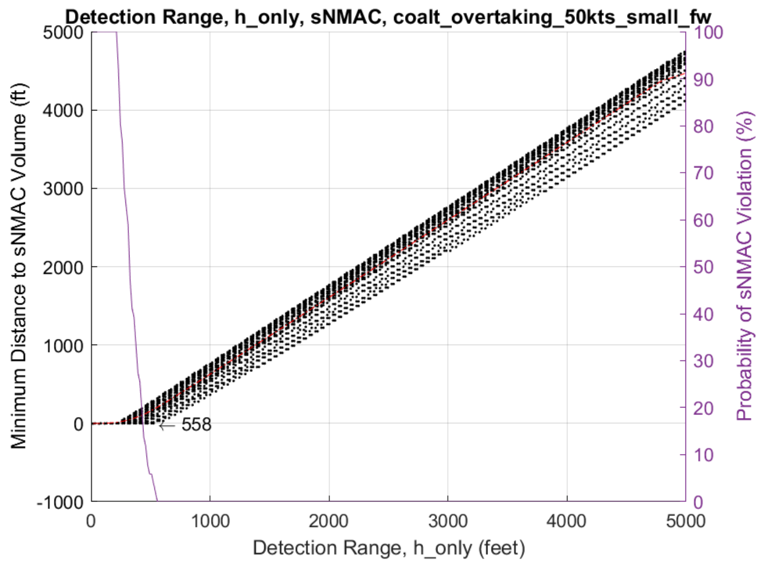


Figure 8. sUAS vs sUAS Following Rules, Overtaking, Horizontal Only, WAAS GPS.

In the case of vertical maneuvering, the GPS uncertainty and the vertical performance had a larger effect on the required detection range varying from 460ft to 1,165ft. The ranges for the vertical performances are 460-673ft for RTK, 460-722ft for WAAS, 476-771ft for SPS, and 591-1,165ft for MAX.

As shown in Table 9 for restricted maneuvering, there are fewer ties and an increase for vertical priority in all except the lowest vertical performance, 250fpm, and highest GPS uncertainty situations. As MAX represents an upper bound for position awareness, this is probably best interpreted as a clearer priority of vertical over horizontal.

Table 9. General interactions, sUAS vs sUAS following RoW rules, overtaking.

Overtaking	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm	Vertical	Both		
750fpm				
1000fpm				

As with head-on and converging scenarios, GPS uncertainty and vertical performance had the largest effect on the detection range. However, unrestricted maneuvering did not always produce the best results. When the aircraft is using a SPS or better GPS and has high vertical performance, 750fpm or greater, the vertical-only maneuvers had better results compared to the unrestricted maneuvering and when the vertical performance is lower, the unrestricted maneuver produced better results.

Detection ranges otherwise varied from 493 ft in the best configuration to 575 ft in the worst case. The required detection ranges for the tested vertical performances are 493-542 ft for RTK, 509-558 ft for WAAS and SPS, and 558-575 ft for MAX.

1.2.2.1.4 Discussion

Unrestricted maneuvers produced equal or better results versus horizontal or vertically restricted maneuvering for the head-on and converging configurations. If the aircraft has reasonable vertical performance of 500fpm or higher and is using SPS or better GPS service, then a detection range of 1,411ft would allow the aircraft to adequately maintain a safe distance from the modified sNMAC volume. If the aircraft is restricted to horizontal, the detection range increases to 1,444ft or 1,608ft for vertical-only maneuvers.

In the case of overtaking geometries with the same above assumptions, a required detection range of 542ft would be adequate for unrestricted maneuvering, 558ft for horizontal-only, and 575ft for vertical-only maneuvering.

To reiterate, we assume in these scenarios that both UAS follow right-of-way rules. A summary of the restricted maneuver results for the tested geometries and GPS uncertainties are shown in Table 10. The vertical only portion of this table shows the required ranges for the 500fpm configuration since this provides a reasonable average vertical performance. With a reasonable minimum vertical performance of 500fpm or larger and using SPS GPS or better, a detection range of 1,608ft is sufficient to maintain separation following the Task 2 proposed Right-of-Way rules in unrestricted and restricted maneuvering.

Table 10. Maximum required detection ranges for sUAS vs sUAS following right-of-way rules.

	Horizontal-only	**Vertical-only (500fpm)**			
Geometry	**All GPS**	**RTK**	**WAAS**	**SPS**	**MAX**
Head-on	1,329ft	1,280ft	1,296ft	1,313ft	1,641ft
Converging from right	1,444ft	1,411ft	1,559ft	1,608ft	2,231ft
Overtaking	575ft	509ft	558ft	575ft	788ft

1.2.2.2 Not Following Right-of-Way Rule

In the following scenarios, we simulate results when the opposing aircraft does not respond or follow the proposed right-of-way rules. Where the opposing aircraft has the right-of-way, this would not change results significantly. When the ownship aircraft has right-of-way but the opposing aircraft fails to give way, the ability to separate from the conflict creates a difficult scenario for the ownship that requires a larger buffer and detection range in order to maintain the sNMAC volume. The same overall methodology, parameters, and configuration from the following right-of-way rules section above are used for this section except now the ownship has right-of-way and the intruder fails to give way resulting in the ownship having to perform an avoidance maneuver to maintain a safe distance. The required detection ranges in the results of this section represent the distance at which the ownship would have to detect the intruder and make the determination that the intruder is not going to give way and deviate from their path.

1.2.2.2.1 Head-on

For the head-on geometries, in the case of sUAS vs sUAS not following right-of-way interactions, the intruder aircraft will not deviate right while the ownship deviates right.

For restricted maneuvering, a detection range of 1,444-1,477ft is required for horizontal-only while the vertical-only maneuvering required a 1,280ft to 3,298ft range depending on the GPS uncertainty and vertical performance. The required detection ranges for the tested vertical performances are 1,280-1,821ft for RTK, 1,296-2,100ft for WAAS, 1,313-2,166ft for SPS, and 1,657-3,298ft for MAX. In this case, the non-right-of-way compliance of the intruder did have a larger effect on the required detection range, especially in the lower vertical performance configurations.

The results are similar to the following right-of-way rules section but with horizontal-only performing better in low vertical performance or high GPS uncertainty configurations. When using a lower uncertainty GPS and a higher performance climb, vertical-only represented the best maneuver while horizontal-only was the best in lower vertical performance or high GPS uncertainty configurations, as shown in Table 11.

Table 11. General interactions, sUAS vs sUAS not following RoW rules, head-on.

Head-on	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm	Both			
750fpm	Vertical			
1000fpm				

When using an unrestricted maneuver, the detection range varied depending on the GPS uncertainty and vertical performance and ranged from 1,264ft to 1,493ft. For the tested vertical performances, the required detection ranges are 1,264-1,428 ft for RTK, 1,296-1,460 ft for WAAS and SPS, and 1,477-1493 ft for MAX. This type of maneuver provided the best overall performance compared to restricted with required detection ranges being about the same as or better than the restricted maneuvering.

1.2.2.2.2 Converging from Left

For the converging from left geometries, in the case of sUAS vs sUAS not following right-of-way rules interactions, the ownship will deviate to the left to avoid the intruder aircraft that fails to pass behind on the right.

For horizontal-only restricted maneuvering the required detection range did change with GPS uncertainty with WAAS or better requiring 1,395ft and MAX requiring 1,411ft. Due to the change from converging from the right to left and the direction of the maneuver, towards the intruder, the required detection range had some variance compared to the following right-of-way scenario but was still in the same general range. The effect of GPS uncertainty was larger for vertical-only maneuvering along with the vertical performance. The tested configurations needed 1,247-3,199ft with the tested vertical performances requiring 1,247-1,772ft for RTK, 1,280-2,051ft for WAAS, 1,296-2,100ft for SPS, and 1,608-3,199ft for MAX. In this case, the required detection range did not change compared to the following right-of-way scenario since the vertical-only maneuver is deviating in the same way at the same distances with the same relative geometry, just flipped from right side to the left side of the ownship.

A similar trend is found where horizontal-only maneuvering is preferred in lower vertical performance or higher GPS uncertainty configurations with similar results compared to head-on. As shown in Table 12, more of the configurations have better performance when performing horizontal-only maneuvers, especially in the case of low vertical performance, 500fpm or less, or high GPS uncertainty, MAX.

Table 12. General interactions, sUAS vs sUAS not following RoW rules, converging from left.

Converging from left	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm	Both			
750fpm	Vertical			
1000fpm				

Again, an unrestricted maneuver provides the best overall results with almost all of the configurations producing about the same or better results compared to restricted. The required detection ranges were similar to the best of horizontal-only and vertical-only individually varying from 1,231ft to 1,428ft with each of the tested vertical performances requiring 1,231-1,395 ft for RTK, 1,264-1,395 ft for WAAS, 1,264-1,411 ft for SPS, and 1,428 ft for MAX.

1.2.2.2.3 Overtaking

For the overtaking geometries, in the case of sUAS vs sUAS not following right-of-way rules interactions, the ownship has the right-of-way but the intruder will fail to pass requiring the ownship to maneuver. This is a taxing maneuver for the ownship compared to the following right-of-way rules scenario.

In the case of horizontal-only maneuver, none of the configurations were able to maintain a safe distance to the sNMAC volume within the maximum range tested. Increasing the maximum detection range for the simulations could result in the ownship being able to maintain a safe distance but this would be a significantly larger distance than required distances for vertical-only. Because of the capped maximum detection range, a safe distance could not be maintained given the types of maneuvers available to the ownship aircraft. In earlier maneuver samples, the aircraft could potentially remain clear given a larger distance and/or a different maneuver using, for example, a higher bank angle, but we regard these as beyond the scope of these tests. Disregarding these edge cases, individual traffic encounters could maintain clearance from sNMAC, but not the entire sweep of potential geometries.

Unlike horizontal-only, vertical-only is able to maintain a safe distance and is therefore the best type of restricted maneuver, as shown in Table 13, with a required detection range of 460ft-1,165ft with each of the GPS uncertainties requiring 460-624ft for RTK, 493-771ft for WAAS, 509-771ft for SPS, and 624-1,165ft for MAX. These results are similar to the following right-of-way rules scenario but with slight variance due to changing the aircraft that is maneuvering. Overall this is a change compared to the follow right-of-way scenario where horizontal-only is the best in some of the configurations.

Table 13. General interactions, sUAS vs sUAS not following RoW rules, overtaking.

Overtaking	RTK	WAAS	SPS	MAX
250fpm	Vertical			
500fpm				
750fpm				
1000fpm				

Unlike head-on and converging, an unrestricted maneuver did not always produce the same or better results. When the aircraft is using SPS or better GPS and 500fpm or greater vertical performance similar or better results are produced but in the other configurations the vertical-only maneuver would produce better results. Here, the ranges varied from 460-1,838ft and the required detection ranges for the tested vertical performances are 460-968 ft for RTK, 493-1,001 ft for WAAS, 509-1,034 ft for SPS, and 624-1,838 ft for MAX.

1.2.2.2.4 Discussion

An unrestricted maneuver produced the best results or at worst about the same results as restricted maneuvering for almost all of the head-on and converging configurations. If the aircraft has reasonable vertical performance, 500fpm or larger, and is not using GPS with MAX uncertainty, then a detection range of 1,428ft would allow the aircraft to adequately maintain a safe distance from the modified sNMAC volume used during testing with an unrestricted maneuver. If the aircraft's maneuvering is restricted, then the required detection range increases to 1,641ft for vertical maneuvers and 1,477ft for horizontal maneuvers.

In the case of overtaking geometries with the same above assumptions, a required detection range of 558ft would be adequate for unrestricted or restricted maneuvering. Horizontal-only maneuvering is not effective in this scenario for overtaking.

To reiterate, we assume in these scenarios that the intruder UAS does not follow the right-of-way rules. From the test results the required detection ranges for the GPS uncertainties and a reasonable lower vertical performance of 500fpm are shown in Table 14. With a reasonable minimum vertical performance of 500fpm or larger and using SPS GPS or better, a detection range of 1,641ft is sufficient to maintain separation in the scenario where the intruder fails to follow the Task 2 proposed Right-of-Way rules in unrestricted or restricted maneuvering.

Table 14. Maximum required detection ranges for sUAS vs sUAS not following right-of-way rules.

	Horizontal-only	Vertical-only (500fpm)			
Geometry	**All GPS**	**RTK**	**WAAS**	**SPS**	**MAX**
Head-on	1,477ft	1,444ft	1,592ft	1,641ft	2,281ft
Converging from left	1,411ft	1,411ft	1,559ft	1,608ft	2,231ft
Overtaking	NA	509ft	558ft	558ft	821ft

The detection range, 1,641ft, is only slightly larger than the 1,608ft distance required in the case where both aircraft follow the proposed right-of-way rules but is dependent on the ownship realizing the intruder failed to give way at this range. The required ranges would need to be larger than the values found during testing for sUAS vs sUAS scenarios to allow for the pilot to make the determination if the intruder is going to follow the right-of-way rules.

1.2.3 sUAS vs Crewed (UND)

1.2.3.1 Following Right-of-Way Rules

From Task 2, sUAS vs Crewed scenarios, the crewed aircraft has right-of-way so the sUAS must perform avoidance maneuvers. Table 15 provides the simulation parameters used for the interactions. Due to the larger delta between the aircrafts performance and the larger safety volume the best restricted maneuver for each of the tested geometries is more consistent compared to the sUAS vs sUAS scenarios. Horizontal-only is the best maneuver in the case of converging and head-on geometries for all tested configurations, as shown in Table 16, Table 17, and Table 18. The only exception for this is horizontal-only and vertical-only are about the same for head-on geometries with 1000fpm vertical performance and an SPS or better GPS uncertainty. For overtaking, the best maneuver is the vertical-only, as shown in Table 19. The results given and used in the discussion below correspond to the pessimistic case (5s pilot response time). The full results can be found in the appendix.

The same overall methodology and geometries for the sUAS vs sUAS scenarios were used for investigating the interactions of sUAS vs. Crewed, except that a small well clear volume is used instead of the sNMAC volume defined as 2000 ft horizontally and 250 ft vertically [2].

Table 15. Parameters for sUAS vs Crewed following right-of-way rule simulations.

Ownship Cruise Speed	50 kts
Intruder Cruise Speed	120 kts
Ownship Maneuvering Speed	50 kts
Vertical Speed limits	250, 500, 750, and 1000 ft/min
Horizontal maneuver	110°
Bank Angle Limit	45°
Pilot Response Delay	1s and 5s
Track Update Rate	1s
Location Uncertainty	RTK, WAAS, SPS, and MAX
Detection Range Increment	~49.21ft (15m)

1.2.3.1.1 Head-on

For the head-on geometries, in the case of sUAS vs Crewed following ROW rules interactions, both aircraft will deviate right while passing. The following simulations had both aircraft deviate to the right using the maneuver defined in the best turn section at the moment of detection after a specified pilot response delay of 1s or 5s, the results discussed below use a 5s pilot response delay.

The required detection range for horizontal-only maneuvering was 7,924ft and did not change between the GPS and vertical performance configurations. In the case of vertical-only, the GPS uncertainty and vertical performance had a larger effect on the required detection ranges which varied from 7,924ft to 13,583ft. For these tests, the 250fpm was unable to maintain a safe distance within the max range tested so it was not included in the results. The other vertical performances required 7,924-11,959ft for RTK, 7,973-12,205ft for WAAS, 7,973-12,451ft for SPS, and 8,514-13,583ft for MAX. Horizontal-only represented the best maneuver in almost all configurations except for the highest tested vertical performance, 1,000fpm, and GPS uncertainties less than MAX. In this case, horizontal-only and vertical-only performed about the same, as shown in Table 16.

Table 16. General interactions, sUAS vs Crewed following RoW rules, head-on.

Head-on	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm				
750fpm				
1000fpm	Both			

With 750ftpm or better vertical performance, unrestricted maneuvering represents the best option for this scenario but when the vertical performance is less than this, the unrestricted maneuver is only as good as the horizontal-only maneuver. Unrestricted requires detection range of 6,497-8,121ft with each of the tested vertical performances requiring 6,497-7,924 ft for RTK, WAAS, and SPS and 6,743-8,121 ft for MAX.

Overall, unrestricted provides the best performance when the aircraft has high vertical performance and in the case of lower vertical performance, 500fpm or less, the horizontal-only restricted maneuvering provided about the same results.

1.2.3.1.2 Converging from Left

For the converging from left geometries, in the case of sUAS vs Crewed following right-of-way rules interactions, the Crewed aircraft has right-of-way so the ownship will give way to pass behind the intruder aircraft.

For horizontal-only maneuvering, a detection range of 7,382ft is needed for the lowest GPS uncertainty, MAX, with the rest of the tested GPS uncertainties requiring 7,235ft. In the case of vertical-only maneuvering, the aircraft was unable to maintain a safe distance when limited to 250fpm within the max range tested so these results are excluded from the discussion. The required vertical-only detection ranges varied from 7,825-13,436ft with each of the remaining vertical performances requiring 7,825-11,861ft for RTK, 7,875-12,107ft for WAAS, 7,973-12,304ft for SPS, and 8,563-13,436ft for MAX. For restricted maneuvering, horizontal-only represented the best maneuver in all configurations as shown in Table 17.

Table 17. General interactions, sUAS vs Crewed following RoW rules, converging from left.

Converging from left	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm				
750fpm				
1000fpm				

Overall, the horizontal-only and unrestricted maneuvering produced about the same results except for when the aircraft has high vertical performance, 1000fpm, in this case the unrestricted maneuvering produced better results than the horizontal-only results. The unrestricted maneuvering ranges varied from 6,546-7,382ft with each of the vertical performances requiring 6,546-7,382 ft for RTK, 6,644-7,382 ft for WAAS, 6,693-7,382 ft for SPS, and 7,038-7,382 ft for MAX.

1.2.3.1.3 Converging from Right

For the converging from right geometries, in the case of sUAS vs Crewed following right-of-way rules interactions, the Crewed aircraft has right-of-way so the ownship will deviate to pass behind the intruder aircraft.

Unlike the converging from left results, the converging from right horizontal-only results did not vary with GPS uncertainty with a required detection range of 7,382ft. Again, the aircraft was unable to maintain a safe distance when limited to 250fpm vertical performance, but the rest of the vertical performances required ranges varied from 7,875ft-13,485ft. The required ranges for each of the vertical performances are 7,875-11,861ft for RTK, 7,875-12,107ft for WAAS, 7,924-12,353ft for SPS, and 8,465-13,485ft for MAX.

For restricted maneuvering, horizontal-only represented the best maneuver in all configurations as shown in Table 18. Converging from the right had similar results and ranges with slight variances due to the change in relative geometries and the performed maneuver, towards vs away from the Crewed intruder.

Table 18. General interactions, sUAS vs Crewed following RoW rules, converging from right.

Converging from right	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm				
750fpm				
1000fpm				

For this scenario, the horizontal-only and unrestricted maneuvering produced about the same results except for when the aircraft has high vertical performance, 1000fpm, in this case the unrestricted maneuvering produced better results than the horizontal-only results. The unrestricted results varied from 6,497-7,530 ft with each of the vertical performances requiring 6,497-7,382 ft for RTK, 6,693-7,382 ft for WAAS and SPS, and 7,038-7,530 ft for MAX.

1.2.3.1.4 Overtaking

For the overtaking geometries, in the case of sUAS vs Crewed following right-of-way rules interactions, the ownship does not have right-of-way and needs to maneuver to maintain a safe distance to the Crewed aircraft. This is a stressful maneuver for the ownship compared to the sUAS vs sUAS scenarios due to the larger performance delta between the aircraft. The following simulations had the intruder not deviate and the ownship deviate to the left.

Given the maneuvers available to the ownship aircraft, a safe distance could not be maintained in some edge case encounters given the maximum detection range which was capped to ~19,700ft. In some cases, the aircraft potentially could remain clear if given a larger distance and/or a different maneuver (as opposed to the standard maneuver, as shown in Table 19.), but this was considered to be beyond the scope of the testing. Disregarding these edge cases could have resulted in maintaining well clear, but not across the entire sweep of encounter geometries. In the case of vertical-only maneuvering, the GPS uncertainty and vertical performance had a large effect on the required ranges which varied from 5,709-15,453ft. For each of the tested vertical performances the required distances are 5,709-13,632 ft for RTK, 5,758-13,977 ft for WAAS, 5,808-14,125 ft for SPS, and 6,152-15,453 ft for MAX.

Table 19. General interactions, sUAS vs Crewed following RoW rules, overtaking.

Overtaking	RTK	WAAS	SPS	MAX
250fpm	Vertical			
500fpm				
750fpm				
1000fpm				

Unrestricted maneuvering represented the best maneuver for this scenario with almost all of the configurations producing better results or at worse the same results as the vertical-only. The required detection ranges varied from 5,611-15,256 ft with each of the vertical performances requiring 5,611-13,436 ft for RTK, 5,709-13,780 ft for WAAS, 5,808-13,977 ft for SPS, and 6,152-15,256 ft for MAX.

1.2.3.1.5 Discussion

From Task 2 proposals, the UAS must yield in all cases except in shielded environments where the crewed aircraft is NOT equipped with ADS-B. This means that in the preceding simulations, the sUAS must give way, even where being overtaken by the crewed aircraft. Required detection distances given these requirements becomes large; Table 20 illustrates this fact for an aircraft climbing or descending at 500ft/min. Notably, the required distances shift with avoidance strategy. For head-on and converging traffic geometries, vertical maneuvers become mostly untenable while horizontal maneuvers require large distances. This reverses in the overtaking cases to the point that horizontally restricted maneuvers cannot successfully avoid the opposing aircraft for all tested geometries.

Table 20. Maximum required detection ranges for sUAS vs Crewed following right-of-way rules.

	Horizontal-only	**Vertical-only (500fpm)**			
Geometry	**All GPS**	**RTK**	**WAAS**	**SPS**	**MAX**
Head-on	7,924ft	11,959ft	12,205ft	12,451ft	13,583ft
Converging from Left	7,382ft	11,861ft	12,107ft	12,304ft	13,436ft
Converging from right	7,382ft	11,861ft	12,107ft	12,353ft	13,485ft
Overtaking	NA	8,268ft	8,465ft	8,613ft	9,302ft

These results pose the possibility that the proposed rules in Task 2 for UAS vs. Crewed right-of-way will require some detailed situational prescriptions for UAS maneuvers in specific cases which may not be tenable and an alternate prescription such as utilizing reserved airspace may be necessary. On the other hand, adequate guidance in the form of pilot/operator education on best-practices may be sufficient.

The head-on and converging geometries had similar performance and best maneuvers with both geometries performing best with horizontal-only when restricted. Overall, unrestricted maneuvers usually produced the same or better results versus restricted vertical-only maneuvering, especially with high vertical performance configurations. If the aircraft uses 500fpm climb performance and is not using a GPS with high uncertainty (MAX), then 7,924ft would be required for horizontal-only or unrestricted maneuvers and 12,451ft for vertical maneuvers.

In the case of overtaking geometries with the same performance assumptions as the head-on and converging geometries, unrestricted maneuvering represented the best maneuver with a required detection range of 8,416ft. If the aircraft is restricted to vertical maneuvering the range increases to 8,613ft.

The proposed rules place the burden of avoidance on the unmanned aircraft. This results in larger required detection ranges compared to the sUAS vs sUAS scenario, due to the lower performance of the sUAS compared to crewed aircraft and especially circumstances where the crewed aircraft does not deviate from its path. For this scenario, a detection range of 12,451ft would allow the aircraft to maintain a safe distance when using unrestricted or restricted maneuvering.

For the sUAS to maintain a safe distance in this scenario, the sUAS should have a long-range sensor, functional to at least 12,451ft, or a cooperative and/or DAA system capable of detecting and avoiding the crewed aircraft at the required distance when the aircraft is capable of at least 500fpm vertical performance and equipped with a SPS or better GPS. If the sUAS can meet these requirements, then the proposed rules are acceptable. If they cannot, a different separation structure such as reserved airspace should be considered.

1.2.4 Single and Multiple sUAS vs Crewed (KU)

1.2.4.1 Single sUAS vs Crewed

Simulations were conducted for general interactions between a single sUAS vs a crewed aircraft which does not deviate from its intended path, that is, it does not obey right of way rules—because the assumption is that the pilot cannot see the sUAS. The simulations were conducted for numerous heading angles to essentially cover all possible head-on, converging, and overtaking encounters. Figure 9 shows the definition of the heading angle between the sUAS and the crewed aircraft. Each aircraft heading angle was defined with respect to a global system, and the sUAS heading was always set to be at 0 degrees in the simulations.

Note that for all encounters, the sUAS is flying at a constant 45 ft/s, but the crewed aircraft speed ranged from 145 ft/s to 170 ft/s to 195 ft/s to see the effect of varying the relative speeds. Also, note that the morphing potential field guidance and navigation algorithm is used for all encounters. Modifications to this algorithm are on-going, including a modification to consider non-constant speeds for the sUAS, which is expected to, for instance dramatically decrease the distance a sUAS must deviate from course to avoid traffic. This is further discussed in the section on flight in a corridor.

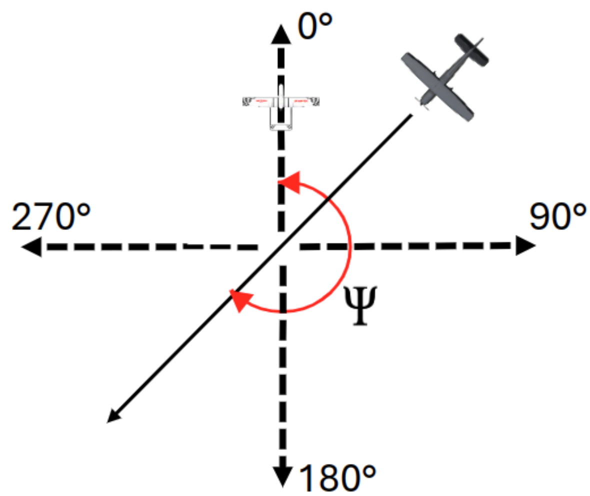


Figure 9. Non-cooperative Aircraft Heading Angle Definition

To highlight the performance of the morphing potential field, the following figures highlight three scenarios when:

1) The detection range is large, causing the sUAS to successfully avoid the non-cooperative aircraft Figure 10.
2) The detection range is an intermediate value, which still allows the sUAS to avoid the non-cooperative aircraft but performs a slightly more evasive maneuver Figure 11.
3) The detection range is too low, causing a ROW violation between the sUAS and the non-cooperative aircraft along with a severe avoidance maneuver Figure 12.

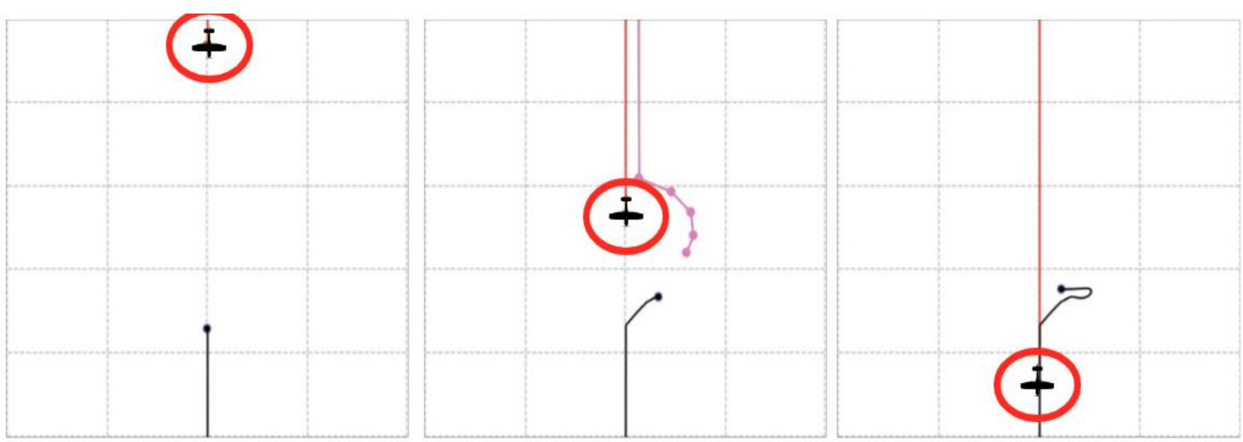


Figure 10. Large Detection Range with Successful Avoidance

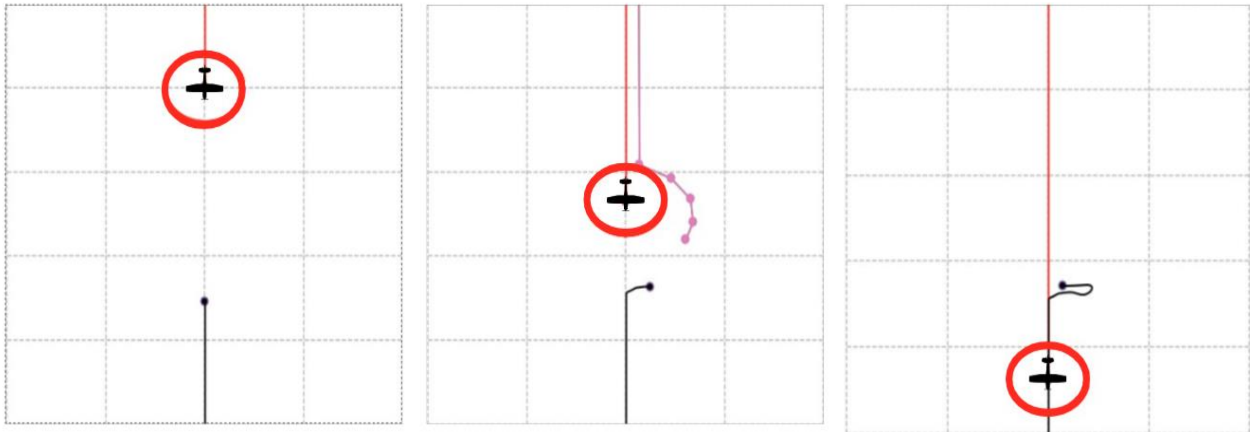


Figure 11. Intermediate Detection Range with Successful Avoidance

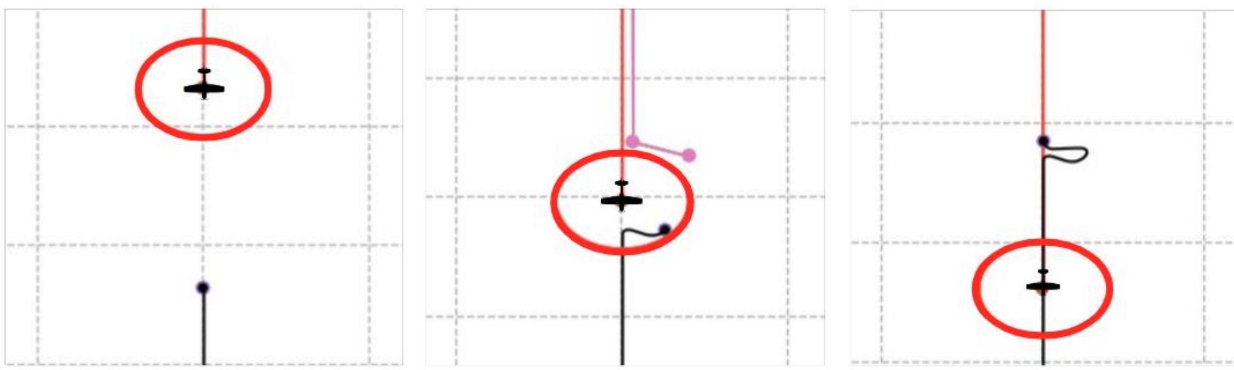


Figure 12. Low Detection Range with ROW Violation

The graphs below highlight the results of the single sUAS vs. Crewed encounters. The graphs are a combination of three plots. One is the detection distance vs the minimum distance between the aircraft during the simulation. The other is the detection distance vs the percentage right-of-way violations (P_{ROWV}) and percentage of near midair collisions (P_{NMAC}). Any simulation case with a minimum distance of 2000 ft or lower is considered a ROW violation, and any with a distance less than 500 ft is considered an NMAC.

The red region shows the percentage of simulations where the sUAS and the Cessna 172 nearly collided midair at the corresponding detection distance. The yellow region shows the percentage of simulations where the sUAS and the Cessna 172 violated the right of way requirement at the corresponding detection distance. The green region shows simulations where the sUAS successfully avoided a NMAC and ROW violation with the simulated crewed aircraft.

As an example of the type of results generated, Figure 13 below shows the results of an non-cooperative aircraft flying at 170 ft/s overtaking a single sUAS with collision angles between 0 and 90 degrees. For there to be no ROW violations, the minimum detection distance was computed to be at least 10,888 ft.

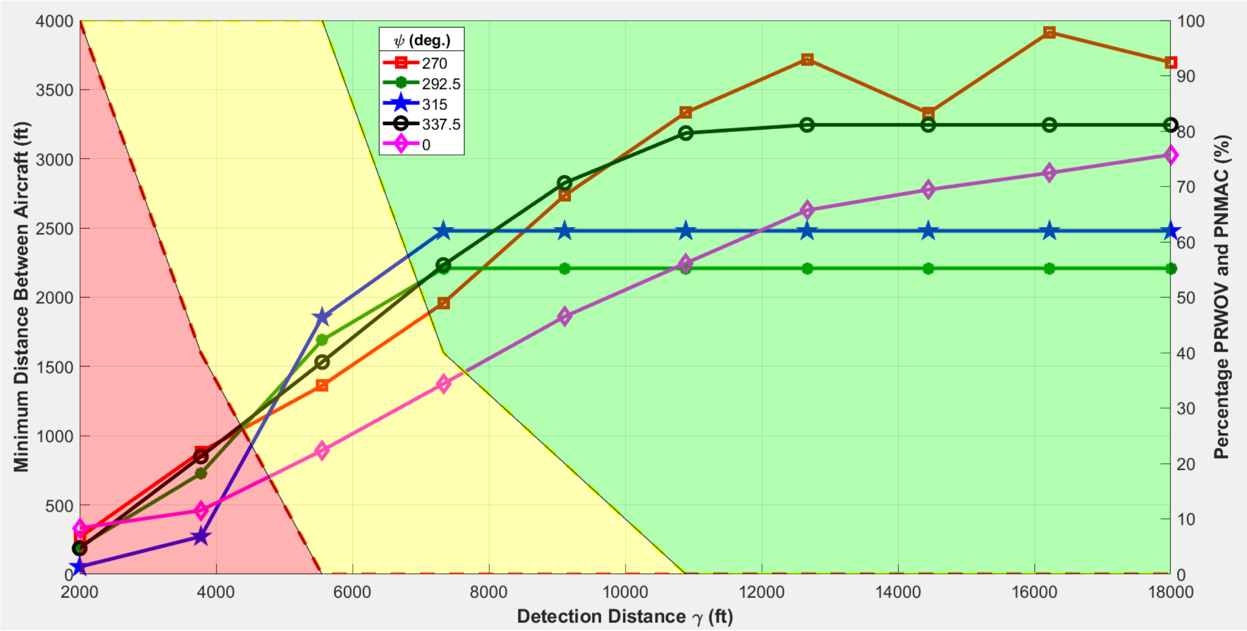


Figure 13. General Interactions 170ft/s Overtaking Single sUAS.

Figure 14 below shows the results of an non-cooperative aircraft flying towards a single sUAS for collision angles between 90 and 180 degrees, once again with the Cessna flying at 170 ft/s. Similar to the data from the overtaking cases, the minimum detection distance must be at least 10,888 ft for the sUAS to avoid ROW violations. Note that the 90-degree encounter angle for both the overtaking and head on converging case are identical. This is so the results can be compared more directly.

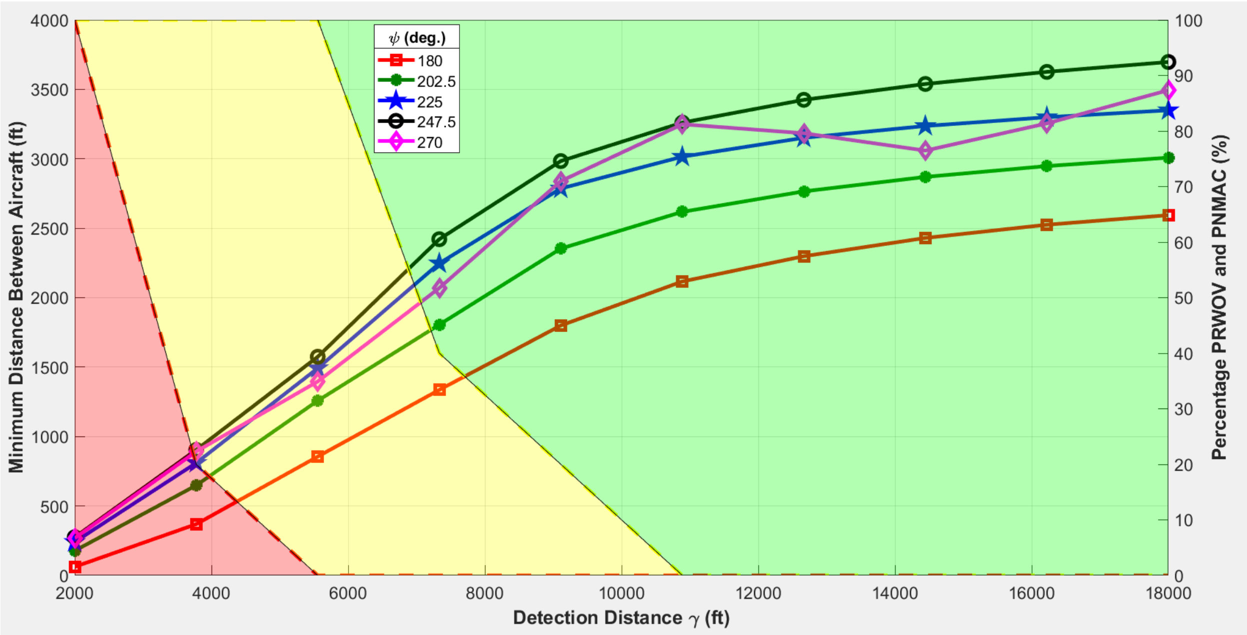


Figure 14. General Interactions 170 ft/s Head-On Converging Single sUAS.

Considering now the simulations with a higher, 195 ft/s, speed of the Cessna, for the head-on converging angles there are a greater number of overall ROW violations, while NMACs remain at the same percentage likelihood. At this higher closing speed, the required detection distance for a worst-case scenario is higher, at 12,600 ft. Figure 15 can be seen compared directly with Figure 14 to see the differences caused by the different closing speeds. All graphs for the head on converging and overtaking scenarios can be found in the appendix.

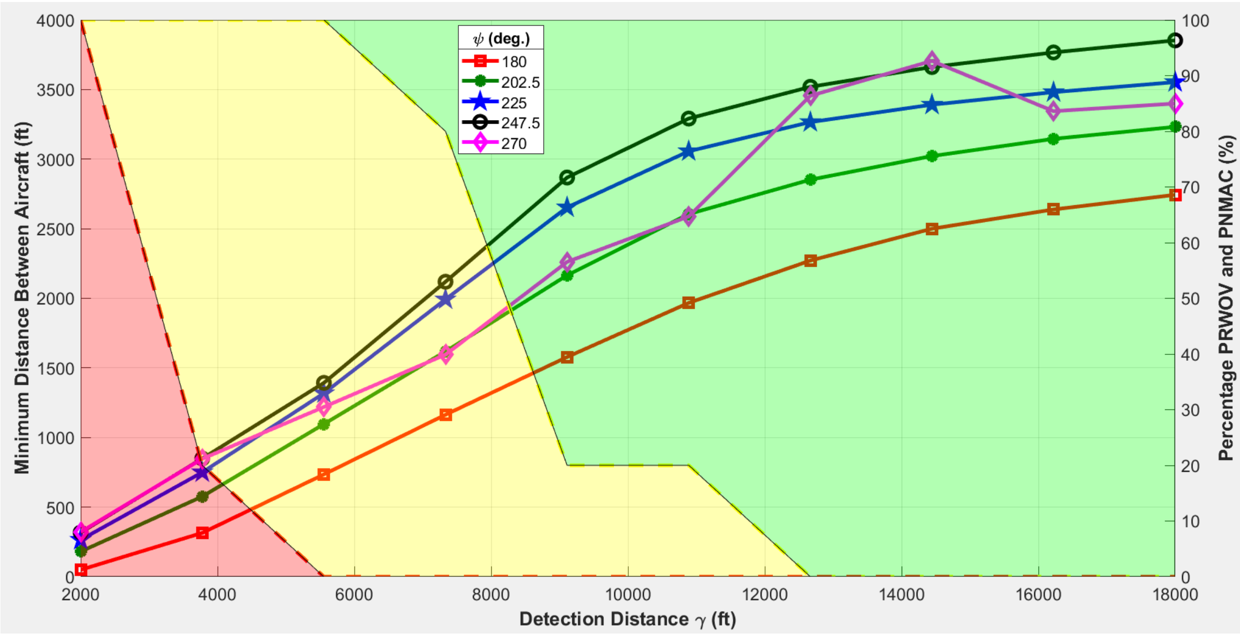


Figure 15. General Interactions 195 ft/s Head-On Converging Single sUAS.

Based on all the General Interactions studied, the highest yaw and roll rates required for a successful avoidance maneuver, are given in Table 21. Worst Case Roll and Yaw and Roll Rates for General Interaction Simulations. Roll rates greater than 45 degrees/s and yaw rates at or above 20 degrees/s were considered undesirable. These values approach the threshold for being considered undesirable but are still within the maneuvering capabilities of the SkyHunter UAS.

Table 21. Worst Case Roll and Yaw and Roll Rates for General Interaction Simulations.

V_{C172} (ft/s)	Roll Rate (deg./s)	Yaw Rate (deg./s)	Proximity (ft)	Det. Dis. (ft)	ψ_{sUAS} (deg.)
145	41	18	3040	18000	0
145	24	19	2530	7300	45
170	43	19	3030	18000	90
195	32	16	3060	10800	135
195	28	20	2750	9100	67

As can be seen in the appendix, the Yaw and Roll rates for the sUAS are well within safe ranges while the sUAS or multiple sUAS is evading the crewed aircraft [5]. There are only a few cases where an sUAS in the multiple sUAS has a higher than recommended roll rate. Yaw Rates above 20 degrees/s and Roll Rates above 45 degrees/s are highlighted in yellow as possible points of concern for the integrity of the sUAS. These cases represent situations where the detection distance was very low, causing a drastic change in sUAS attitude due to attempting an avoidance maneuver. This is due to the morphing potential field, as the strength of the potential field increases with proximity. Detection of the non-cooperative aircraft at the last second causes the sUAS to experience a very strong potential field which leads to severe avoidance maneuvers and undesirable attitude rates.

A graphical example of the worst sUAS attitude rates found can be seen in Figure 16 and Figure 17. They show the roll rates and yaw rates experienced by a single sUAS while attempting to prevent a ROW violation at different heading angles. The direct relationship between low detection distances and undesirable attitude rates can be clearly inferred, as the sUAS makes sudden movements with little time to prevent violations. It can also be seen that most of the attitude rates lie in the acceptable range with no rates approaching adverse levels.

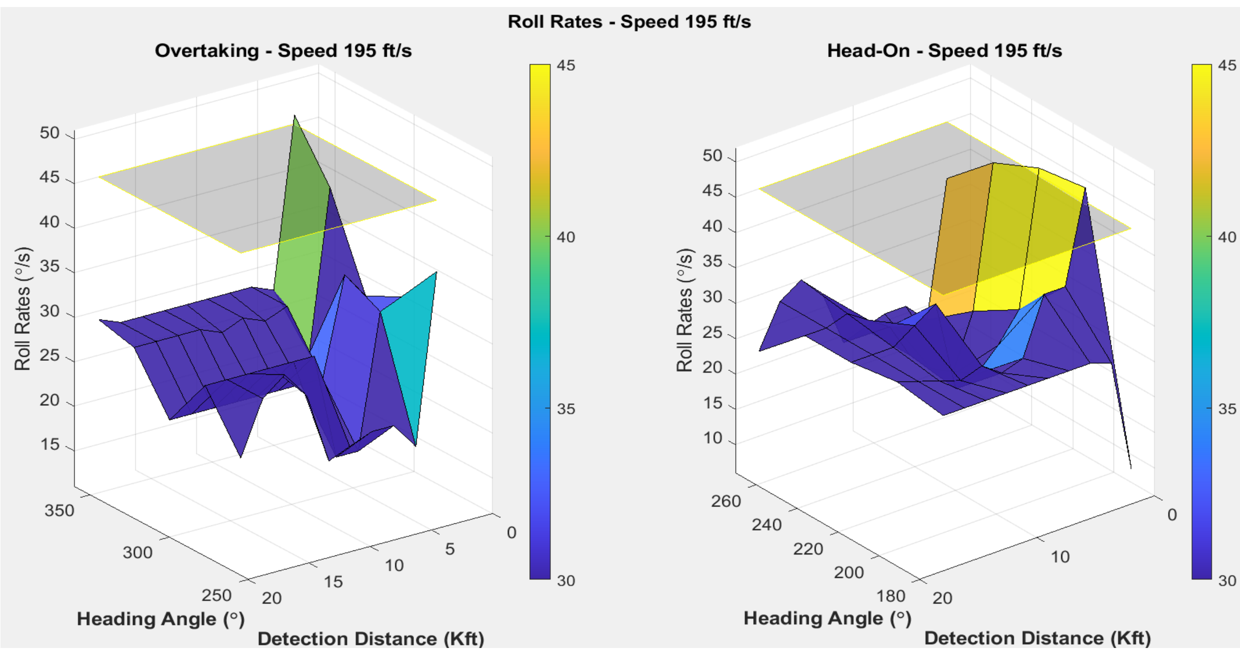


Figure 16. Maximum attained Roll Rates 195 ft/s Head-On Converging Single sUAS.

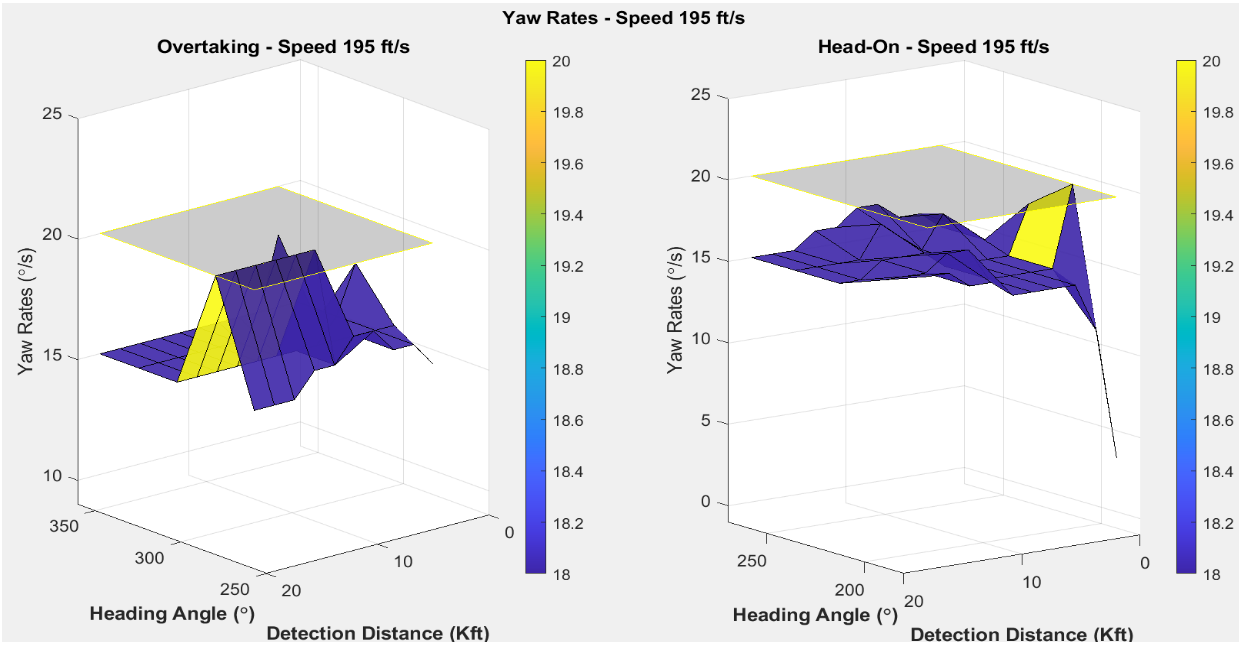


Figure 17. Maximum attained Yaw Rates 195 ft/s Head-On Converging Single sUAS.

1.2.4.2 Multiple sUAS vs Crewed Aircraft

For the General Interaction encounters between multiple sUAS and crewed aircraft, the same head-on, converging, and overtaking cases were investigated. Two sUAS are considered in these simulations. The two sUAS are laterally separated by 500 ft and maintain the same altitude over the full simulation. When experiencing the morphing potential field, there are some cases in which the sUAS are predicted to collide with each other to avoid the crewed aircraft. These cases occur rarely, only when a low detection distance causes a severe avoidance maneuver. A possible solution is to modify the simulation to command the sUAS to different altitudes either when appropriate or as soon as the crewed aircraft is detected. However, the determination of minimum detection distance to avoid a RoWV is not affected by not separating the sUAS vertically.

To highlight the performance of the morphing potential field with multiple sUAS, Figure 18 showing a successful avoidance maneuver with the Cessna flying at 170 ft/s with a large detection range is displayed below.

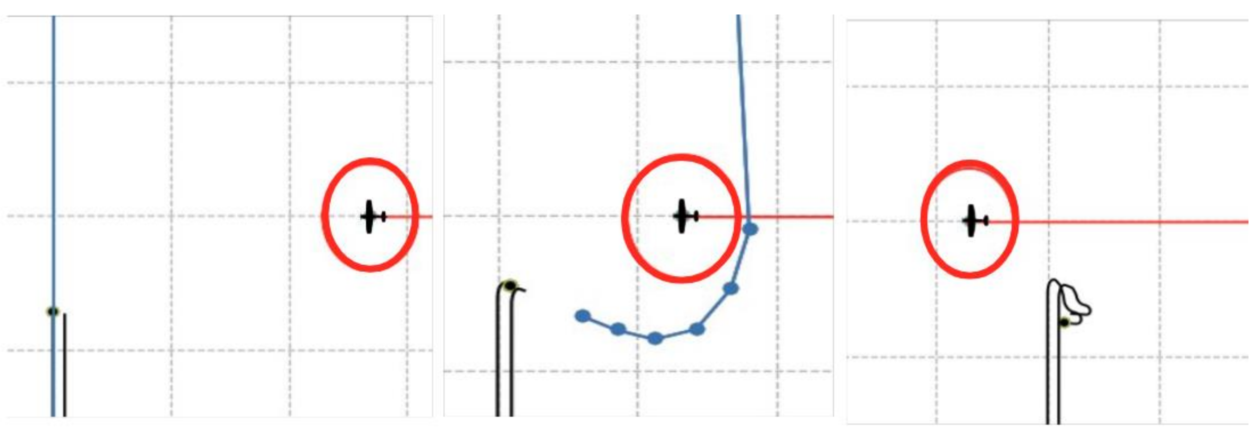


Figure 18. Two sUAS Flying in Formation with Successful Maneuver.

For the General Interaction, multiple sUAS vs Crewed aircraft scenario, the data shows that a 10,888 ft detection distance on the multiple sUAS would mitigate the probability of NMACs and ROW violations. NMACs appear more likely to occur in the overtaking configuration at lower detection distances while ROW violations appear more likely to occur in the head-on converging configuration at lower detection distances.

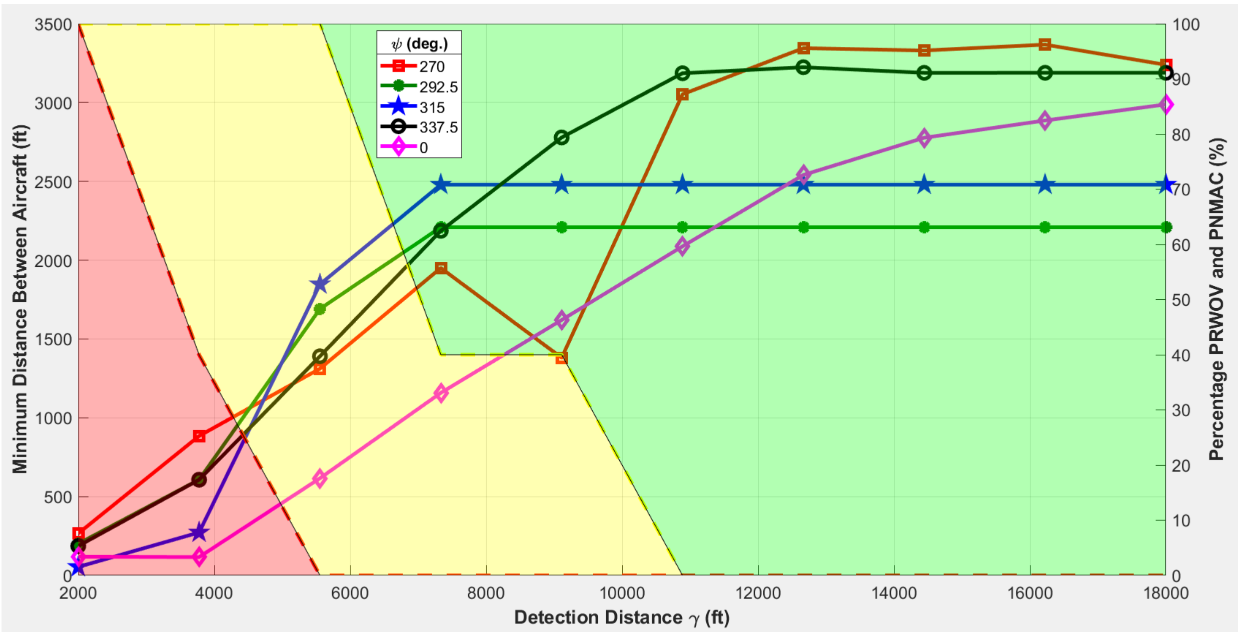


Figure 19. General Interactions Overtaking Multiple sUAS.

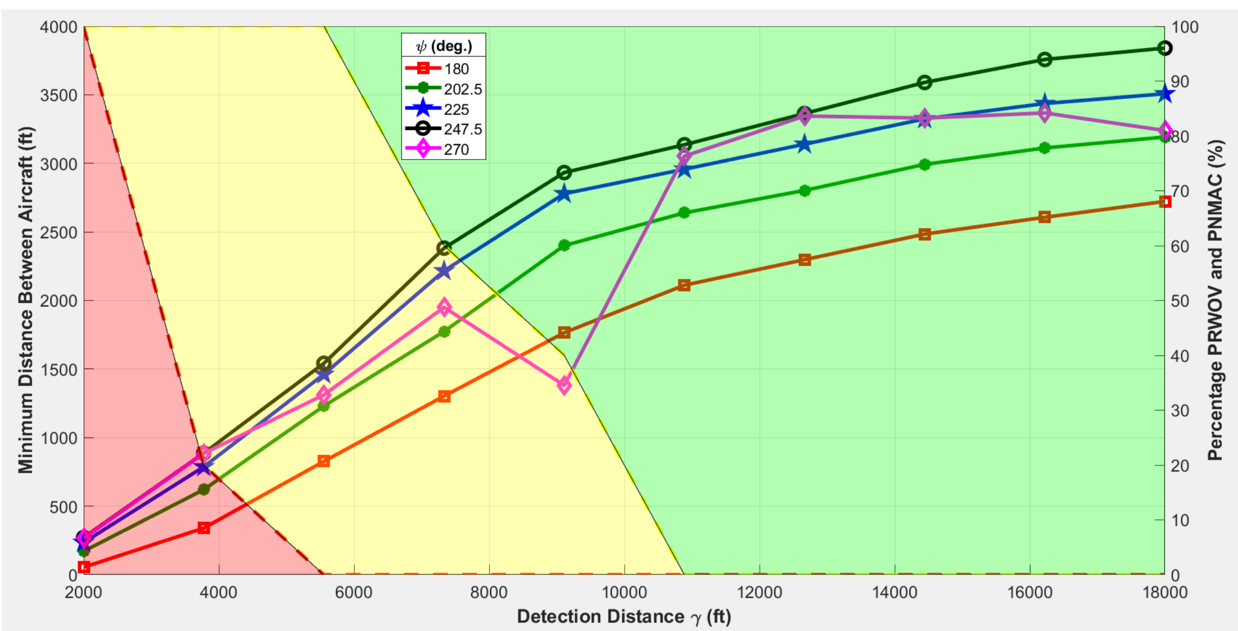


Figure 20. General Interactions Head-On Converging Multiple sUAS.

In both of the above figures, a sudden drop in minimum distance between aircraft occurs direct head-on and overtaking scenarios between the 8000 and 10,000 ft detection distance. This is due to a nonlinearity not seen in sUAS simulations. When comparing results for different closing speeds of the non-cooperative aircraft, many results align with those for the single sUAS. For instance, for lower closing speeds there are less ROW violations even with multiple sUAS, but the minimum required detection distance is 10,800 ft. However, at higher closing speeds with the non-cooperative aircraft approaching the multiple sUAS head-on and overtaking, the worst-case scenario requires a larger detection distance of 12,600 ft. An example of the higher closing speed at the overtaking angles is highlighted below. The data for the lower closing speeds is displayed in the appendix.

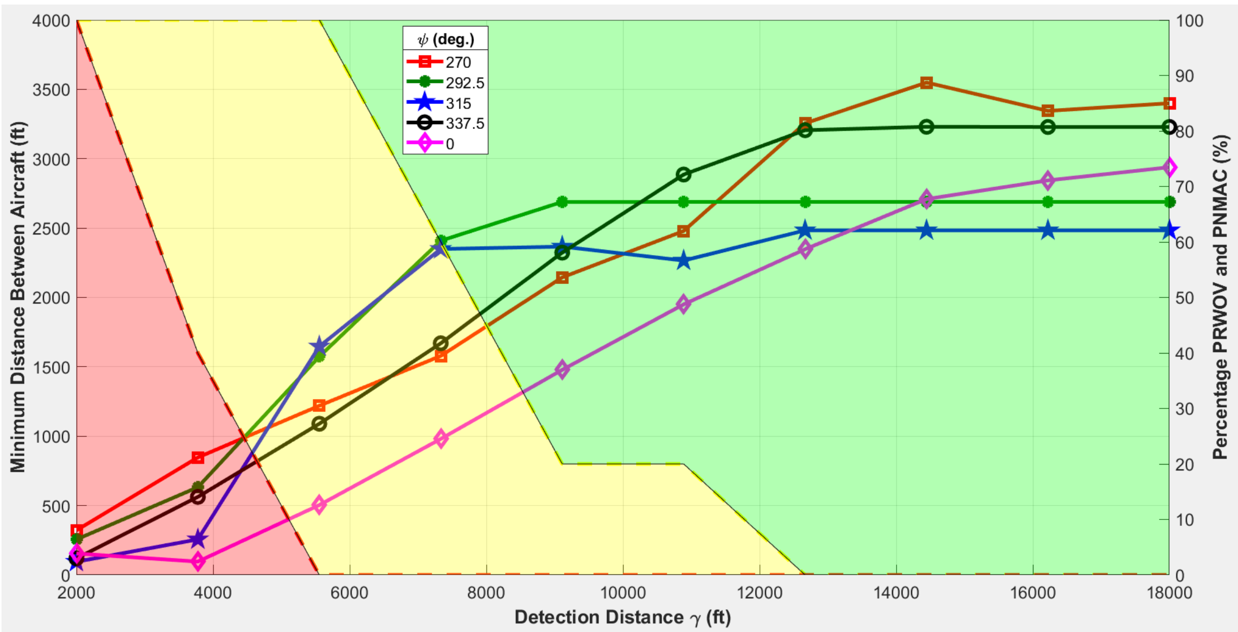


Figure 21. 195 ft/s Overtaking Multi sUAS.

The Table 22 displays the highest roll and yaw rates experienced by either sUAS. Note that some of the roll and yaw rates are slightly above the undesirable threshold, likely due to the added nonlinearity of multiple sUAS flight. These undesirable rates are only experienced briefly during avoidance maneuvers. Furthermore, loss of control from undesirable rates mainly occurs when the sign of the rate changes (oscillatory behavior). In the case of these simulations, however, the undesirable rates remain exclusively positive or exclusively negative until they return to 0, signifying a successful maneuver and no loss of control.

Table 22. Worst Case Roll and Yaw and Roll Rates for General Interaction Simulations.

V_{C172} (ft/s)	Roll Rate (deg. /s)	Yaw Rate (deg. /s)	Proximity (ft)	Det. Dis. (ft)	ψ_{sUAS} (deg.)
145	48	21	2950	9100	22
170	25	21	2210	7300	67
170	43	19	2990	18000	0
195	47	24	2140	9100	90

As can be seen in the appendix, the Yaw and Roll rates for the sUAS are well within safe ranges while the sUAS or multiple sUAS is evading the crewed aircraft [5]. There are only a few cases where an sUAS in the multiple sUAS has a higher than recommended roll rate. Yaw Rates above 20 degrees/s and Roll Rates above 45 degrees/s are highlighted in yellow as possible points of concern for the integrity of the sUAS. Again, these cases represent situations where the detection distance was very low, causing a drastic change in sUAS attitude due to attempting an avoidance maneuver.

A graphical example of the worst sUAS attitude rates found can be seen in Figure 22 and Figure 23. They show the roll rates and yaw rates experienced by multiple sUAS while attempting to prevent a ROW violation at different heading angles. The direct relationship between low detection distances and undesirable attitude rates can again be clearly inferred, as the sUAS makes sudden movements with little time to prevent violations. It can also be seen that most of the attitude rates lie in the acceptable range with no rates approaching adverse levels.

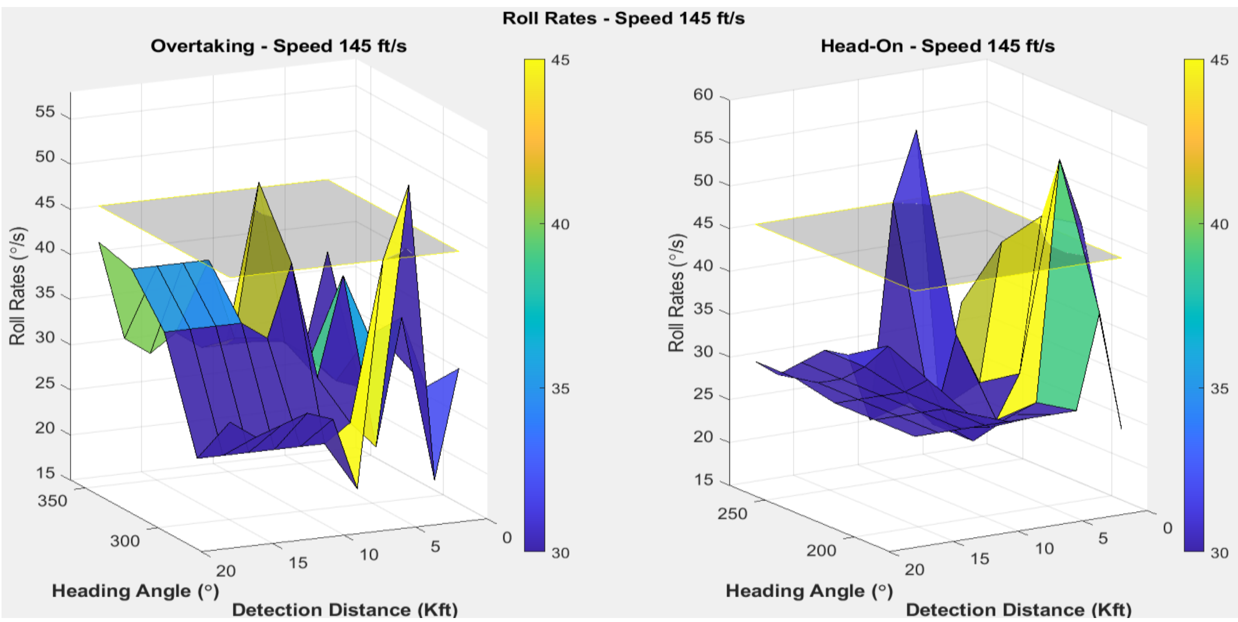


Figure 22. Maximum attained Roll Rates 145 ft/s Head-On Converging Multiple sUAS.

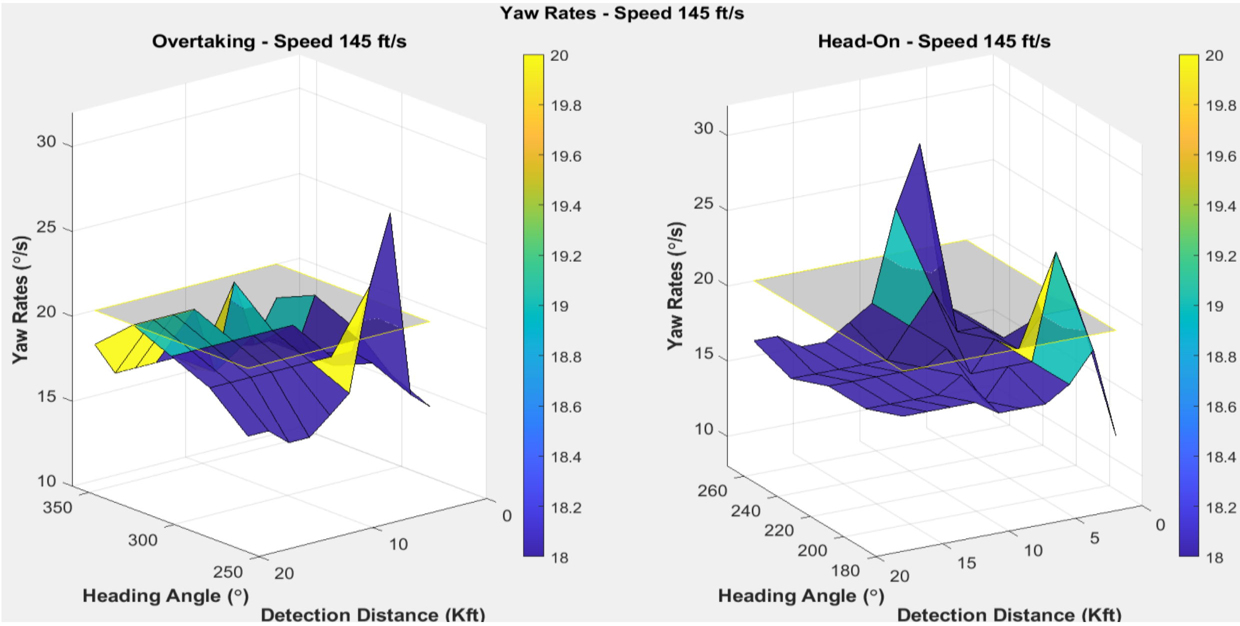


Figure 23. Maximum attained Yaw Rates 145 ft/s Head-On Converging Multiple sUAS.

1.2.4.3 Observations

When observing the effect of different closing speeds for head-on and overtaking encounters, a few trends were noticed.

- For both single and multiple sUAS, a lower closing speed resulted in less ROW violations overall
- At intermediate crewed aircraft speeds, the multiple sUAS resulted in a higher number of ROW violations than the single sUAS.
- At higher crewed aircraft speeds against a single sUAS, head-on encounter angles required a higher detection distance to perform a worst-case RoWV avoidance maneuver.
- For multiple sUAS, both head-on and overtaking encounter angles require a higher detection distance to perform a successful avoidance maneuver; thus, a multiple sUAS is more susceptible to ROW violations, especially higher crewed aircraft speeds.

After investigating the General Interaction encounter scenarios, the following observations have been made:

- For all encounter angles for an non-cooperative aircraft at a relatively low speed (145 ft/s), both single and multiple sUAS must be able to detect the non-cooperative aircraft at 10,888 ft in a worst-case encounter.
- For all encounter angles for an non-cooperative aircraft at an intermediate speed (170 ft/s), both single and multiple sUAS detection distance must be 10,888 ft.
- For all encounter angles for an non-cooperative aircraft at higher speed (195 ft/s), single and multiple sUAS require a larger detection distance to perform successful avoidance maneuvers, at 12,600 ft.

1.2.4.4 Possible Recommendations Affecting Right of Way Rules

To determine the required detection distance for combinations of sUAS and non-cooperative aircraft speed not simulated here, it would be desirable to have a non-dimensional equation. One approach is to relate the worst case required detection range for a given relative speed (over all encounter angles) to that relative speed. The worst-case relative speed is always in the head-on scenario, which is just the velocity of the two aircraft added together. Considering a *linear* relationship, the required distance could be calculated by multiplying the worst-case relative speed by a scaling factor. Table 23 shows the scaling factors for the three cases studied, that is the required detection distance by the relative velocity. Note that this data is the same for both single and multiple sUAS.

Table 23. Scaling Factors for a Linear Equation Relating Relative Velocity to Required Detection Distance.

Highest Relative Velocity	**Required Detection Distance**	**Scaling Factor (s)**
190	10888	57
215	10888	51
240	12600	53

Using the most conservative scaling factor (57), the equation to find the recommended, required detection distance (*D)* for single or multiple sUAS encounters with a crewed aircraft is:

$$D\ (ft)\ =\ V_{rel}\left(\frac{ft}{s}\right)\cdot 57\ (s) \tag{3}$$

Note that this equation can be interpreted as requiring a DAA system to have roughly a minute (vs 57 seconds) to detect a crewed aircraft flying in airspace for typical sUAS, that is, under 400 ft AGL.

1.2.5 Intruder Maneuvering (i.e., Following Right of Way Rules (ERAU)

The objective of Round 1 ROW experiments is to collect results on how well standard ROW procedure performs with UAS versus Helicopters, or more generally Crewed Aircraft. In this special case, crewed vehicles are given right of way, leading to UAS being responsible for maintaining safe separation. Due to the drone always yielding, a right-hand turn may not always be a safe avoidance maneuver, leading to alternatives needing to be considered. This section overviews how well the standard ROW maneuver performed in the ERAU’s agent-based simulations for Helicopter vs sUAS.

1.2.5.1 Experiment Configurations

The parameters that were explored during the course of these simulations are outlined in Table 24 through Table 27, where each manifest has a start, stop, steps, and unit column. The start and stop columns define the lower and upper bound of the parameters. The steps column defines how many steps to take from the lower bound. Parameters that are held constant have 0 steps value. All the parameters that vary are tested at the low, middle, and high values of their range, except for the drone response distance, which is explored at a higher granularity. Converging has been decomposed into Converging Left and Converging Right, where left and right is which side of the helicopter the drone is approaching from.

Table 24. Head On Parameter Manifest.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_direction	180	180	0	degrees
drone_x_pos	11000	11000	0	feet
drone_y_pos	4500	7500	2	feet
drone_response_distance	3000	10000	10	feet
drone_horizontal_turn_rate	6	20	2	degrees/s
drone_horizontal_turn_angle	90	90	0	degrees
force_right_turn	1	1	0	bool

Table 25. Overtaking Parameter Manifest.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_direction	0	0	0	degrees
drone_x_pos	10000	10000	0	feet
drone_y_pos	4500	7500	2	feet
drone_response_distance	3000	10000	10	feet
drone_horizontal_turn_rate	6	20	2	degrees/s
drone_horizontal_turn_angle	90	90	0	degrees
force_right_turn	1	1	0	bool
bounds_x	17000	17000	0	feet

Table 26. Converging Left.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_x_pos	6000	7000	1	feet
drone_y_pos	5980	11990	2	feet
drone_direction	270	270	0	degrees

drone_response_distance	3000	10000	10	feet
drone_horizontal_turn_rate	6	20	2	degrees/s
drone_horizontal_turn_angle	90	90	0	degrees
force_right_turn	1	1	0	bool

Table 27. Converging Right.

Parameter Name	Start	Stop	Steps	Unit
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_x_pos	6000	7000	1	feet
drone_y_pos	20	6020	2	feet
drone_direction	90	90	0	degrees
drone_response_distance	3000	10000	10	feet
drone_horizontal_turn_rate	6	20	2	degrees/s
drone_horizontal_turn_angle	90	90	0	degrees
force_right_turn	1	1	0	bool

1.2.6 Intruder Maintaining Course (i.e., Not Following Right of Way Rules

This section overviews how well the non-standard ROW maneuvers performed in the ERAU's agent-based simulations for Helicopter vs sUAS. The maneuvers that are tested are a Horizontal turn and Vertical ascent maneuver. The horizontal maneuver differs from ROW when the drone needs to turn left to avoid cross the path of the helicopter.

1.2.6.1 Experiment Configurations

The parameters that were explored during the course of these simulations are outlined in Table 28 through Table 35, where each manifest has a start, stop, steps, and unit column. The start and stop columns define the lower and upper bound of the parameters. The steps column defines how many steps to take from the lower bound. Parameters that are held constant have 0 steps value. All the parameters that vary are tested at the low, middle, and high values of their range, except for the drone response distance, which is explored at a higher granularity. Converging has been decomposed into Converging Left and Converging Right, where left and right is which side of the helicopter the drone is approaching from. The manifests are organized by scenario and maneuver type.

Table 28.Head On Horizontal Manifest.

Parameter Name	Start	Stop	Steps	Unit
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_direction	180	180	0	degrees
drone_x_pos	11000	11000	0	feet
drone_y_pos	4500	7500	2	feet
drone_response_distance	3000	10000	10	feet
drone_horizontal_turn_rate	6	20	2	degrees/s

drone_horizontal_turn_angle	90	90	0	degrees

Table 29. Head On Vertical Manifest.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_direction	180	180	0	degrees
drone_y_pos	4500	7500	2	feet
drone_x_pos	11000	11000	0	feet
drone_response_distance	3000	10000	10	feet
drone_ascent_rate	8	28	2	fps

Table 30. Overtaking Horizontal Manifest.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_direction	0	0	0	degrees
drone_x_pos	10000	10000	0	feet
drone_y_pos	4500	7500	2	feet
drone_response_distance	3000	10000	10	feet
drone_horizontal_turn_rate	6	20	2	degrees/s
drone_horizontal_turn_angle	90	90	0	degrees
bounds_x	17000	17000	0	feet

Table 31. Overtaking Vertical Manifest.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_direction	0	0	0	degrees
drone_x_pos	10000	10000	0	feet
drone_y_pos	4500	7500	2	feet

drone_response_distance	3000	10000	10	feet
drone_ascent_rate	8	28	2	fps
bounds_x	17000	17000	0	feet

Table 32. Converging Left Horizontal Manifest.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_x_pos	6000	7000	1	feet
drone_y_pos	5980	11990	2	feet
drone_direction	270	270	0	degrees
drone_response_distance	3000	10000	10	feet
drone_horizontal_turn_rate	6	20	2	degrees/s
drone_horizontal_turn_angle	90	90	0	degrees

Table 33. Converging Left Vertical Manifest.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_x_pos	6000	7000	1	feet
drone_y_pos	5980	11990	2	feet
drone_direction	270	270	0	degrees
drone_response_distance	3000	10000	10	feet
drone_ascent_rate	8	28	2	fps

Table 34. Converging Right Horizontal Manifest.

Parameter Name	**Start**	**Stop**	**Steps**	**Unit**
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_x_pos	6000	7000	1	feet

drone_y_pos	20	6020	2	feet
drone_direction	90	90	0	degrees
drone_response_distance	3000	10000	10	feet
drone_horizontal_turn_rate	6	20	2	degrees/s
drone_horizontal_turn_angle	90	90	0	degrees

Table 35. Converging Right Vertical Manifest.

Parameter Name	Start	Stop	Steps	Unit
drone_speed	30	50	2	mph
heli_speed	100	125	2	mph
drone_x_pos	6000	7000	1	feet
drone_y_pos	20	6020	2	feet
drone_direction	90	90	0	degrees
drone_response_distance	3000	10000	10	feet
drone_ascent_rate	8	28	2	fps

1.2.6.2 Helicopter vs sUAS Interpretations (Discussions)

Follows Right of Way Rules:

This section presents the results from executing the standard ROW procedure for self-separation within the Round 1 tests. Within Table 36, the performance of the ROW maneuver is presented. For Head-On and Overtaking, the mean severity suggests that around half of the simulations resulted in a violation. The severity implies that the drone fell inside the violation region by 50% or more. However, the Converging Right and Left scenarios have a low risk. This is due to the fact that if the drone turns in time, turning left or right does not effect the odds of a violation. The ROW maneuver, however, has the major concern of flying in the same direction as the Helicopter, which is not captured by these metrics. For Converging Right, the ROW maneuver does result in the drone flying in the same direction as the Helicopter.

Table 36. Round 1 ROW Results.

Scenario	Maneuver	Simulation Count	Mean Severity	Violation Percent	Risk
Head On	ROW	891	52%	50%	26%
Overtaking	ROW	891	52%	45%	23%
Converging Right	ROW	1782	17%	25%	4%
Converging Left	ROW	1782	17%	24%	4%

The response distance corresponds to a reduction in risk, which is documented in **Table 37.** ROW Risk over Response Distance. The risk shows a gradual decline with response distance.

Table 37. ROW Risk over Response Distance.

Scenario	**Maneuver**	**3000ft**	**3700ft**	**4400ft**	**5100ft**	**5800ft**	**6500ft**	**7200ft**	**7900ft**	**8600ft**	**9300ft**	**10k ft**
head on	ROW	31.3%	27.5%	26.4%	22.8%	18.6%	13.9%	9.9%	7.2%	4.8%	3.0%	1.6%
overtaking	ROW	27.7%	26.0%	23.0%	18.0%	13.7%	10.5%	7.2%	4.8%	2.8%	1.7%	1.2%
conv left	ROW	12.8%	11.7%	10.7%	9.8%	9.3%	9.3%	9.2%	9.2%	9.2%	9.2%	9.2%
conv right	ROW	14.7%	12.9%	11.4%	10.4%	9.8%	9.7%	9.3%	9.3%	9.3%	9.3%	9.3%

Does Not Follow Right of Way Rules:

This section presents the results from executing non-standard ROW procedure for self-separation within the Round 1 tests. These results are broken up by scenario and response maneuver. Here, an obvious reduction in risk can be seen, where the highest risk of 17% is from the Head On scenario with a Vertical Maneuver. This peak percentage is less than the lowest risk of the ROW tests. The other maneuvers and scenarios manage to stay between 4 and 7%. The largest contributor to the risk reduction is from reduced violation probability, but the mean severity has decreased as well.

Table 38. ERAU Round 1 Results.

Scenario	**Maneuver**	**Simulation Count**	**Mean Severity**	**Violation Percent**	**Risk**
Head On	Vertical	891	47%	36%	17%
	Horizontal	891	30%	20%	6%
Overtaking	Vertical	891	47%	12%	6%
	Horizontal	891	28%	15%	4%
Converging Right	Vertical	1782	48%	14%	7%
	Horizontal	1782	15%	21%	3%
Converging Left	Vertical	1782	48%	17%	8%
	Horizontal	1782	17%	24%	4%

The response distance corresponds to a reduction in risk, which is documented in Table 39 the vertical scenario seems to require a larger response distance to remain well-clear. In contrast with ROW at the 10k response distance, most risk has been eliminated entirely.

Table 39: Non-ROW Risk over Response Distance

scenario	maneuver	3000ft	3700ft	4400ft	5100ft	5800ft	6500ft	7200ft	7900ft	8600ft	9300ft	10k ft
head on	vertical	45.5%	32.3%	26.5%	15.7%	15.1%	15.1%	13.9%	11.1%	6.1%	0.6%	0.0%
head on	horizontal	12.6%	5.9%	4.0%	2.3%	1.2%	0.5%	0.2%	0.0%	0.0%	0.0%	0.0%
overtaking	vertical	25.7%	15.1%	11.7%	4.5%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
overtaking	horizontal	5.4%	3.7%	2.4%	1.1%	0.5%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%
conv left	vertical	12.2%	6.8%	3.9%	3.5%	3.4%	3.0%	2.6%	2.3%	2.3%	2.3%	2.3%
conv left	horizontal	7.5%	4.0%	2.2%	0.9%	0.5%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
conv right	vertical	13.1%	7.0%	4.1%	3.5%	3.4%	3.1%	2.6%	2.3%	2.3%	2.3%	2.3%
conv right	horizontal	8.4%	4.4%	2.3%	1.0%	0.5%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%

1.2.7 General Interactions - Summary

In the case of sUAS vs sUAS interactions the proposed right of way rules appears to be adequate for maintaining a safe distance, given that the performance of both aircraft is close. From testing if the aircraft have reasonable vertical performance of 500fpm or greater and a GPS uncertainty of SPS or better the aircraft can maintain a safe distance with a detection range of 1,657ft assuming a 5s pilot response time. This distance also works with the case of the intruder sUAS failing to give way under the assumption that the operator is able to determine that the intruder will fail to give way at the required detection range of 1,657ft.

In the case of sUAS vs Crewed interactions, placing the avoidance burden on the sUAS will require the sUAS to have a long-range sensor or cooperative/DAA system that is capable of handling and avoiding at the required distances of 12,254ft. This is due to the larger performance delta between the aircraft and the larger Well Clear safety volume. If the sUAS is not able to meet this requirement, it would be better for the sUAS to minimize interactions with crewed aircraft by operating in areas that are restricted for Crewed aircraft, Crewed aircraft not equipped with ADS-B Out when the drone is operating, such as reserved airspace.

The Round 1 Helicopter vs sUAS experiments aimed to evaluate the performance of standard and non-standard ROW procedures for UAS versus Helicopters (crew aircraft). In standard ROW scenarios, crewed vehicles have priority, and UAS must maintain safe separation. This study highlighted that a right-hand turn by a UAS is not always a safe avoidance maneuver, necessitating alternative strategies. Parameters explored included start, stop, steps, and unit, with low, middle, and high values tested for most parameters, while drone response distance was examined more granularly. Results showed that in head-on and overtaking scenarios, about 50% of simulations resulted in violations with a mean severity of 52%. Converging scenarios had higher severity, particularly converging right at 65% severity and 40% violation rate. Risk reduction correlated with increased response distance, significantly decreasing from 31.3% at 3000ft to 1.6% at 10,000ft in head-on scenarios.

The study also evaluated non-standard ROW maneuvers, including horizontal and vertical turns. Non-standard maneuvers demonstrated a clear reduction in risk compared to standard ROW procedures. Vertical maneuvers, in particular, significantly reduced risk, with the highest observed risk at 17% for head-on scenarios, much lower than the lowest risk in standard ROW tests.

Horizontal maneuvers generally showed lower risk, with some scenarios as low as 3-4%. Risk for vertical maneuvers decreased from 45.5% at 3000ft to 0.0% at 10,000ft, while horizontal maneuvers showed a decrease from 12.6% at 3000ft to 0.0% at 10,000ft. These findings indicate that non-standard ROW maneuvers, especially vertical ones, can substantially enhance safety and reduce violation rates.

1.3 Reserved Airspace Concept (Round 2)

The reserved airspace concept, or RAC, encompasses the possibility of scheduling and bounding aircraft within limited airspace for a specified period. How this would operate is beyond the scope of this Task, but several potential implementations create questions that can be answered in simulations and testing. Much of the focus is on discrete areas, especially in rural areas where operations on a single unit of property is easy to define. One potential alternative, however, is the possibility of reserving temporary time along a linear corridor as is currently common in linear inspection (pipeline, rail, and power). Future airspace designs may also regard these regions as useful for implementing UAS transit from point to point, creating potential traffic corridors. Regardless of the use, interactions of UAS in this limited space require investigations to understand risks and benefits of this potential airspace structure.

1.3.1 Scenarios

To this end, three scenarios were proposed for flight testing of the reserved airspace concept involving varying sizes and shapes of reserved airspace with a focus on the most likely ones, a corridor or a large rectangular region.

The first scenario involves UAS reserving a four-dimensional corridor of airspace to conduct shielded operations such as linear infrastructure inspection of a pipeline or powerline or for transit from a runway to an operation area or between operation areas. RoW interactions for this scenario can involve other aircraft using the corridor for similar operations, transiting through the corridor, or operating near the corridor.

The second scenario involves an aerial applicator reserving a large area of land, 1.5 sq. miles, up to and including 400ft AGL to conduct spraying operations, simultaneously one or more UAS passes through the area at several altitudes and speeds.

The third scenario involves an aircraft in distress entering the reserved airspaces described in scenarios one and two.

1.3.2 sUAS vs sUAS (UND)

1.3.2.1 Methodology

UND focused on sUAS vs sUAS interactions in a corridor scenario for the RAC testing. This corridor scenario uses the same general setup as the general interactions but adds a maneuver restriction. The aircraft in question must remain within the corridor and should avoid backtracking, as this is generally considered poor airmanship; it should proceed in a forward direction. Avoidance maneuvers, therefore, may be substantially different compared to those used in the general interactions section. Due to the narrow airspace, the simulations were limited to head-on and overtaking as converging encounters would be less common and feasible between aircraft inside a narrow corridor.

The corridor was created from ground level up to 400ft AGL with a minimum width running for a long enough distance to allow interactions to fully complete during the simulation. The width chosen for the corridor represents a reasonable minimum for sUAS vs sUAS interactions: the sum of the 100ft sNMAC volume used during testing, a maximum GPS uncertainty of ~50ft, and a reasonable distance for the aircraft itself. The sum of these values was rounded up to 200ft with an additional buffer. This resulted in a required minimum width of 400ft which allows a sUAS to maintain a safe distance from another sUAS that is flying in the center of the corridor.

Three different maneuver restrictions were tested: horizontal-only, vertical-only, and an unrestricted maneuver. Horizontal-only is likely the best maneuver in scenarios where the ownship cannot deviate vertically due to ground cover or other environmental restrictions from flying in close proximity to the ground. Vertical-only maneuvers are likely the best for scenarios where the ownship cannot deviate horizontally due to obstacles or infrastructure present in the area. An example of this would be a sUAS inspecting a powerline from the side where it cannot easily maneuver horizontally. An unrestricted maneuver is best in cases where the sUAS is less restricted in its maneuvering within the corridor.

1.3.2.2 Corridor Maneuver and Restriction

The RAC testing involved head-on and overtaking geometries with the added restrictions of staying inside the corridor while maneuvering and not allowing the aircraft to backtrack during avoidance. These geometries were used in two different RoW scenarios, sUAS vs sUAS following right-of-way rules and sUAS vs sUAS not following right-of-way rules.

For the case of following the RoW rules, the sUAS performed the maneuver shown in Figure 24 where the blue aircraft is the ownship and the orange aircraft is the intruder. The corridor is centered on the ownship and depending on the geometry being tested, the intruder could be inside the corridor or outside of the corridor at the time of detection. If the intruder is outside the corridor, it is assumed that it will maneuver in a way that allows it to enter the corridor and maneuver to the correct side of the corridor. Both aircraft perform pre-turns and follow the correct edge of the corridor based on the type of interaction being tested once it is reached.

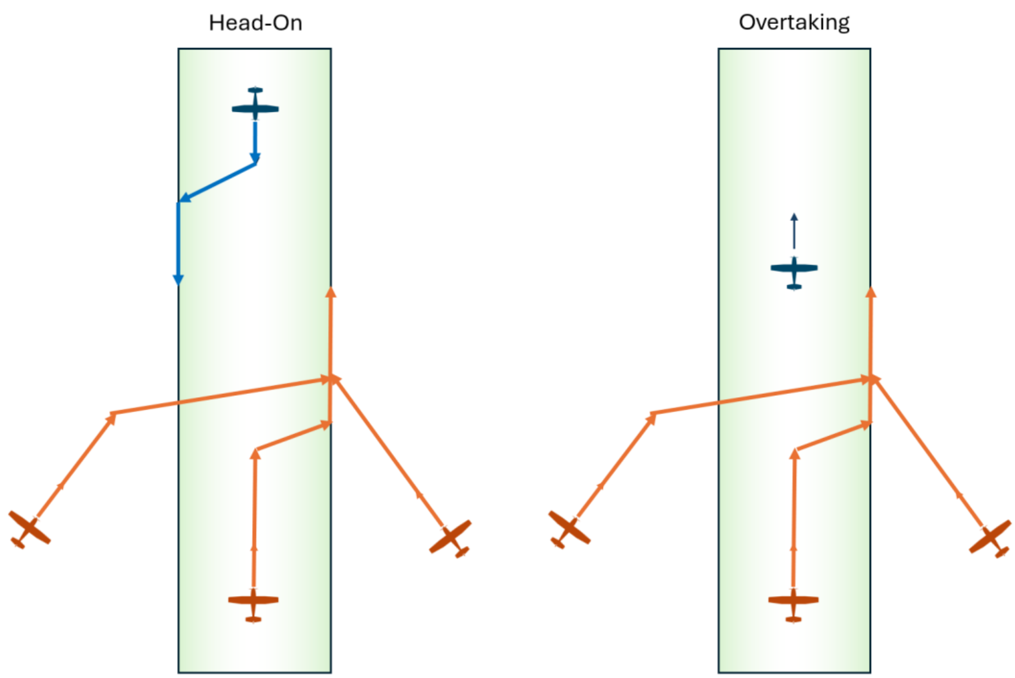


Figure 24. Reserved Airspace Corridor sUAS vs sUAS following rules maneuver.

In the case of head-on geometry and when following RoW rules, the ownship and intruder both turn right towards the side of the corridor based on their direction of travel. In the case of overtaking, the ownship does not maneuver and the intruder maneuvers to the right side of the corridor. The only exception to this is the case of the intruder being outside the corridor on the right side. In this case the intruder continues its path as normal but follows the side of the corridor once it reaches it.

When not following RoW rules, the intruder fails to maneuver while the ownship does maneuver as shown in Figure 25. For this scenario, the intruder does not deviate from its path and continues towards and down the middle of the corridor. In the case of head-on geometries, the ownship performs the same maneuver as the following rules scenario but in the case of overtaking, the ownship deviates to the left.

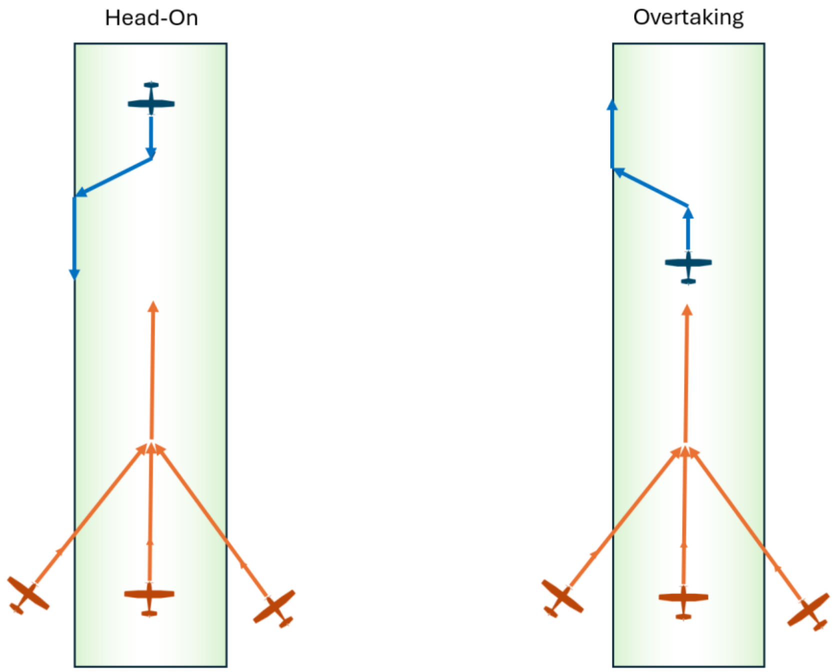


Figure 25. Reserved Airspace Corridor sUAS vs sUAS not following rules maneuver.

1.3.2.2.1 Fixed Maneuver for Corridor

Similar to the fixed maneuver used for the general interaction and remote ID testing, a single maneuver is used to allow for direct comparison of results between different configurations without being influenced by the maneuver itself. The primary difference here is that the aircraft may not backtrack; they may only continue forward within the corridor or at the least, fly perpendicular relative to the corridor. To accomplish this, the simulations limit the maneuvers for each of the geometries so that the aircraft is bounded by a perpendicular line to the corridor, as shown in Figure 26**.**

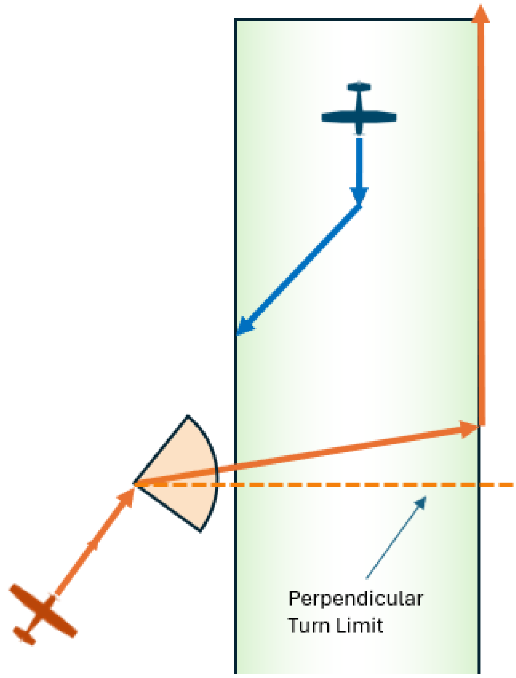


Figure 26. Reserved Airspace Concept Corridor Turn Limit.

With the above restrictions present, the best turn simulations were rerun in a similar fashion to general interactions maneuver testing including head-on and overtaking scenarios with a 400ft wide corridor with and without a SPS GPS uncertainty.

For head-on geometries, the minimum required turn for success was 44-degrees without and 48-degrees with SPS GPS uncertainty, as shown in Figure 27 and Figure 28 respectively. These results begin to plateau around 60-degrees so this would be a reasonable heading change without forcing all of the geometries to the limit described above.

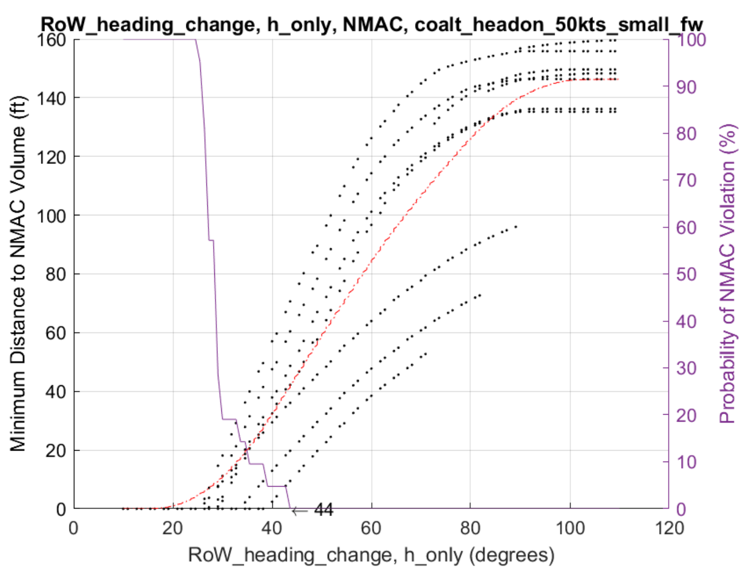


Figure 27. RAC corridor fixed heading change for head-on geometry without GPS uncertainty.

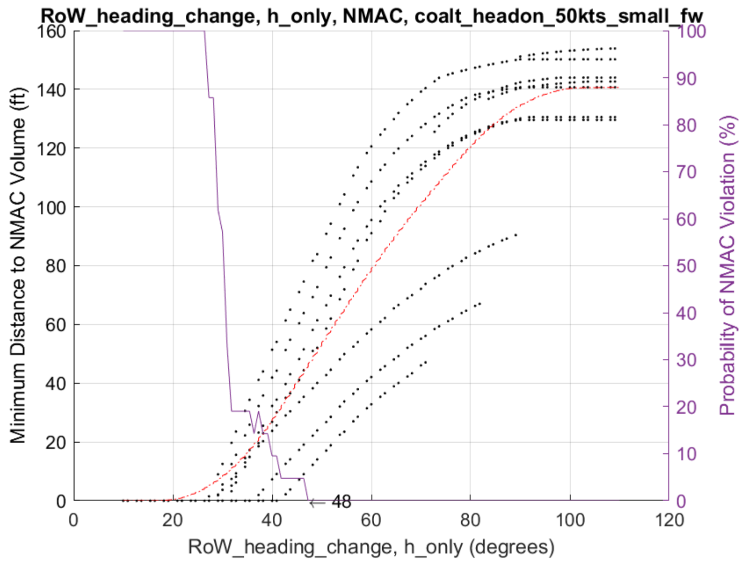


Figure 28. RAC corridor fixed heading change for head-on geometry with SPS GPS uncertainty.

For overtaking, the minimum required turn was about 39-degrees without GPS uncertainty and 42-degrees with SPS GPS uncertainty as shown in Figure 29 and Figure 30 respectively. The geometries start to plateau around 50-degrees and fully plateau around 60-degrees so a reasonable heading change would be somewhere between 50 and 60-degrees.

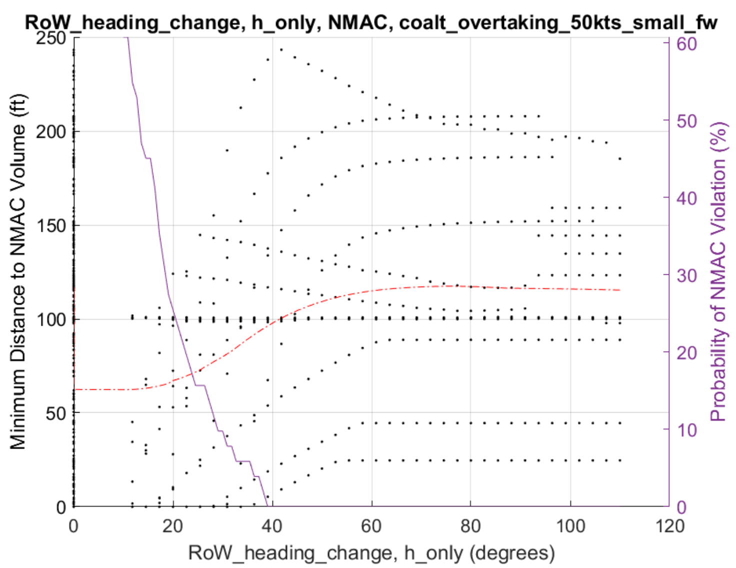


Figure 29. RAC corridor fixed heading change for overtaking geometry without GPS uncertainty.

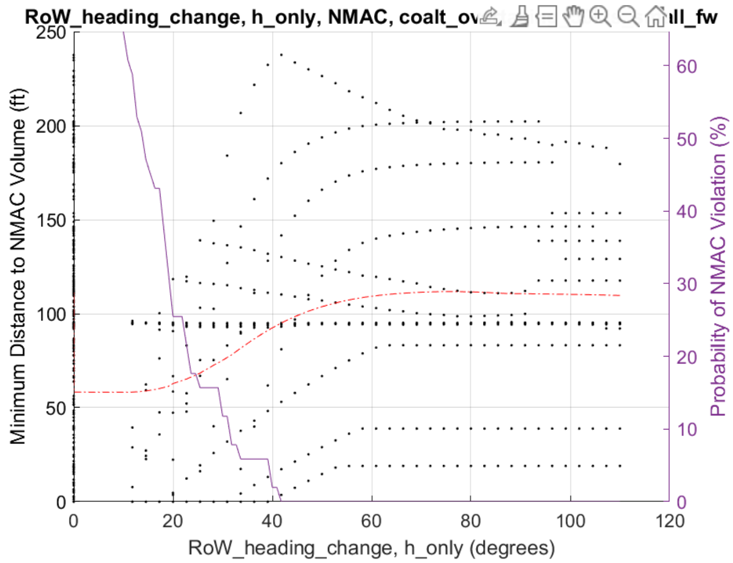


Figure 30. RAC corridor fixed heading change for overtaking geometry with SPS GPS uncertainty.

Based on these results, a fixed heading change of 60-degrees is most appropriate for head-on and overtaking geometries as this provides a reasonable amount of avoidance without forcing all of the geometries to reach the perpendicular turn limit.

1.3.2.2.2 Entering and Exiting the Corridor

When entering and exiting linear RAC airspace there is not yet thought given to how to maneuver, however a nominal maneuver when entering and exiting a RAC corridor should be in some way tied to existing best practices and airmanship. When merging with instrument approaches and visual flight rules traffic patterns, the 45-degree entry is in common use and so we continue the practice here.

1.3.2.3 Following Right-of-Way Rules

Testing for the RAC used the same methodology, configuration, and setup as the general interactions in Table 6, but with the added restriction of staying within the corridor and a different fixed heading maneuver due to this restriction. The same sNMAC volume of 100ft horizontal and 25ft vertical was used alongside the same four GPS uncertainties, vertical performance limits, and three maneuvering modes. The default behavior for both aircraft without detection or when they are not following the right-of-way rules is flying down the middle of the corridor and maneuvering towards the middle of the corridor in case of the intruder.

The RAC results use the same base analysis for the results used in general interactions and the same legend for best maneuver type, as shown in Figure 5. Blue indicates that horizontal-only maneuvers would be more effective, while green indicates that vertical-only maneuvers would be more effective. Yellow indicates that the vertical-only maneuver is within +/-5% of the horizontal-only maneuver and either would potentially be viable.

These simulations were run for pilot response times of 1sec and 5sec but only the results for the more pessimistic 5s case are described below. The full set of results for both 1s and 5s pilot response times can be found in the appendix.

1.3.2.3.1 Head-on

In Task 2, UAS are of equal priority and in the case that they are following right-of-way rules, both aircraft will deviate to the right for head-on geometries. The following simulations used the maneuver defined in the corridor fixed maneuver section after a specified pilot response delay of 5s. After approaching the appropriate side of the corridor, including any required altitude adjustments, the aircraft would preturn into and follow the edge of the corridor.

When restricted to horizontal-only maneuvering and given a 5s pilot response delay, a detection range of 1,477-1608ft is needed. The required ranges for the tested GPS uncertainties were 1,477ft for RTK, 1,493ft for both WAAS and SPS, and 1,608 for MAX. These values are larger than the general interaction section and are due to the change in the fixed heading maneuver and the restriction of staying inside the corridor.

In the case of vertical-only maneuvering, the GPS uncertainty had a larger effect on the required ranges with the required detection ranges varying from 1,149ft to 2,248ft. The required ranges for the tested GPS uncertainties were 1,149-1,444ft for RTK, 1,165-1,575ft for WAAS, 1,264-1,625ft for SPS, and 1,313-2,248ft for MAX. These distances are similar to those of thegeneral interaction section but the required ranges for the lowest vertical performance, 250fpm, were higher than the general interaction for the WAAS configuration.

For restricted maneuvering, vertical-only represented the best maneuver for most of the configurations except for the lowest vertical performance configuration of 250fpm, as shown in Error! Reference source not found.. This is a change from the general interaction section because t he increased required distance for horizontal-only maneuvers due to the smaller fixed heading maneuver and the restriction of staying inside the corridor.

Table 40. RAC corridor, sUAS vs sUAS following RoW rules, head-on.

Head-on	RTK	WAAS	SPS	MAX
250fpm	Same	Horizontal		
500fpm	Vertical			
750fpm				
1000fpm				

When using an unrestricted maneuver, the vertical performance and GPS uncertainty have a larger effect on the required range, same as the vertical-only maneuver. The required ranges varied from 1,149 to 1,625ft with each of the GPS uncertainties being 1,149-1,313ft for RTK, 1,165-1,428ft for WAAS, 1,231-1,444ft for SPS, and 1,313-1,625ft for MAX. The unrestricted maneuver represented the best maneuver for this scenario with the required detection ranges most commonly around or better than the best of the restricted maneuvers, in this case the vertical-only maneuver for most of the configurations.

1.3.2.3.2 Overtaking

For overtaking geometries in sUAS encounters, both sUAS have the same priority but the ownship has the RoW and continues on course down the middle of the corridor while the intruder aircraft passes on the right. The aircraft followed the maneuver defined for the corridor scenario with a pilot response of 1s and 5s with the results discussed below using the 5s pilot response delay.

In the case of horizontal-only maneuvering the required detection range is 558-624ft with the tested GPS uncertainties requiring 558ft for RTK, WAAS, and SPS and 624ft for MAX. These values are similar to the general interaction section with the only difference being the required range for the MAX uncertainty being larger.

For vertical-only maneuvering the GPS uncertainty and vertical performance has a larger effect on the required range, varying from 460ft to 1,280ft. The required range for each of the GPS uncertainties are 460-624ft for RTK, 460-689ft for WAAS, 476-7,39ft for SPS, and 558-1,280ft for MAX. These distances are comparable to the general interaction section but the required ranges for the lower vertical performance, 250fpm and 500fpm, were higher than the general interaction results.

Vertical maneuvering represented the best maneuver for most of the restricted maneuvering configurations except for the lowest vertical performance, 250fpm, or the highest GPS uncertainty, MAX, with vertical rates below 1,000fpm, as shown in **Error! Reference source not found.**.

Table 41. RAC corridor, sUAS vs sUAS following RoW rules, overtaking.

Overtaking	RTK	WAAS	SPS	MAX
250fpm	Horizontal			
500fpm	Vertical	Same		
750fpm				
1000fpm				

When using an unrestricted maneuver, the vertical performance and GPS uncertainty have a larger effect on the required range. The required ranges varied from 476ft to 591ft with each of the GPS uncertainties being 476-558ft for RTK, 509-558ft for WAAS, 509-558ft for SPS, and 558-591ft for MAX. The unrestricted maneuver represented the best maneuver for this scenario when the aircraft had lower vertical performance or was using a high uncertainty GPS. In the case the aircraft was using an SPS or better GPS with higher vertical performance greater than 500fpm the vertical-only maneuver produced better results than the unrestricted maneuver.

1.3.2.3.3 Discussion

The corridor scenario had comparable results to the general interactions section with the vertical-only producing almost the same results except in the case of low vertical performance where the corridor required a larger range. In the case of horizontal-only the required ranges increased compared to the general interaction set due to the different fixed maneuver and the restriction of the corridor. The unrestricted maneuver also increased compared to the general interaction results, especially in the case of low vertical performance for the same reason.

An unrestricted maneuver produced equal or better results versus horizontal or vertically restricted maneuvering for head-on and if the aircraft has reasonable vertical performance of 500fpm or higher and is using SPS or better GPS service, then a detection range of 1,296ft would allow the aircraft to adequately maintain a safe distance from the modified sNMAC volume used during testing. If the aircraft is restricted, the detection range increases to 1,493ft for horizontal-only and 1,313ft for vertical-only maneuvers.

In the case of overtaking geometries with the same above assumptions, a required detection range of 558ft would be adequate for all tested maneuver types.

To reiterate, we assume in these scenarios that both sUAS aircraft follow right-of-way rules. From the test results the required detection ranges for the GPS uncertainties and a reasonable lower vertical performance of 500fpm are shown in **Error! Reference source not found.**. With a reasonable minimum vertical performance of 500fpm or larger and using SPS GPS or better, a detection range of 1,493ft is sufficient to maintain separation following the Task 2 proposed Right-of-Way rules in unrestricted and restricted maneuvering within a RAC corridor of at least 400ft wide and 400ft tall. This requirement is nearly equivalent to the general interaction set and shows the addition of the corridor did not have a major effect on the ability of the sUAS to maintain right-of-way rules within a corridor with a minimum of the dimensions used during testing.

Table 42. Maximum required detection ranges for sUAS vs sUAS following RoW rules in a RAC corridor.

	Horizontal-only	**Vertical-only (500fpm)**			
Geometry	All GPS	RTK	WAAS	SPS	MAX
Head-on	1,608ft	1,280ft	1,296ft	1,313ft	1,641ft
Overtaking	624ft	509ft	542ft	558ft	788ft

1.3.2.4 Not Following Right-of-Way Rules

When not following RoW rules, the intruder fails to maneuver when otherwise required resulting in a more stressful scenario compared to the following RoW rules scenario. This results in a greater stressed edge case within the restricted corridor, especially for overtaking when the ownship aircraft has right-of-way. This scenario uses the same methodology, configuration, setup, sNMAC, and test parameters as those for the general interaction section, given in **Error! Reference source not found.**, but with an added requirement to remain within the corridor. It must also conduct a different fixed heading maneuver due to this restriction. The default behavior of both aircraft absent traffic is to fly down the middle of the corridor.

These RAC results use the same formatting and base analysis for the results that was used in the general interaction section and the same legend for best maneuver type as seen in Figure 5. As before, blue indicates horizontal-only maneuvers would be more effective while green indicates that vertical-only maneuvers would be more effective. Yellow indicates that the vertical-only maneuver is within +/-5% of the horizontal-only maneuver and either would potentially be viable.

The simulations ran for 1sec and 5sec pilot response times but only the results for the 5s pessimistic cases are described below. The full set of results for 1s and 5s pilot response times can be found in the appendix.

1.3.2.4.1 Head-on

For the head-on geometries, in the case of sUAS vs sUAS not following right-of-way interactions, the intruder aircraft will not deviate from its path while the ownship deviates right. Once the aircraft approaches the appropriate side of the corridor or the center of the corridor in the case of the intruder the aircraft will perform a preturn and begin following the edge of the corridor.

For horizontal-only maneuvering, a detection range of 1,625-1,772ft is required with each of the tested GPS uncertainties requiring 1,625ft for RTK and WAAS, 1,641ft for SPS, and 1,772ft for MAX. Again, the required ranges are larger than the general interaction section and are due to the change in the fixed heading maneuver and the restriction of staying inside the corridor.

In the case of vertical-only maneuvering, the required ranges varied between 1,280ft and 3,413ft depending on the vertical performance and GPS uncertainty. The required range for each of the tested GPS uncertainties are 1,280-1,805ft for RTK, 1,296-2,100ft for WAAS, 1,313-2,231ft for SPS, and 1,657-3,413ft for MAX. These distances are again similar to the general interaction section but have a larger maximum due to the lowest vertical performance configurations, 250fpm, requiring a larger detection range.

For restricted maneuvering, the results are comparable to the general interaction section but the lowest vertical performance, 250fpm, and maximum GPS uncertainty, MAX, results preference horizontal-only maneuvering more. There is a clear preference for vertical maneuvering compared to horizontal-only for configurations with reasonable vertical performance and GPS uncertainty, as shown in **Error! Reference source not found.**.

Table 43. RAC corridor, sUAS vs sUAS not following RoW rules, head-on.

Head-on	RTK	WAAS	SPS	MAX
250fpm	Horizontal	Horizontal	Horizontal	Horizontal
500fpm	Vertical	Same	Same	Horizontal
750fpm	Vertical	Vertical	Vertical	Horizontal
1000fpm	Vertical	Vertical	Vertical	Vertical

When using an unrestricted maneuver, the detection range varied depending on the GPS uncertainty and vertical performance and ranged from 1,264ft to 1,789ft. The required ranges for the tested GPS uncertainties and vertical rates were 1,264-1,625ft for RTK, 1,296-1,641ft for WAAS, 1,296-1,723ft for SPS, and 1,608-1,789ft for MAX. The unrestricted maneuver provided a similar or better performance compared to the restricted maneuvers and was the best option for most of the tested configurations.

1.3.2.4.2 Overtaking

For the overtaking scenarios, in the case of sUAS vs sUAS not following right-of-way rules interactions, the ownship has the right-of-way but the intruder fails to give way and continues down the center of the corridor requiring the ownship to maneuver towards the left side of the corridor. This is an edge case for the ownship compared to the following right-of-way rules scenario.

For horizontal-only maneuvering, the required detection range rose, varying from 1,920ft to 2,330ft with the tested GPS uncertainties requiring 1,920ft for RTK, 1,969ft for WAAS and SPS, and 2,330ft for MAX. This is a change compared to the general interaction section where the ownship was unable to maintain a safe distance for all tested overtaking geometries. This is due to the fact the intruder enters the corridor to fly a path down the center of the corridor instead of flying a straight path through the corridor. The ownship can more easily avoid the intruder in this scenario because of this change in intruder path behavior compared to the general interaction set where it continues to fly straight.

In the case of vertical-only maneuvering, the required detection range varied from 460ft to 1,067ft with each of the tested GPS uncertainties requiring 460-624ft for RTK, 493-722ft for WAAS, 509-722ft for SPS, and 575-1,067ft for MAX. Like the horizontal-only maneuver, the vertical-only maneuver performs better than the general interaction section due to the same reasons and has a reduced maximum required range for the tested GPS uncertainties. Overall, vertical-only proved the best option for the restricted maneuvering, as shown in Table 44 and aligns with the general interactions results in this case.

Table 44. RAC corridor, sUAS vs sUAS not following RoW rules, overtaking.

Overtaking	RTK	WAAS	SPS	MAX
250fpm	Vertical			
500fpm				
750fpm				
1000fpm				

Similar to the general interaction results, an unrestricted maneuver did not always produce the same or better results. Vertical-only produce similar or better results when using an SPS or better GPS combined with a 750fpm or greater vertical performance. For the rest of the configurations, the vertical-only results produced better results compared to the unrestricted maneuver.

1.3.2.4.3 Discussion

The corridor scenario results were comparable to those of the general interactions in both vertical-only and unrestricted maneuvering cases except for very low climb/descent performance. For horizontal-only maneuvers, the required range increased in head-on encounters primarily to the way the avoidance maneuver changed as well as due to the corridor airspace restrictions. In overtaking cases, the horizontal-only ownship aircraft was able to maintain well clear for all tested geometries. This was an improvement from general interactions due to changes in how the intruder aircraft conducted itself in the corridor.

Unrestricted maneuvers produced equal or better results versus horizontal or vertically restricted maneuvering for head-on and if the aircraft has reasonable vertical performance of 500fpm or higher and is using SPS or better GPS service, then a detection range of 1,460ft would allow the aircraft to adequately maintain a safe distance from the modified sNMAC volume used during testing. If the aircraft's maneuver is restricted, the detection range increases to 1,641ft.

In the case of overtaking geometries with the same above assumptions, a required detection range of 624ft would be adequate for vertical-only or an unrestricted maneuver and 1,969ft for a horizontal-only maneuver. Due to the significantly larger required range for horizontal-only, the other maneuver types would be better in this scenario.

For this scenario, the intruder does not follow the right-of-way rules and instead maneuvers towards the center of the corridor. The results for a reasonable vertical performance of 500fpm are shown in **Error! Reference source not found.**. With a reasonable minimum vertical performance of 500fpm or larger, using SPS GPS or better, and ignoring the horizontal-only results for overtaking, a detection range of 1,641ft is sufficient to maintain separation in the scenario where the intruder does not follow the proposed Right-of-Way rules in unrestricted and restricted maneuvering within a RAC corridor of at least 400ft wide and 400ft tall. This requirement is the same as the general interaction set and shows the addition of the corridor did not have a major effect on the ability of the sUAS to maintain right-of-way rules within a corridor with a minimum of the dimensions used during testing.

Table 45. Maximum required detection ranges for sUAS vs sUAS not following RoW rules in a RAC corridor.

	Horizontal-only	**Vertical-only (500fpm)**			
Geometry	All GPS	RTK	WAAS	SPS	MAX
Head-on	1,772ft	1,444ft	1,592ft	1,641ft	2,281ft
Overtaking	2,330ft	509ft	542ft	558ft	722ft

1.3.2.5 Emergency

For the emergency corridor scenario, general corridor results can be applied for a subset of emergency interactions to get an initial estimate of the ability of the sUAS to maintain a safe distance from a sUAS in emergency while staying within the corridor. For this analysis, the emergency aircraft has priority and will not give way to the other aircraft and will use the corridor as an approach/landing area. Because the emergency aircraft will most likely be transitioning through altitudes towards the ground it is considered a column of avoidance, and vertical maneuvers are not feasible in this situation. These assumptions mean the sUAS vs sUAS not following right-of-way rules results can be applied to this specific emergency scenario, specifically the horizontal-only maneuver results.

Using the general corridor results, the required detection range for a sUAS avoiding an aircraft in emergency in the above-described scenario would require 1,772ft to maintain a safe distance in a head-on geometry and 2,330ft for an overtaking geometry. This means the sUAS would need at least a 2,330ft detection range to maintain a safe distance against another sUAS in emergency that is using the corridor as an approach/landing area. This distance does require the sUAS in distress to specifically use the corridor and does not work if the aircraft in emergency is flying through the corridor. In this case the sUAS may be required to land or leave the corridor to maintain a safe distance from the sUAS in emergency.

1.3.3 Reserved Airspace Simulations for Flight in a Corridor (KU)

In the flight in a corridor scenario, the sUAS or multiple sUAS is flying along the center of a reserved airspace corridor. This reserved airspace corridor is representative of an observation mission for rail or power lines over a long distance. The single sUAS or multiple sUAS is geographically constrained by the reservation such that it cannot exit the reserved airspace. Because of this restriction, the sUAS or multiple sUAS must avoid the crewed intruder while remaining inside of the reserved airspace. The recommendations and results for the flight in a corridor scenario are based upon the simulated avoidance maneuvers in the General Interactions scenario, which cover the full range of encounter angles for a sUAS flying along a straight line.

1.3.3.1 sUAS Encounters with a Crewed Aircraft

As shown in Figure 31, the sUAS flies along the center line of the corridor. The crewed aircraft will then enter the corridor for head-on, converging, and overtaking scenarios, prompting the sUAS to perform an avoidance maneuver--without leaving the corridor. Due to the similarities with round 1 simulations, it was decided to *derive* the required corridor width from the maximum deviation of an sUAS from its intended path (over all encounter angles), distance *b* in the figure. The required minimum width of a corridor, *W*, would then be twice the distance *b.* As noted earlier, since the autonomous sUAS is programmed to return to its desired flight path after an encounter, if the corridor is sufficiently wide, there will be the same minimum-required detection distance determined in General Interaction simulations to avoid a right of way violation. This would guarantee the sUAS does not leave the corridor even for the most severe maneuvers if traffic detection occurs at a distance greater than or equal to the minimum required distance.

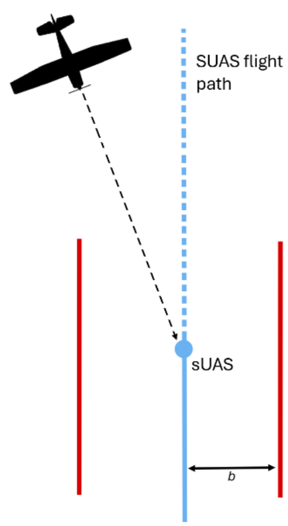


Figure 31. sUAS Encounter with a Crewed Aircraft While Flying in a Reserved Airspace Corridor.

When investigating the Round 1 data, it is plainly seen that as the detection distance gets larger, so does the divergence from the original sUAS flight path. All Round 1 data for head-on, converging and overtaking encounter angles, non-cooperative aircraft speeds, and both single and multiple sUAS were used to find the largest deviation from the intended flight path in the avoidance maneuver.

As shown in Figure 32, for a sUAS encountering a crewed aircraft traveling at 145 ft/s at a 270-degree heading, the largest divergence from the straight-line path of the single sUAS is roughly

4500 ft. Based on this information, the safest corridor width would be twice this, or 9000 ft. Note that other navigation and guidance algorithms may not require such a wide corridor.

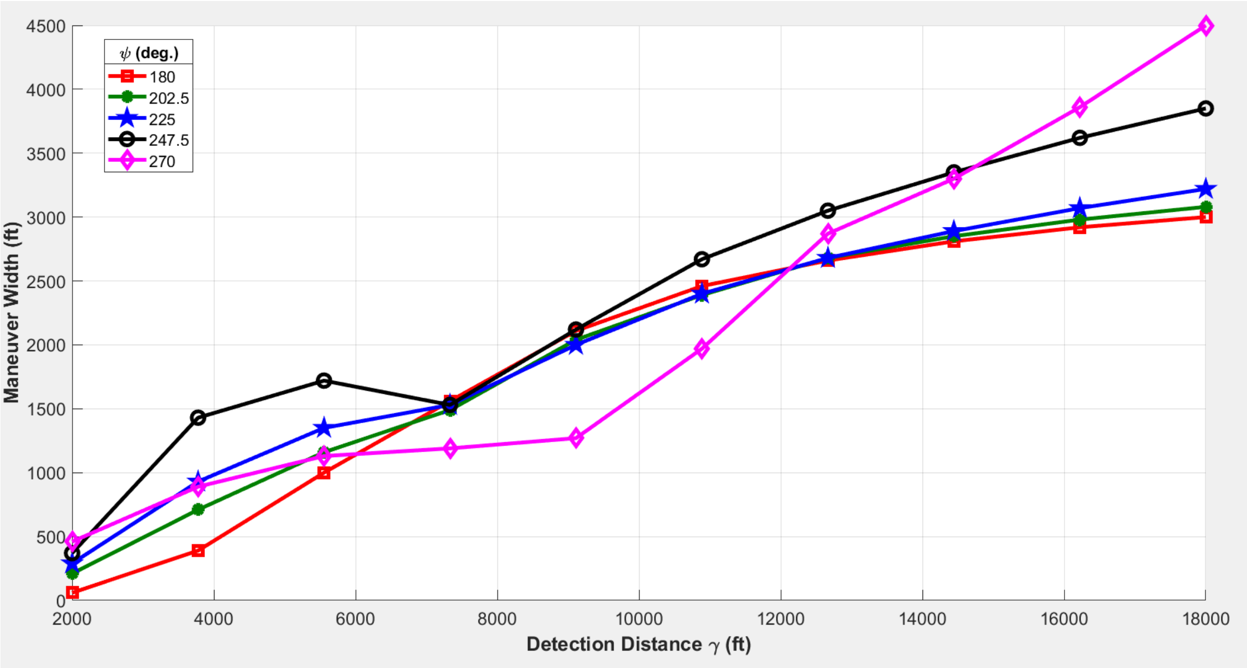


Figure 32. Single sUAS Maneuver Width for 145 ft/s Cessna.

The reason the largest maneuver occurs for the slowest crewed aircraft with ADS-B out aircraft is that the repulsive morphing potential field is experienced for the longest duration, pushing the sUAS further and further. For a fast-moving Cessna, the morphing potential field is experienced by the sUAS for a shorter time as the non-cooperative aircraft is not in its vicinity as long. Utilizing the ROW violation graphs presented in the general encounters, it can be seen that lower detection distances with smaller maneuvers still compete the goal of 'well clear', but this does not guarantee that the sUAS will remain in the prescribed corridor throughout the maneuver.

In Figure 33, the left tile shows the width of the avoidance maneuver for a 145 ft/s Cessna approaching an sUAS at 270 degrees. The right title shows the same encounter but with a Cessna traveling at 195 ft/s. As seen, the maneuver from the slower aircraft is much larger in width.

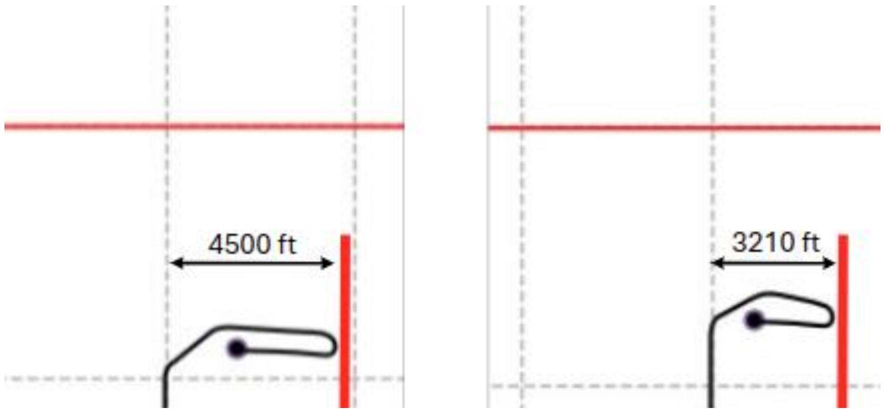


Figure 33. Single sUAS Required Corridor Width for 270º Encounter with Crewed Aircraft Flying at 145 ft/s (l) and 170 ft/s (r).

For the intermediate (170 ft/s) and fast (195 ft/s) non-cooperative Cessna speeds, the maximum divergence from the sUAS flight path from a maneuver are both roughly 3500 ft but occur at different heading angles. For an intermediate speed, non-cooperative Cessna, the largest maneuver occurs at a 270-degree heading. For the fast moving, non-cooperative Cessna, the largest avoidance maneuver occurs at a heading angle of 247.5 degrees. The remaining data for the maneuver divergence or 'width' is shown in later sections.

For further investigation, performance of the detect and avoid system utilizing the morphing potential field was paired with a loiter system. Once the non-cooperative Cessna is detected by the sUAS, the sUAS loiters about its current position until the distance between the non-cooperative crewed aircraft and the sUAS increases. An example of a successful loiter is shown in Figure 34.

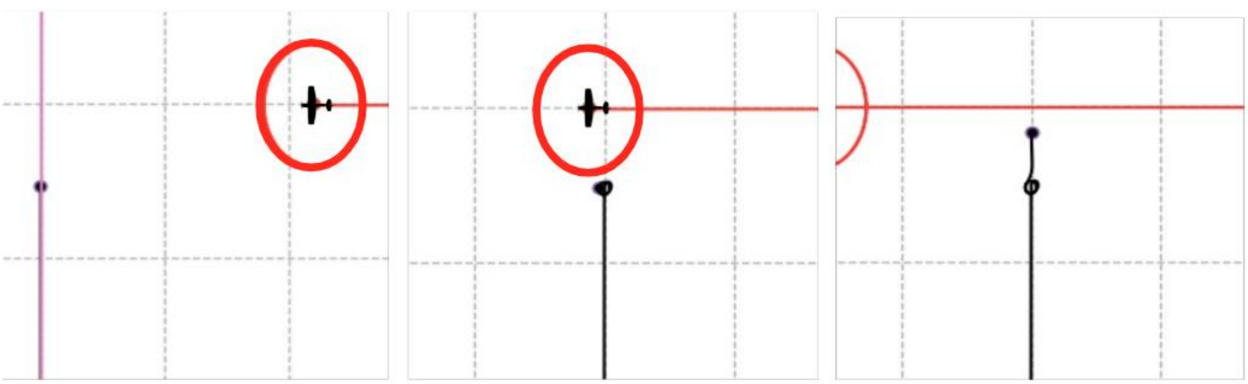


Figure 34. Sucessful Loiter Manuever.

This loiter maneuver has the same deviation from the sUAS path no matter the non-cooperative aircraft speed, as the sUAS enters the loiter circle as soon as the crewed aircraft is detected. The figure below highlights two loiter maneuvers at the same detection distance and incoming crewed aircraft angle, with a 145 ft/s Cessna shown in the left and a 195 ft/s Cessna on the right.

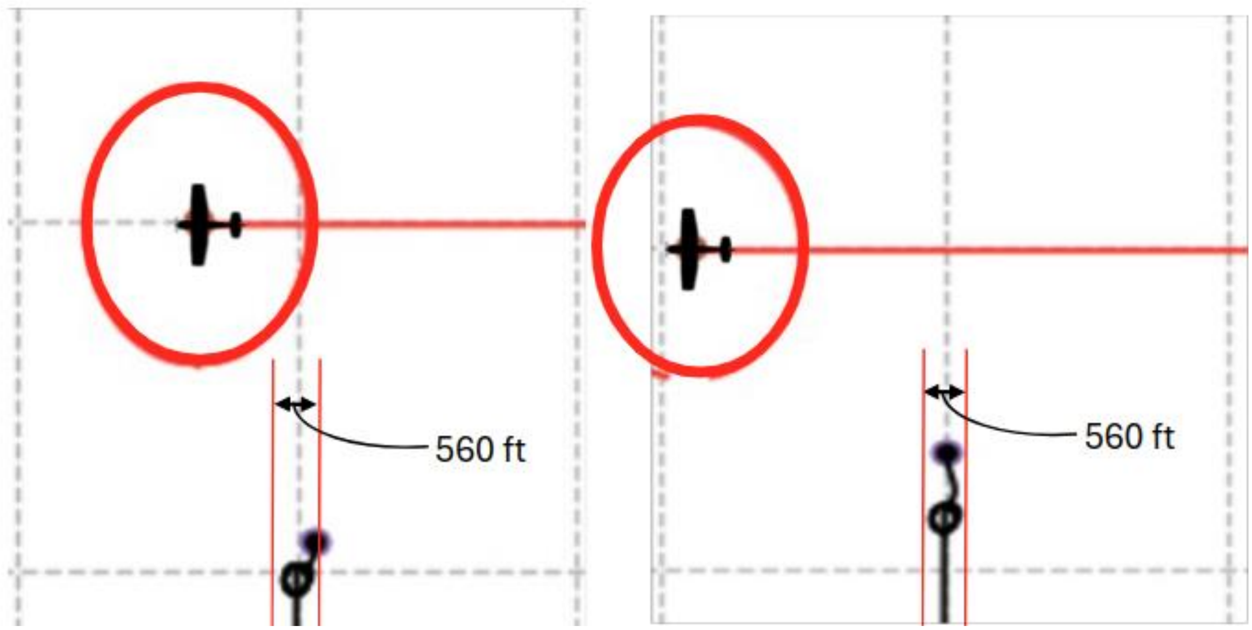


Figure 35. Maneuver Width at Varying Cessna Speeds.

This new loiter maneuver for the detect and avoid system was studied to compare the success of alterative collision avoidance logic that minimizes avoidance maneuvers. When implementing this logic, it was known that it would not be successful for a perfectly head-on and overtaking crewed aircraft as the sUAS loiters about its own flight path. This is plainly seen in Figure 36, which shows that for head-on and very near head-on non-cooperative aircraft heading angles, the percentage RoWV and NMAC are 100%.

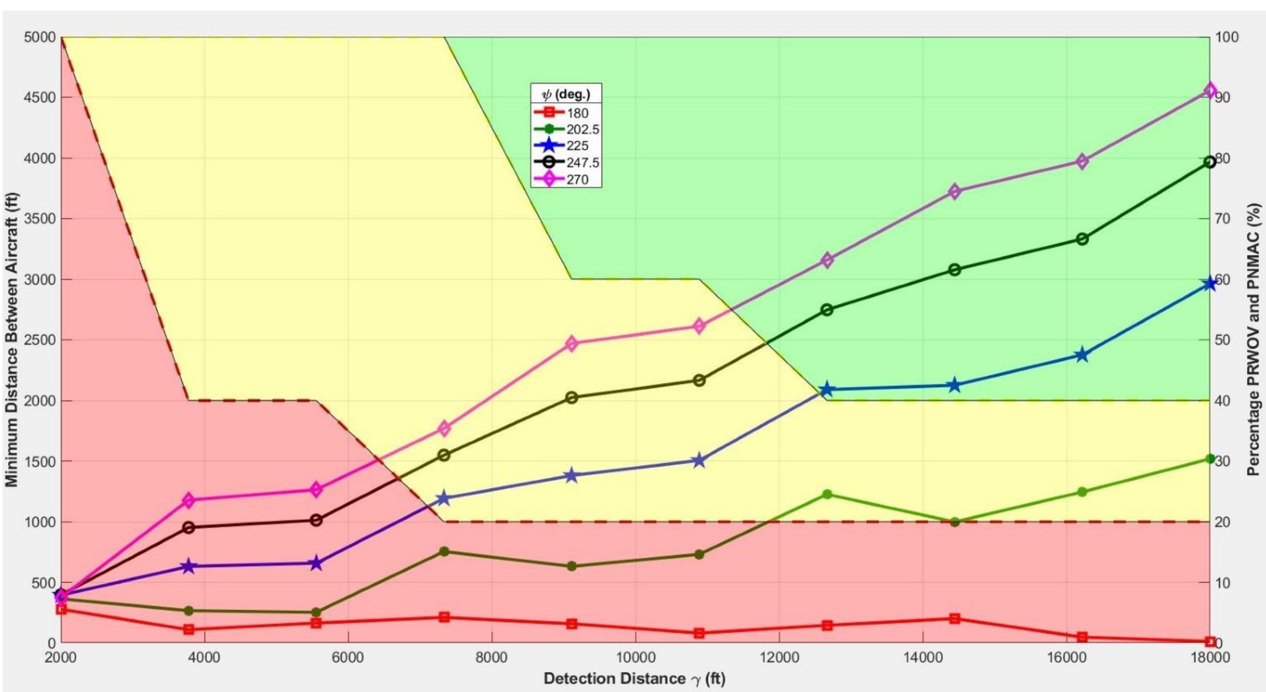


Figure 36. 170 ft/s Cessna Head-on All Angles.

To highlight scenarios in which the loiter maneuver is successful, the near-head-on and head-on heading angles were removed, and the data was replotted. As seen, the loiter maneuver has similar success to the morphing potential field and does not require a large corridor.

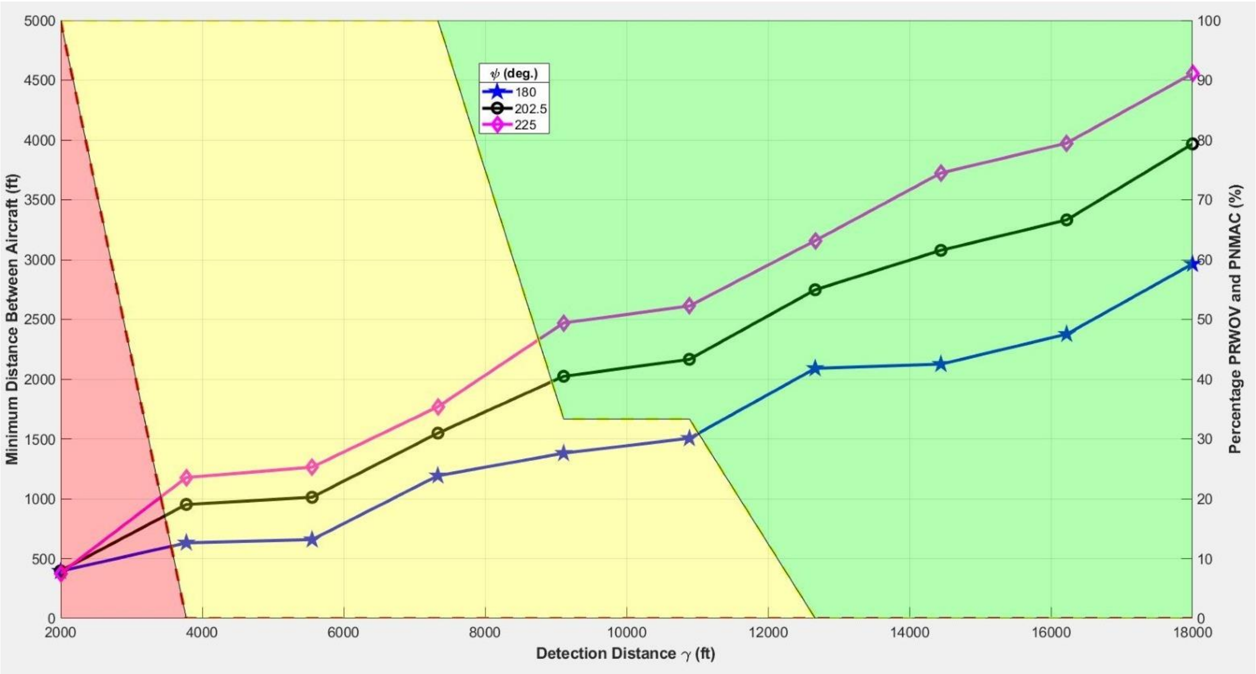


Figure 37. 170 ft/s Cessna Head-On.

The diameter of the loiter circle is roughly 560 ft, and this is typically the maximum the aircraft diverges from its flight path. In some cases, due to the nonlinearity of the aircraft encounter, the sUAS will make a wide turn to make it back on its flight path. This is due to the location that the sUAS exits the loiter circle from, and some examples are provided in Figure 38. On the right the loiter maneuver with a preferable exit from the loiter circle, and on the left is a loiter maneuver with a non-preferable exit. In this case, the non-preferable exit creates a 990 ft divergence from the sUAS flight path, meaning the corridor needs to be 1,990 ft.

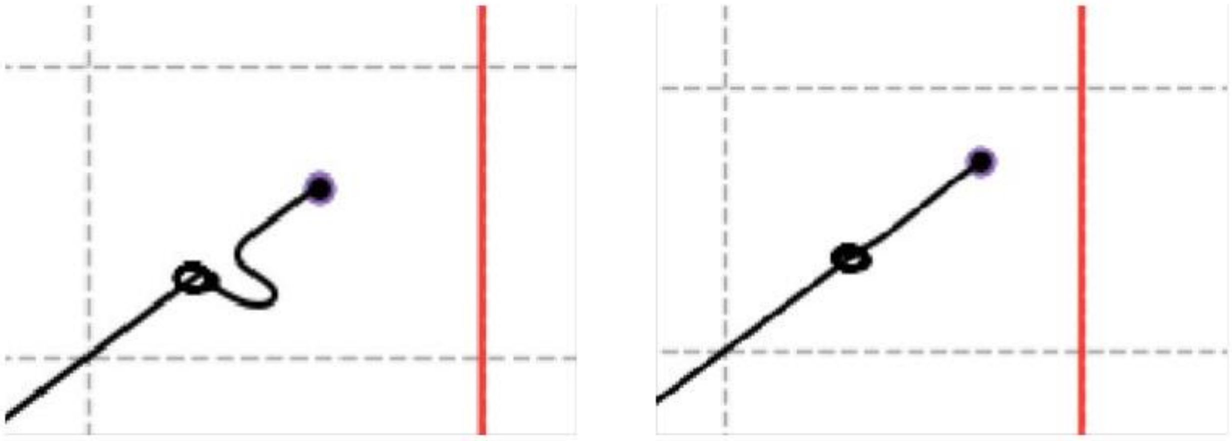


Figure 38. Loiter Maneuver Exit.

The maneuver widths for a full set of encounters is highlighted in Figure 39**,** showing the consistency of the loiter circle and its maneuver width. The data for all encounters is provided in the appendix.

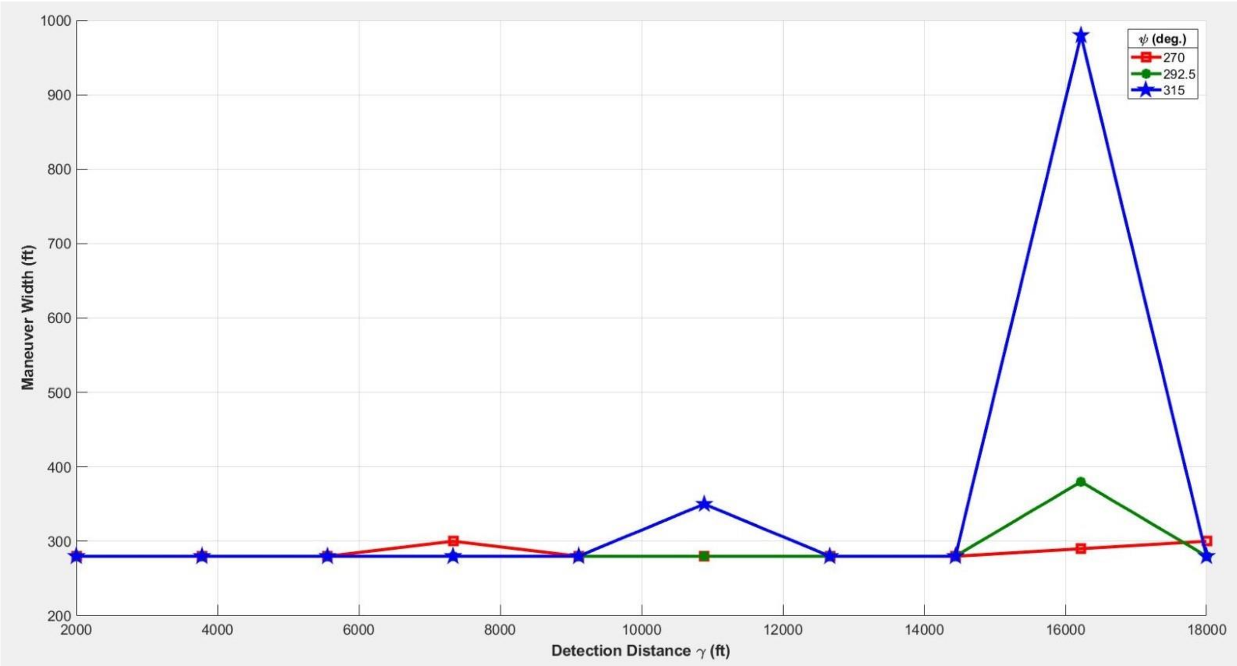


Figure 39. Maneuver Width for 170 ft/s Cessna Overtaking Angles.

As evident by the data, the loiter maneuver is not useful at all in direct head-on/overtaking and the next adjacent simulated angles. However, it seems for non-cooperative aircraft heading angles from roughly 225 degrees to 315 degrees, the loiter maneuver is successful at detection distance like the morphing potential field and minimizes the corridor width. Even with a non-desirable exit from the loiter circle, the corridor width is very small compared to the previous results shown by the morphing potential field. The worst case loiter maneuver creates a divergence from the flight path of 990 ft, resulting in a corridor width of 1,980 ft. This is less than the bare minimum required to include the 'buffer' of 2000 ft, so for the loiter maneuver the corridor should be 4000 ft to include the buffer on either side. One possible takeaway from this is to have a more complex guidance which incorporates the benefits of both the loiter maneuver and the morphing potential field.

1.3.3.2 Multiple sUAS Encounters with a Crewed Aircraft

When investigating the maneuver divergence or 'width' from the preplanned flight path of multiple sUAS, the maximum still occurred at a detection distance of 18,000 ft for a relatively slow (145 ft/s) non-cooperative Cessna at a heading angle of 270 degrees. However, the maneuver width was much larger, nearly 5,200 ft, due to multiple sUAS. Even if the lateral separation of 500 ft between the sUAS is subtracted from the maneuver width, it would still be a larger divergence. This is evidence that a larger corridor is needed when flying with multiple sUAS. The multiple sUAS encounter with the largest maneuver width is highlighted in Figure 40.

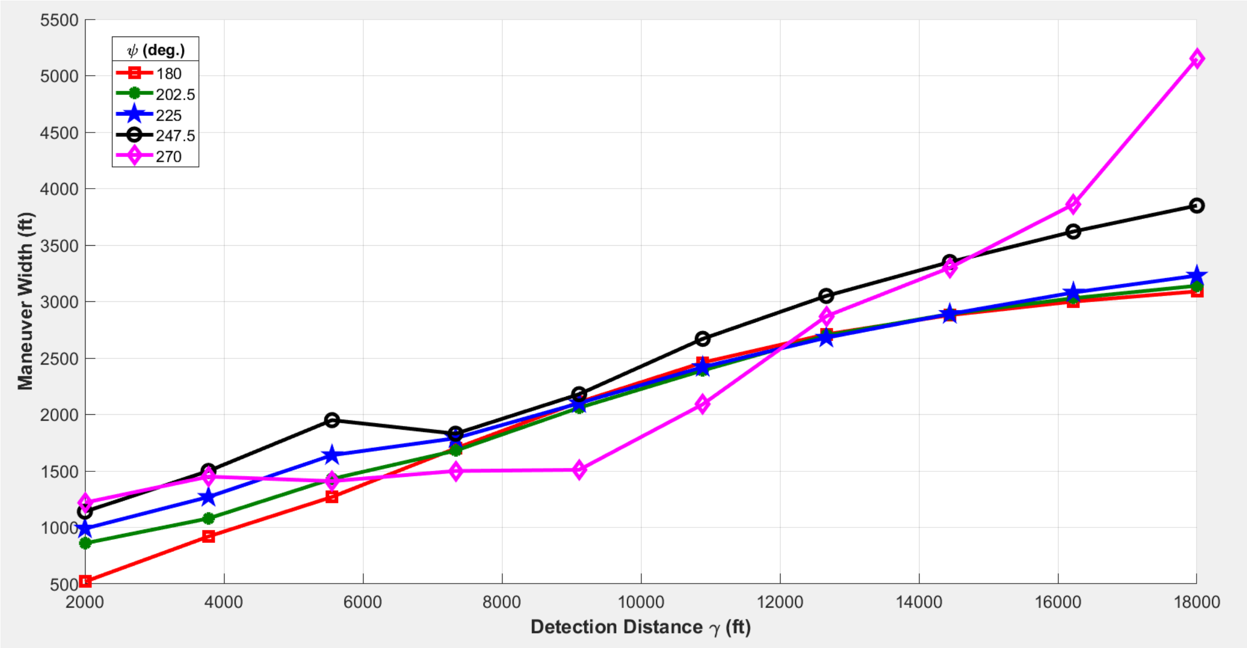


Figure 40. Multiple sUAS Maneuver Width for 145 ft/s Cessna.

For the intermediate (170 ft/s) and fast (195 ft/s) non-cooperative Cessna speeds, the maximum maneuver width is only slightly larger than the single sUAS, with widths slightly over 3600 ft. For the intermediate and fast speeds, the maximum maneuvers width occurs at heading angles of 270 degrees and 247.5 degrees respectively. Once again, leveraging the data from the general encounters between multiple sUAS and the non-cooperative Cessna shows that at lower detection distances, smaller maneuver widths will still result in successful avoidance maneuvers. However, if the corridor width is based on these, for a larger detection distance the sUAS would leave the prescribed corridor. The remaining data for the maneuver width of the multiple sUAS is in the appendix. Figure shows the largest corridor widths at each aircraft closing speed for single and multiple sUAS.

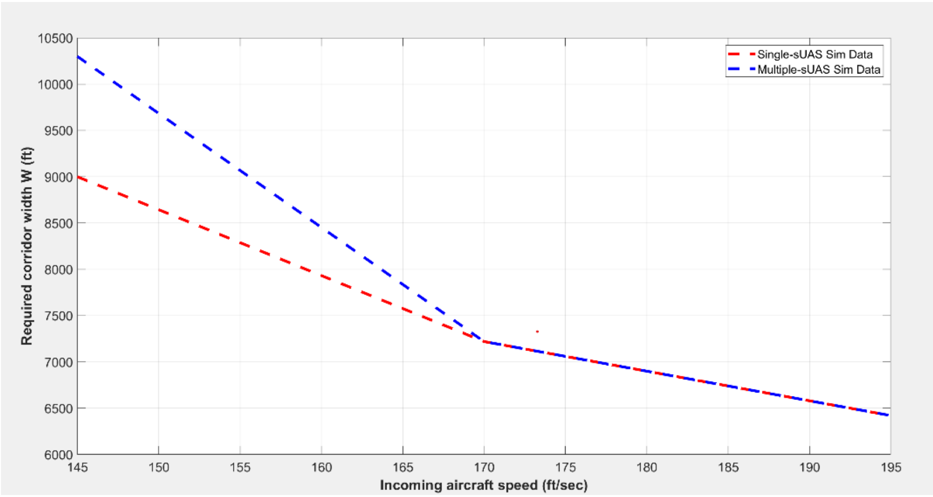


Figure 41**.** Required Corridor Width for sUAS Flying at 45 ft/s Encountering Crewed Aircraft.

1.3.3.3 Observations

When examining the maneuver widths for single and multiple sUAS, it is interesting that the largest maneuvers occur at the lowest non-cooperative crewed aircraft speed. The governing encounter is one in which the UAS approaches the crewed aircraft at 90^o or 270^o from its path. In this case, the sUAS turns and "waits" for the crewed aircraft to fly by. For a slower sUAS, this takes it further from the intended path and therefore demands a larger corridor width. As previously stated, this is due to the chosen navigation and guidance algorithm, and the result may be different for others. In particular, for an algorithm that allows changes in sUAS velocity, slowing down as the sUAS approaches the crewed aircraft path could reduce the deviation from the sUAS path and result in a smaller required corridor width. After leveraging the General Interaction encounter scenarios to derive the minimum corridor widths, the following observations have been made for a relative velocity of 190 ft/s (for the slowest crewed aircraft velocity studied:

- When flying with a single sUAS, to stay within the prescribed corridor, it is recommended that the corridor be 9000 ft wide.
- When flying with multiple sUAS, to stay within the prescribed corridor, it is recommended that the corridor be 10,400 ft wide.

1.3.3.4 Possible Recommendations Affecting Right of Way Rules

As in the general interaction scenarios, it is desirable to have a simple, conservative equation to determine the minimum safe corridor width to avoid a RoWV . In this case, the required corridor width is inversely related to the relative velocity. Using the lowest relative velocity encounter case, the scaling factor can be found by multiplying the relative velocity by the required corridor width. **Error! Reference source not found.** gives these scaling factors for a single and multiple sUAS.

Table 46. Non-dimensional scaling factor.

sUAS	**Required Corridor Width**	**Scaling Factor**
Single	9000	1,710,000
Multiple	10400	1,957,000

The equation to find the recommended corridor width *(W)* for single sUAS engaged in corridor-constrained flight is:

$$W\ (ft)\ =\ \frac{1710000\left(\frac{ft^2}{s}\right)}{V_{rel}\left(\frac{ft}{s}\right)} \qquad (4)$$

The equation to find the recommended corridor width *(W)* for multiple sUAS engaged in corridor constrained flight is:

$$W(ft)\ =\ \frac{1957000\left(\frac{ft^2}{s}\right)}{V_{rel}\left(\frac{ft}{s}\right)} \qquad (5)$$

1.3.4 Reserved Airspace Simulations for a Grid Survey Mission (KU)

1.3.4.1 Single sUAS Survey Mission

Figure 42 shows the definition of the grid survey pattern that was used for these simulations. The survey pattern for the sUAS was arbitrarily set to 6,500 feet "north to south" and 4,500 feet "east to west". To allow for cooperative aircraft to fly on the edge of ***any*** reserved airspace without causing an avoidance maneuver, a 2,000-foot buffer is needed at a minimum if there are no GPS inaccuracies on either the sUAS or the crewed aircraft ***and*** if there are no crosswinds. To account for GPS uncertainty and winds, the buffer must actually be larger than 2000 ft, possibly an extra 100 or so feet.

For the 6500 ft by 4500 ft survey region, a number of RA sizes were studied. However, the final size selected as the best size for this case was 10,500 ft X 10,500 ft, represented by side length *a* in the figure. Note that the buffers in the east-west direction are greater than in the north-south direction. This is primarily due to the particular separation concept studied. In particular, when the avoidance maneuver begins, the sUAS is directed to one of the four corners of the reserved airspace. This is enabled by an expanded east-west direction buffer.

Preliminary investigations considered a range of sizes of reserved airspace starting at 8500 ft in both dimensions, which gives the minimum possible north-south buffer size. The number of right of way violations were recorded for all encounter angles. When the size was increased in simulation to 9500 ft square, the percentage of ROW violations decreased. However, increasing the size to 10,500 ft did not result in any less violations. The remaining ROW violations occurred from having too little detection range and were not a function of the size of the reserved airspace.

Based on preliminary simulations, it was found that the four points indicated in the figure below were the points for which the sUAS had the highest likelihood for a RoWV. These points are referred to as unmitigated encounter points—the points at which a collision would be predicted if neither the sUAS nor crewed aircraft changes path. Simulations were run for 5 non-cooperative aircraft heading angles (190-270 degrees), 10 detection distances (2,000-18,000 ft), and 3 non-cooperative aircraft speeds (145-195 ft/s), for a total of 600 simulations.

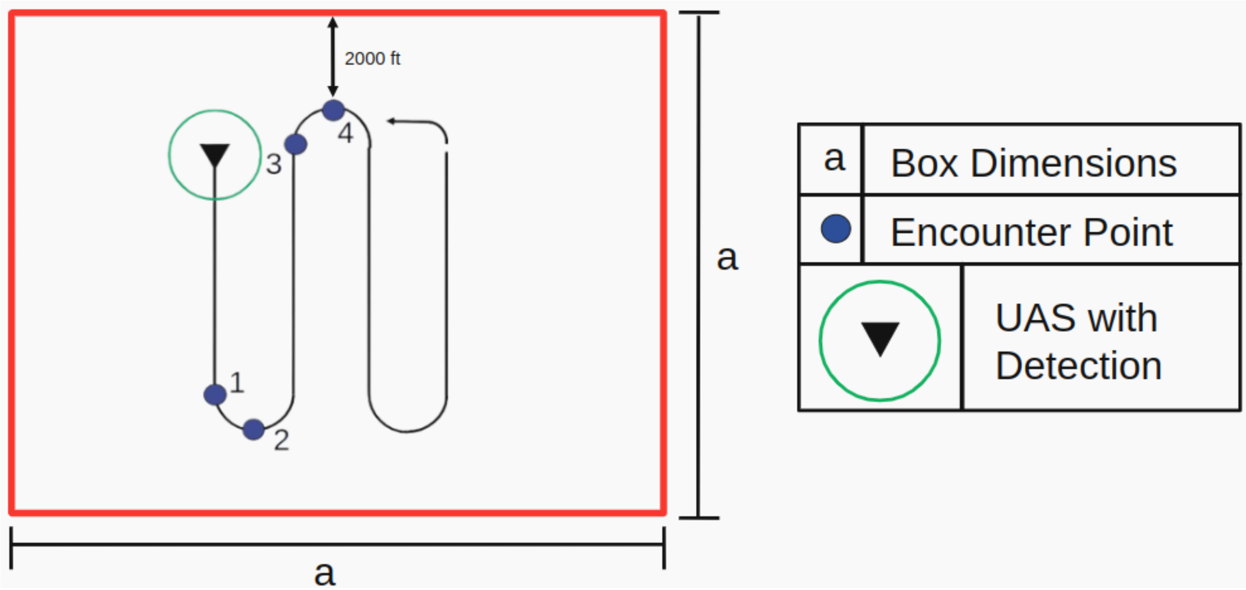


Figure 42. Survey Grid Encounter Point Definitions.

For the reserved airspace simulations, a different collision avoidance algorithm, the "corner optimization algorithm" was used in place of the morphing potential field To maximize the distance from the non-cooperative aircraft, it was decided the sUAS would travel to and loiter in a corner of the reserved airspace until the non-cooperative aircraft was no longer a concern, i.e., the sUAS is in the 'well clear.' To implement this avoidance and select the best corner for the sUAS to loiter in, a cost function with three terms was created. This cost function takes into consideration how much the sUAS would have to turn,$\Delta\psi$, the distance from the sUAS to the corner, Δd , and if the sUAS will have to cross the non-cooperative aircraft path, v_{rel}. The cost function is created for each corner of the reserved airspace when the avoidance maneuver begins, and the sUAS guidance and navigation algorithm chooses to go to the corner with the lowest cost.

$$J = w_1|\Delta\psi| + w_2\Delta d + w_3 v_{rel} \qquad \text{Equation 6}$$

The highest cost is placed on crossing the non-cooperative aircraft path, w_3, which has the highest likelihood of creating the worst-case scenario, a mid-air collision. If there are two available corners without crossing the non-cooperative aircraft path, the sUAS will then decide based on energy minimization, i.e., the closest corner or the one that will require the smallest turn.

Once the non-cooperative aircraft is detected, the sUAS will choose its corner and then solely focus on reaching/loitering in the corner until 'well clear' is reached. After the "well clear" has been confirmed, the sUAS will return to the point on the survey pattern from which it diverged, and then continue surveying. For the completed simulations, the determination of well clear was chosen to be when the non-cooperative aircraft is safely back outside the detection range. This is a design parameter and can be changed so that the sUAS will return to its surveying mission more quickly if desired. The following figures highlight three scenarios:

1. The detection range is large, causing the sUAS to avoid the non-cooperative aircraft, but then loiter in its chosen corner for too long (Figure).
2. The detection range is an intermediate value, which still allows the sUAS to avoid the non-cooperative aircraft but returns to its survey path more quickly (Figure).
3. The detection range is too low, causing a ROW violation between the sUAS and the crewed aircraft with ADS-B out aircraft (Figure 45).

In each figure, the red circles indicate loiter points that the optimized cost function determined to be non-viable options. The green circles indicate corners that are not across the Cessna's path and would result in a successful avoidance. Ultimately, the sUAS chooses the corner based on its distance or how much it would have to turn. In the case of the figures below, the aircraft chooses the top left corner due to distance, as the cost of distance of the top right corner was higher than the cost of the tighter turn for the top left corner.

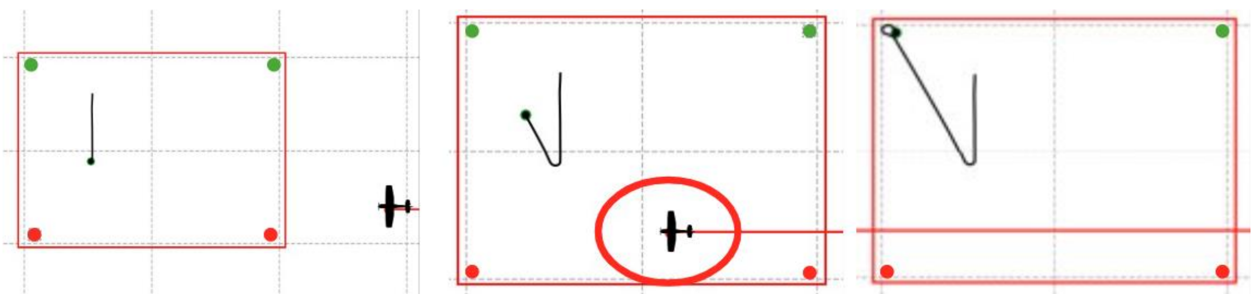


Figure 43. Large Detection Range with Extended Loiter.

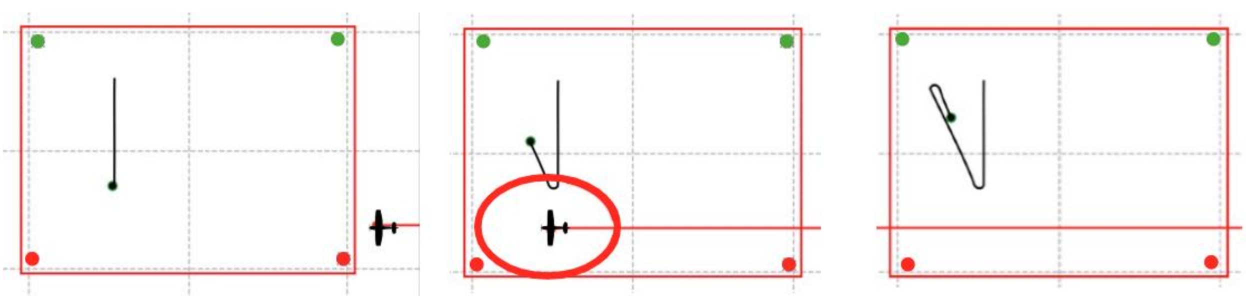


Figure 44. Medium Detection Range with sUAS Returning.

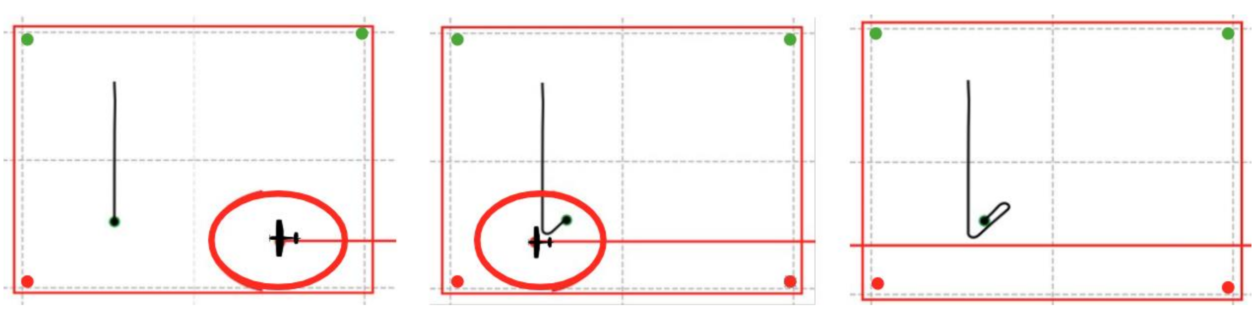


Figure 45. Low Detection Range with ROW violation.

1.3.4.2 Multiple sUAS Survey Mission (KU)

For further investigation about the reserved airspace concept, simulations were run for multiple sUAS with an non-cooperative aircraft. These cases still used the same four encounter points, which were assumed to be the worst locations for an non-cooperative aircraft to intersect the survey path due to proximity with the boundary and sUAS energy exerted to conduct avoidance maneuvers. The same sUAS detections distances, non-cooperative aircraft heading angles and non-cooperative aircraft airspeed were used as with the single sUAS case.

The collision avoidance algorithm for corner choosing was left unaltered, but a second logic was added to insure the multiple sUAS avoided each other. When flying the survey path, the sUAS are separated 100 ft laterally and fly an identical survey path. However, when the non-cooperative aircraft is detected and the sUAS begin traveling to a corner, they are commanded to different altitudes. One sUAS will rise 15 feet and the other will lower 15 ft. This maneuver is not drastic and allows the multiple UAS to loiter about the same corner point without collision. Once the multiple sUAS returns to the survey path, they are commanded back to the original altitude to complete the survey mission. This method resulted in no collision between the multiple sUAS for all simulations. An example of a successful collision avoidance maneuver with multiple sUAS is highlighted in Figure .

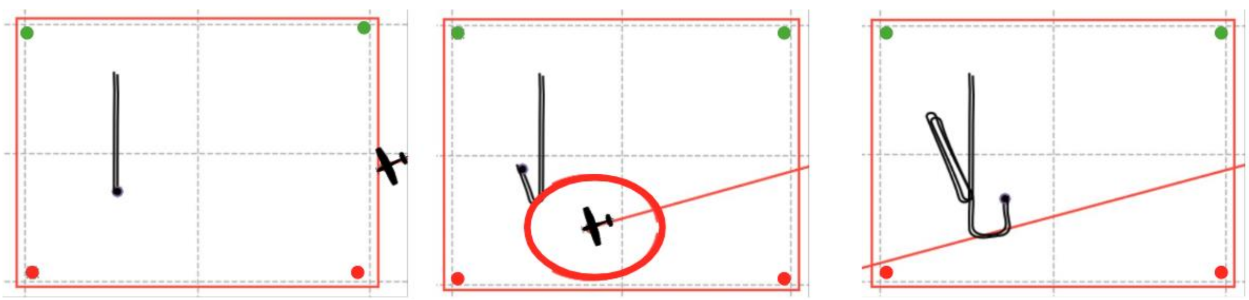


Figure 46. Successful multiple sUAS Avoidance Maneuver.

After completing simulations of all 1,200 cases, 600 for single sUAS and 600 for multiple sUAS, the data was analyzed to investigate the percentages of ROW violations and NMAC. General comments about data trends and highlighted simulations are presented below.

As can be seen in the graphs of the appendix, encounter point 4 consistently required the highest detection distance out of the rest of the points to ensure there were no NMACs or ROW violations. The only time that another point required the same detection distance was when the Cessna 172 had a velocity of 195 ft/s. The results can be found in Error! Reference source not found.. The results are notable as they give the minimum separation distance that the sUAS must start making its avoidance maneuver if it is to avoid a NMAC and a ROW violation. In some capacities, the minimum detection range also represents the minimum decision range for the sUAS to begin making its avoidance maneuver to avoid NMACs and ROW violations. A larger detection range could likely help an autonomous sUAS or multiple sUAS optimize its avoidance maneuver to let it complete a portion of its remaining mission while still getting “well clear” of the non-cooperative crewed aircraft.

Table 47. Minimum Safe Detection Distance.

Intruder Airspeed (ft/s)	**Single sUAS Minimum Detection Range (ft)**	**Multiple sUAS Minimum Detection Range (ft)**
145	10,888	10,888
170	10,888	10,888
195	12,666	12,666

It can easily be seen that with an increase in intruder airspeed, the minimum safe detection distance increases. This study only investigated three different speeds that are common to a Cessna 172 because this is the crewed aircraft the researchers possessed to conduct flight tests to compare the simulation data. Further, crop duster aircraft fly in a speed range similar to a Cessna 172 and spend much more time flying below 400 ft AGL. Alternatively, a faster non-cooperative aircraft could lead to more ROW violations, or even NMACs, if the detection distance on the sUAS is not high enough to account for its airspeed. Alternatively, many rotary wing aircraft fly quite slowly, and require lower safe detection distances as reported by ERAU.

It is important to understand that sUAS airspeed will also play a part in the avoidance capability of the system. A slower sUAS will likely need a higher detection range in order to have enough time to maneuver out of the way of a crewed aircraft while a faster sUAS will likely need a lower detection range in order to have enough time to maneuver.

Error! Reference source not found. also shows that there does not seem to be much of a difference in the avoidance of single sUAS and multiple sUAS. Figure and Figure show a comparison between the 195 ft/s condition for point 4 on the surveying pattern. Although the results look nearly identical, this of course is not the case as there are multiple sUAS that are avoiding the crewed intruder. The simulation is set up that there is a leader sUAS and a follower sUAS, and the leader sUAS avoids the intruder in the same way it would if there was no other sUAS following it. Since the follower sUAS is so close to the leader sUAS, it follows a similar path in its avoidance of the intruder. Furthermore, the small altitude separation allows for the multiple sUAS to converge on the same avoidance path, essentially combining them into a single agent. This gives the impression that there is not much change in the minimum detection distance.

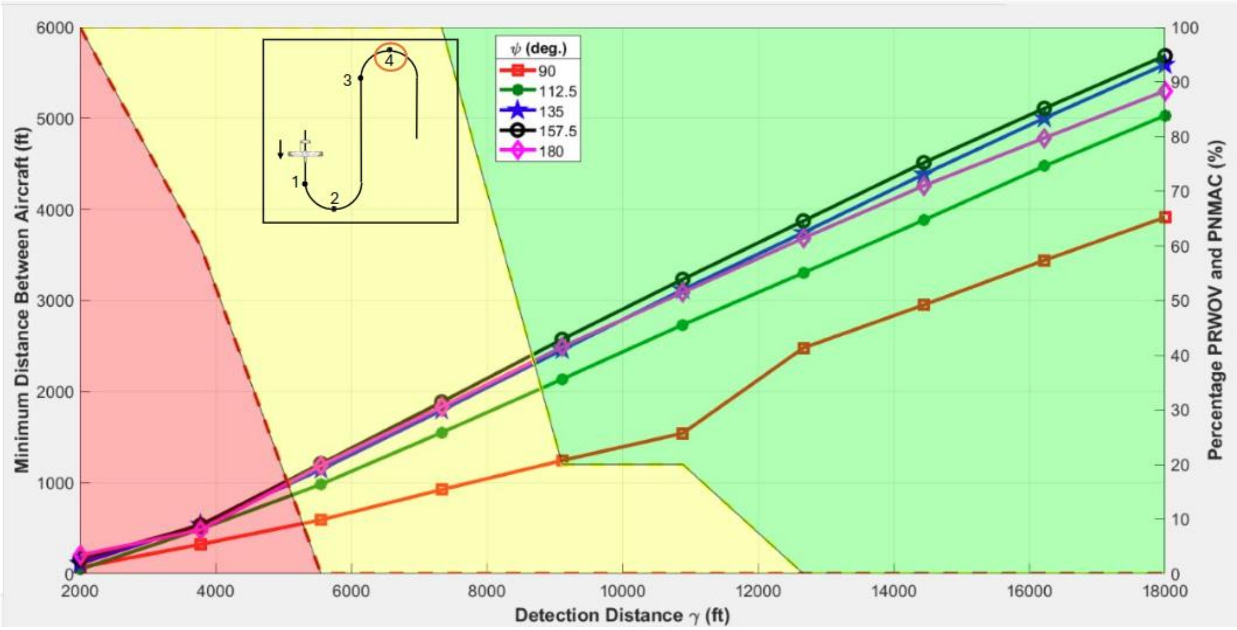


Figure 47**.** Point 4 Single sUAS Encountering 195 ft/s Crewed Aircraft at Point 4.

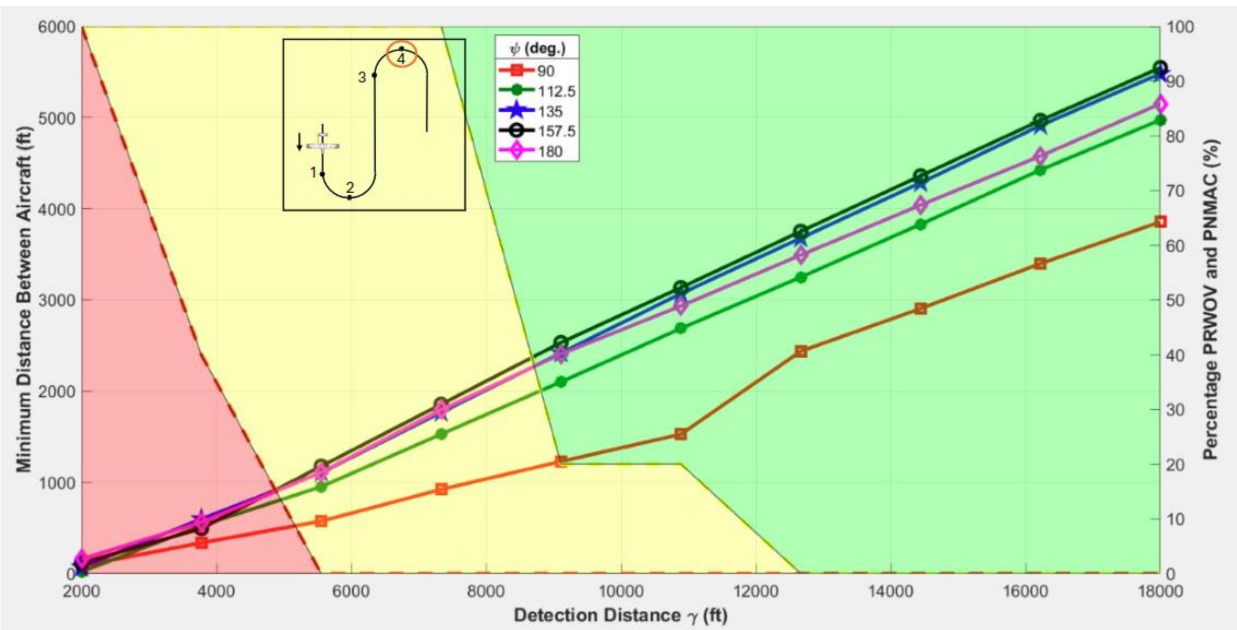


Figure 48. 195 ft/s Point 4 Multiple sUAS.

However, if the distances between the sUAS in formation flight are increased, the required detection distance to avoid a ROW violation would likely increase and a bigger reserved airspace would be required.

1.3.4.3 Observations

For the simulations conducted for an unmitigated collision at point 4—when the sUAS is in the middle of a right turn away from the boundary of the reserved airspace—the required detection distance to avoid a RoWV was the largest. Thus, the minimum detection distance for the single sUAS and multiple sUAS vs. crewed aircraft were derived from simulations for this point.

- For an non-cooperative aircraft flying between 145 and 170 ft/s, the minimum detection distance for a successful avoidance maneuver is predicted to be 10,888 ft.
- For an non-cooperative aircraft flying at 190 ft/s, Further investigation showed that as the closing speed increased, i.e., a faster non-cooperative aircraft, the minimum detection distance for a successful avoidance maneuver is predicted to be 10,888 f.

Additional data for the other encounter points in the appendix show that a slower non-cooperative aircraft requires a lower detection distance, but this is not the worst-case scenario.

The derivation of minimum detection distance can have numerous applications, with one case being a minimum "decision-to-avoid" distance. Although a sUAS might have a sensor capable of detecting an non-cooperative aircraft at great distances, the sUAS could remain on its survey path after detecting the non-cooperative aircraft until it must decide to maneuver to avoid a ROW violation. This concept has not been studied in detail

As with other scenarios, there are some cases where a collision avoidance maneuver requires undesirable roll and yaw rates [5]. This is heavily dependent on the sUAS position at time of detection, as it will prioritize avoiding the non-cooperative aircraft at all costs over smooth, sweeping turns. This is also due to the nature of the guidance used for the reserved airspace. The constrained optimization of choosing the best corner can result in energy-expensive maneuvers to ensure the sUAS not cross the path of a crewed aircraft.

After examining all results and comparing the different scenarios, one key comparison can be made between the chosen detect-and-avoid system. Although 2 different approaches were used, the morphing potential field algorithm and corner optimization algorithm, both converged to the conclusion that the minimum detection distance for a crewed aircraft flying at 170 ft/s is 10,888 ft.

1.3.4.4 Possible Recommendations Affecting Right of Way Rules

As explained earlier the observed worst-case detection distances for single and multiple sUAS will be used to derive a linear equation that can be applied for a range of closing speeds to provide a conservative estimate for reserved airspace size based on the size of the airspace needed to fly the intended mission. By dividing the worst-case detection distance by the worst-case closing speed, a scaling factor is found. The largest scaling factor will then be used in the final equation. Once again, since both single and multiple sUAS encounter resulted in the same worst-case detection distance for different closing speeds, the final equation can be used for both single and multiple sUAS.

Table 48. Scaling Factors for Single and Multiple sUAS Flying in a Grid Survey Reserved Airspace

Highest Relative Velocity (ft/s)	Highest Detection Distance (ft)	Scaling Factor (s)
190	10888	57
215	10888	51
240	12600	53

The conservative equation to find the recommended detection distance (*D)* for single or multiple sUAS engaged in reserved airspace flight is:

$$W\,(ft) \;=\; V_{rel}\left(\frac{ft}{s}\right)\cdot 57\;(s) \tag{7}$$

In addition to recommendations about a conservative detection distance, a new equation was created to provide some recommendations about reserving airspace. For the north-south dimension of the survey pattern studied in this report, a 2000 ft buffer was added along each side. For the east-west dimension of the survey pattern, a larger, arbitrary, 3000 ft buffer was added along each side to make the reserved airspace square. However, considering GPS uncertainty for both the sUAS and crewed aircraft as well as potential winds, it makes sense to include a "safety factor", possibly 1.25, multiplied by the minimum buffer size, 2000 ft. Therefore, the recommended equation to find the required side length of a side of a reserved airspace rectangle, L, is found by adding the buffer width to the North/South or East/West dimension of the flight area, *S:*

$$L(ft) \;=\; S(ft) \;+\; \big(2\cdot(1.25\cdot 2000)\big)(ft) \;=\; S(ft) \;+\; 5000(ft) \tag{8}$$

Note this recommendation is for the corner optimization algorithm, though simulation with the morphing potential field might also be used for future studies, with either constant or variable sUAS speed.

1.3.5 Helicopter vs sUAS (ERAU)

Within Round 2, the Reserved Airspace Concept (RAC) is introduced to define a means by which pilots can reserve a given region for their missions. For a drone reserving such a space, its flight is constrained to the region. The experiments for Round 2 involve two RACs as shown in Figure 49, a Rectangular RAC and a Narrow RAC. The first is 4600ft by 3000ft, and between 0ft and 400ft in altitude. The second is 5200ft by 1700ft, and between 0ft and 400ft in altitude. To guarantee that the drone can feasibly maneuver around the helicopter, a 2000ft buffer region is added along each RAC's perimeter. The drone has a pre-defined mission where it patrols the interior of the RAC. Due to the drone not having a known orientation at the point where the vehicles encounter each other, there is a varying number of simulations that result in each scenario type. This is unlike Round 1, where each scenario was explored independently.

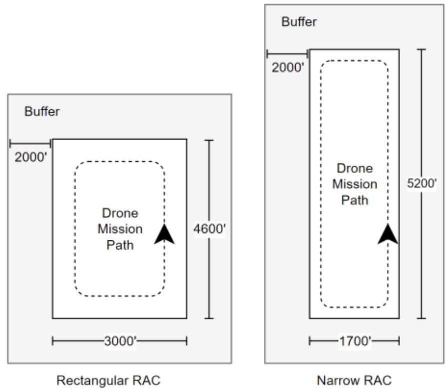


Figure 49. ERAU RAC Configurations.

The helicopter has one of four paths intersecting the RAC. As shown in Figure 50**Error! Reference source not found.**, these paths intersect the RAC along its lateral and longitudinal axes, at both a 45° and 90° angle. This is to explore more varied encounters.

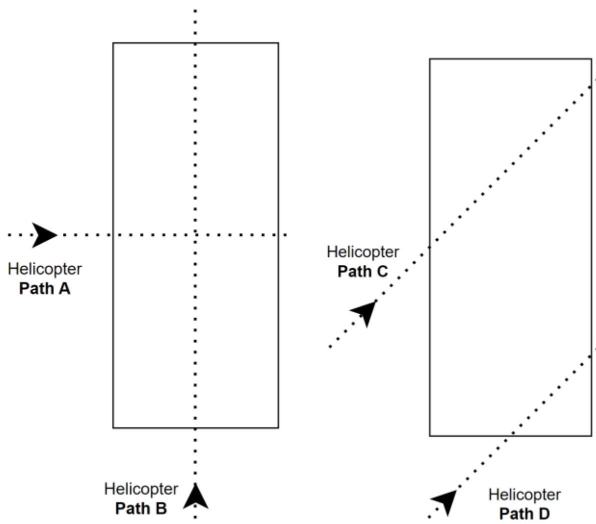


Figure 50. ERAU RAC Helicopter Paths.

The maneuvers that will be compared are the standard ROW right-hand turn maneuver and the safe-zone maneuver. The ROW maneuver involves the drone taking a 90° right turn and traveling until it reaches the edge of the RAC, at which point it will orbit until the end of the simulation. With the safe-zone maneuver, the drone will navigate to the nearest known safe-zone, at which point it will orbit until the end of the simulation. The motivation behind the "safe-zone" maneuver is that determining if a left or right turn is valid depends on the intersection between the helicopter's path and the RAC. An area of the RAC is only safe if it does not fall within the violation region of the helicopter's path, as illustrated in Figure . The drone will default to avoiding crossing the helicopter's path by default, unless there are no available safe zones on its current half of the RAC.

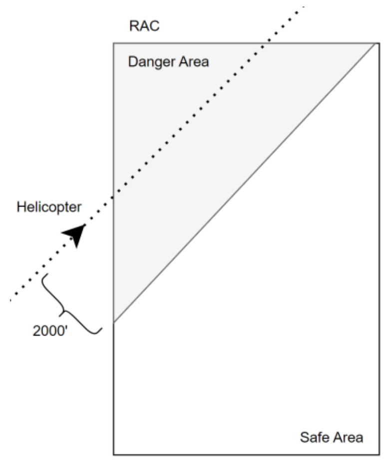


Figure 51. RAC Safe Zones.

1.3.5.1 Helicopter vs sUAS Interpretations (Discussions)

This section overviews the results from Round 2. They are organized by Scenario and Maneuver, and separated by the type of RAC that was simulated.

Within Table 49, the results for the Rectangular RAC are presented. Similar to Round 1, the ROW maneuver performed at a much higher risk than non-ROW. As before, the reduction in risk was predominantly due to a reduction in the percentage of simulations that resulted in a violation.

Table 49. Round 2 Rectangular RAC Results.

Scenario	**Maneuver**	**Simulation Count**	**Mean Severity**	**Violation Percent**	**Risk**
Head On	Horizontal	12526	27%	18%	5%
Overtaking	Horizontal	4627	34%	21%	7%
Converging	Horizontal	11042	26%	19%	5%
Head On	ROW	12526	52%	67%	35%
Overtaking	ROW	4627	54%	72%	39%
Converging	ROW	11042	54%	71%	38%

Within Table 50, the results for the Narrow RAC are presented. The risk for the Narrow RAC are similar to that of the Rectangular RAC, but the ROW risk decreased slightly and the non-ROW risk increased slightly. Overall, the Horizontal maneuver maintained a significant lead in safety.

Table 50. Round 2 Narrow RAC Results.

Scenario	Maneuver	Simulation Count	Mean Severity	Violation Percent	Risk
Head On	Horizontal	12767	30%	28%	8%
Overtaking	Horizontal	5714	36%	24%	9%
Converging	Horizontal	9753	29%	19%	6%
Head On	ROW	12767	49%	62%	30%
Overtaking	ROW	5714	50%	71%	36%
Converging	ROW	9753	54%	65%	35%

1.3.6 Reserved Airspace Concept - Summary

In the case of sUAS vs sUAS interactions in a corridor scenario the proposed right-of-way rules appear to be adequate for maintaining a safe distance. The addition of the corridor restriction did increase the required distance compared to the general interaction results but was not an undue change and did not significantly affect the conclusions and recommendations presented in the general interactions section.

If the aircraft is capable of maintaining a vertical performance of 500fpm or greater and a GPS uncertainty of SPS or better the aircraft can maintain a safe distance with a detection range of 1,641ft assuming a 5s pilot response time for both the following and not-following right-of-way scenarios assuming that the aircraft is not restricted to a horizontal-only maneuver for the overtaking geometries for the not-following right-of-way scenario.

In Round 2 of the experiments, the RAC was introduced, allowing pilots to reserve a specific region for their operation, constraining drone flights within this area. The experiments involved two RAC types: a Rectangular RAC (4600ft by 3000ft, 0ft to 400ft altitude) and a Narrow RAC (5200ft by 1700ft, 0ft to 400ft altitude), each with a 2000ft buffer zone around its perimeter. Drones patrolled the RAC interiors on pre-defined missions, with varying scenarios depending on the encounter points with helicopters. Helicopters had one of four paths intersecting the RAC, exploring different angles and paths.

Two maneuvers were compared: the standard ROW right-hand turn maneuver and the safe-zone maneuver. In the ROW maneuver, drones took a 90° right turn, traveling to the RAC edge and then orbiting until the simulation ended. The safe-zone maneuver involved navigating to the nearest safe zone and orbiting there, aiming to avoid crossing the helicopter's path unless no safe zones were available on the current half of the RAC.

The results showed that in the Rectangular RAC, the ROW maneuver had a much higher risk than the non-ROW horizontal maneuver. For instance, in head-on scenarios, the ROW maneuver resulted in a 67% violation rate and a 35% risk, compared to the horizontal maneuver's 18% violation rate and 5% risk. Similar trends were observed in overtaking and converging scenarios. In the Narrow RAC, the ROW maneuver also showed higher risk and violation rates compared to the horizontal maneuver. Despite slight variations in risk levels between the two RAC types, the horizontal maneuver consistently maintained a significant safety advantage over the ROW maneuver.

1.3.7 Estimated Saturation point for sUAS with non-cooperative crewed aircraft

In a RAC, an area of space is designated for a given period of time for a specific operations. Interactions between a fixed-wing or helicopter, Crewed Aircraft (CA) and UAS were investigated. Right of way is always assumed to belong to the crewed aircraft, requiring the UAS to make the necessary maneuvers to ensure well-clear distance is not violated. To examine how these actions can affect other aircraft in the RAC, we have devised 2 use-case scenarios: 1) A powerline inspection and 2) A package delivery operation

1.3.7.1.1 Use Cases

To simulate a "worst-case" situation, researchers kept all aircraft at an AGL of 20 ft. For each of the below scenarios, the agricultural aircraft (crop duster) traversed a 8000 x 8000 ft field 70 ft swaths at a time. The end of each pass results in a 180-degree turn, for which its speed decreased to 90 MPH (78.21kn) and executed a wide deviation so as to return to the correct trajectory for the next pass. The UASs operated at a steady 40 MPH (34.76kts).

1.3.7.1.2 Scenario #1: Powerline Inspection

The UAS begins from one side of the field and traverses a straight line to the opposite side, to simulate an operation resembling a power line inspection/repair.

1.3.7.1.3 Use Case #2: Package Delivery

Another likely task requiring a drone to cross into a RAC is a package delivery operation. In this scenario, one or many UASs will cross from one side to the other. Scenario #2 differs from Scenario #1 in that the UAS will not need to return to the decision point and will proceed to the exit in the most direct way possible. The modified Depth-First Search (DFS) algorithm is employed to find a path to the UAS's exit point that does not cause a WC violation.

Multiple UASs can be introduced to this environment with the goal of determining the saturation point, where no more UASs can be safely added. Figure 52 illustrates the UAS flightpaths before and after correction.

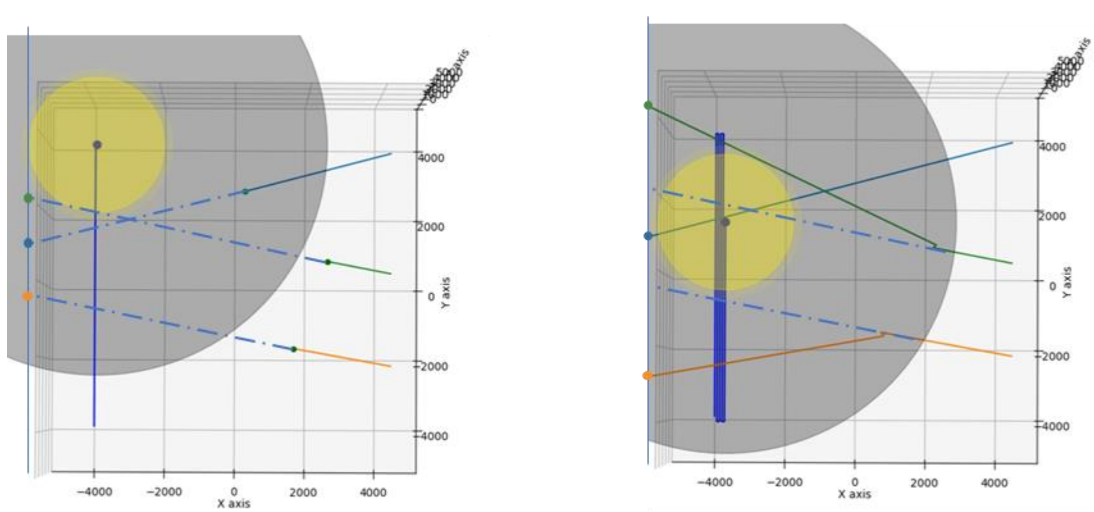


Figure 52. Use Case #2 before course correction (L) and after course correction (R).

The UAS will first attempt to fly directly from its Start Point to its Exit Point. Once inside the defined detection range, the UAS will check for a WC violation. If a WC violation is predicted, the UAS will employ evasive maneuvers. Otherwise, it will continue to its exit point unimpeded.

Once a WC violation is predicted, the algorithm responsible for finding a safe path will engage. The algorithm will simply cause the UAS to wait (hover/holding pattern) in place until an unobstructed path to the exit is available. This decision was made to minimize the amount of airspace taken up by each drone during its maneuvers, thusly reducing the chance for UAS-UAS sMACs and sNMACs. Because the most direct point between a UAS's start and end points is a straight line, the first attempt will be a simple line connecting these two points. Once a WC violation is predicted, the UAS will hover in place until a safe route to a place in that UAS's exit node is available.

A repository of test results was constructed with start times ranging from 0 to 1281 seconds. There are 90 UASs represented in this data, each being released at a randomly selected time from 10-20 seconds apart. Using this test data bank, researchers could instantly choose windows to analyze, without having to re-run the simulation each time. This also ensures even sampling across the time of CA operation. For example, the crop-duster is operating from left to right, and the UASs are traveling from right to left. UASs being released when the CA is closer to the release point may yield differing results than only taking samples while the UAS is close to the starting edge.

Results: The results of the experiment suggest a saturation point of 5 UAS aircraft in Use Case #1 and 9 UAS aircraft in Use Case #2. For these respective scenarios, these are the points in which a UAS vs UAS NMAC first occurs. It is important to remember that there is no coordination or cooperation between UASs in these trials. These numbers could vary if some UAS-UAS coordination was introduced. The full results of the trials can be found in Table and Table in Appendix B.

1.4 Remote ID (Round 3)

The following remote ID interactions investigate the performance of proposed remote ID standards and systems in ASTM F3411 [7] for UAS interactions while obeying proposed right-of-way rules. The performance of remote ID systems is evaluated using multiple types of aircraft interactions including UAS vs UAS, UAS vs Crewed, helicopters vs UAS, and multiple UAS variants of the other mentioned interactions.

1.4.1 sUAS vs sUAS (UND)

1.4.1.1 Following Right-of-Way Rules

This scenario uses the same setup, configuration (**Error! Reference source not found.**), and safety volumes as the corresponding scenarios within the general interactions section of this report but with an increased maximum detection range to accommodate the largest proposed remote ID transmitter ranges. These scenarios also test four update rates: 0.2s, 1s, 3s, and 5s. For these simulations the last received RID message is used as the intruder's state information until a new message is received and is used without any projection or filtering of the intruder's track based on its previous locations.

The primary focus of these investigations is on the performance and viability of the proposed types of transmitters used by Remote ID systems (ASTM F3411) while operating in broadcast mode to communicate directly with other aircraft or ground stations within the transmitters ranges. These types of transmitters for RIDs are Bluetooth 4.0, Bluetooth 5.0, and WiFi Aware which operates at three power levels. Table 51. Remote ID transmitters. provides their corresponding broadcast ranges which were estimated in a rural area of low noise and defined in ASTM F3411 [7]. In the simulations, each type of transmitter used the broadcast nominal range as a threshold for determining if that transmitter will work for a given geometry, scenario, and maneuver restriction type. In the presence of radio frequency interference, these broadcast ranges could be reduced.

Table 51. Remote ID transmitters.

Remote ID Transmitter	**Broadcast Nominal Range**
Bluetooth 4.0	1,312ft (0.4km)
Bluetooth 5.0	3,280ft (1km)
WiFi Aware (14dBm)	3,280ft (1km)
WiFi Aware (20dBm)	6,561ft (2km)
WiFi Aware (26dBm)	13,123ft (4km)

To determine what transmitters are required to maintain a safe distance between the aircraft while following the proposed right-of-way rules, we evaluated the required detection range for a given geometry, configuration, and scenario and then compared it to the maximum ranges of the transmitters. These tests were performed for each of the geometry sets using the same GPS uncertainties and vertical performance limits as those of the above general interactions section. To simplify the analysis of the results, the color coding shown in Figure 53 is used for this section and are different than the ones used in the general interactions section. These colors depict which transmitter technology will offer acceptable performance. With a greater required range, fewer RID transmitters will perform well at that range. When the required detection range is within 5% of the max range of the transmitter, then that cell in the matrix will contain two colors separated by a diagonal line, one color for the transmitter that meets the required range and one for the next higher range transmitter to indicate that the higher performing transmitter may be more suitable.

Range (<1,312ft)	Range: (<3,280ft)	Range: (<6,561ft)	Range: (<13,123ft)	Range: >= 13,123ft
• Wifi 26dBm • WiFi20dBm • Bluetooth 5.0 Wifi 14dBm • Bluetooth 4.0	• WiFi 26dBm • WiFi 20dBm • Bluetooth 5.0 WiFi 14dBm	• WiFi 26dBm • WiFi 20dBm	• WiFi 26dBm	• None

Figure 53. Remote ID transmitter range reference.

By the same reasoning as the general interactions section, the results presented in this section only cover the pessimistic pilot response time (5s). The full set of results for the 1s and 5s pilot response times can be found in the appendix.

1.4.1.1.1 Head-on

In Task 2 when approaching on head-on trajectories, UAS are of equal priority and in the case that they are following right-of-way rules, both aircraft will deviate to the right. The following simulations had both aircraft deviate to the right using the maneuver defined in the best turn section at the moment of detection after a specified pilot response delay of 1s or 5s. The results discussed below assume a 5s pilot response delay and are given for 0.2s, 1s, 3s, and 5s update rates of the intruder's position.

When the aircraft is restricted to horizontal-only maneuvering, a minimum detection range of 1,296-1,329ft for a 0.2s update rate, 1,313-1,329ft for a 1s update rate, and 1,395-1,411ft for 3s or 5s update rate is required. These required ranges are around or a little larger than the max range of Bluetooth 4.0 so a Bluetooth 5.0 or WiFi 14dBm transmitter would be recommended for all tested configurations for this geometry, as shown in Table 52..

Table 52. Remote ID, sUAS vs sUAS following RoW rules, head-on, Horizontal-only.

Head-on	RTK	WAAS	SPS	MAX
0.2s Update Rate				
1s Update Rate	BT 5.0			
3s Update Rate				
5s Update Rate				

In the case of vertical maneuvering, there was more variance in the required ranges depending on the vertical performance and GPS uncertainty with the required ranges varying from 1,132-2,182ft for a 0.2s update rate, 1,149-2,248ft for a 1s update rate, 1,313-2,330ft for a 3s update rate, and 1,313-2,248ft for a 5s update rate. Most of the tested configurations except for the highest vertical performance, GPS accuracy, and fastest update rate configurations where within 5% or above the max range of Bluetooth 4.0 so a Bluetooth 5.0 or WiFi 14dBm transmitter is required, as shown in Table 53.

Table 53. Remote ID, sUAS vs sUAS following RoW rules, head-on, Vertical-only.

Head-on 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	BT 5.0			
500fpm	BT 4.0			
750fpm				
1000fpm				

Head-on 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Head-on 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Head-on 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

When the aircraft was allowed to perform an unrestricted maneuver, it produced results that were as good as or better than the best maneuver of the two restricted maneuvers for a given configuration. The required range for this maneuver type are 1,165-1,329ft for a 0.2s or 1s update rate and 1,329-1,411ft for a 3s or 5s update rate. This maneuver type also had some improvement compared to the restricted maneuver where a few more of the configurations where within 5% of the maximum Bluetooth 4.0 range, as shown in Table 54.

Table 54. Remote ID, sUAS vs sUAS following RoW rules, head-on, Unrestricted.

Head-on 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm				BT 5.0
500fpm	BT 4.0			
750fpm				
1000fpm				

Head-on 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Head-on 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Head-on 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

For this geometry and scenario, at least a Bluetooth 5.0 or a WiFi 14dBm transmitter with at least the maximum range shown in Table 51. is required to properly follow the proposed right-of-way rules for all of the geometries tested. If the UAS is using a high precision GPS, has high vertical performance, and a fast update rate, it would likely function with a Bluetooth 4.0 transmitter, but a Bluetooth 5.0 transmitter would be more beneficial due to its increased range.

1.4.1.1.2 Converging from Right

When two UAS of equal priority of category converge and the opposing aircraft is approaching from the right, according to Task 2, the ownship aircraft will cede the right-of-way and deviate to the right to pass behind the intruder aircraft.

For horizontal-only restricted maneuvering, a minimum detection range of 1,395-1,428ft for a 0.2s update rate and 1,428-1,444ft for a 1s, 3s, or 5s update rate is required. This distance is a little more than the head-on geometry but still above a Bluetooth 4.0 transmitters range so a Bluetooth 5.0 or WiFi 14dBm transmitter is needed to maintain a safe distance, as shown in Table 55.

Table 55. Remote ID, sUAS vs sUAS following RoW rules, Converging from Right, Horizontal-only.

Converging from right	RTK	WAAS	SPS	MAX
0.2s Update Rate	BT 5.0			
1s Update Rate				
3s Update Rate				
5s Update Rate				

Again, in the case of vertical maneuvering, there was more variance in the required ranges but with a larger spread compared to the head-on results with the required ranges varying from 1,198-3,199ft for a 0.2s update rate, 1,247-3,216ft for a 1s update rate, 1,329-3,298ft for a 3s update rate, and 1,329-3,544ft for a 5s update rate. Because of this larger spread, less of the higher vertical performance and GPS accuracy configurations were able to maintain a safe distance using a Bluetooth 4.0 transmitter while the lowest performance configuration required a WiFi 20dBm transmitter. For the cases where a Bluetooth 4.0 transmitter is acceptable, the required range was approaching 5% of the maximum range so using a conservative estimate, a Bluetooth 5.0 or WiFi 14dBm transmitter would be best, as shown in Table 56. This is depicted in the figure using both blue and green fields.

Table 56. Remote ID, sUAS vs sUAS following RoW rules, Converging from Right, Vertical-only.

Converging from right 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	BT 5.0			
500fpm				
750fpm				
1000fpm	BT 4.0			

Converging from right 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				WiFi 20dBm
500fpm				
750fpm				
1000fpm				

Converging from right 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging from right 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

As with the head-on geometry, the converging geometry produced results that represented the best distance of the restricted maneuvers for a given configuration with the required detection ranges being 1,198-1,477ft for a 0.2s update rate, 1,247-1,542ft for a 1s update rate, 1,329-1,723ft for a 3s update rate, and 1,329-1,887ft for a 5s update rate. It also had some improvement in the required transmitter for higher vertical performance and GPS accuracy configurations, as shown in Table 57.

Table 57. Remote ID, sUAS vs sUAS following RoW rules, Converging from Right, Unrestricted.

Converging from right 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	BT 5.0			
500fpm				
750fpm				
1000fpm	BT 4.0			

Converging from right 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging from right 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging from right 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Using a conservative estimate, the converging from right geometry has the same recommended transmitter as the head-on geometry of a Bluetooth 5.0 or WiFi 14dBm transmitter to maintain a safe distance while following the proposed right-of-way rules. If the UAS is using a high precision GPS and has high vertical performance, it could potentially be successful with a Bluetooth 4.0 transmitter, but a Bluetooth 5.0 transmitter would be valid for all configurations.

1.4.1.1.3 Overtaking

Given overtaking geometries in sUAS vs sUAS encounters in Task 2, the ownship has the right-of-way and should maintain course while the opposing aircraft passes on the right.

Due to the rapid divergence rate in this scenario once maneuvering takes place, the required ranges for horizontal-only maneuvering are significantly smaller than both the head-on and converging geometries with the 0.2s update rate requiring 525-558ft, the 1s update rate requiring 558-575ft, the 3s update rate requiring 673ft, and the 5s update rate requiring 771ft. These reduced distances mean the UAS can function with a Bluetooth 4.0 transmitter, as shown in Table 58..

Table 58. Remote ID, sUAS vs sUAS following RoW rules, Overtaking, Horizontal-only.

Overtaking	RTK	WAAS	SPS	MAX
0.2s Update Rate	BT 4.0			
1s Update Rate				
3s Update Rate				
5s Update Rate				

When restricted to vertical maneuvering the required detection ranges varied more with the highest performance configurations requiring less range but the lower performance configurations requiring more compared to the horizontal-only results. The required detection ranges varied from 443-1,165ft for a 0.2s update rate, 460-1,165ft for a 1s update rate, 542-1,264ft for a 3s update rate, and 591-1,329ft for a 5s update rate. Vertical-only maneuvers still required only a Bluetooth 4.0 transmitter except in the case of the lowest vertical and GPS accuracy configuration at a 3s or 5s update rate where it was within 5% of the maximum range of the Bluetooth 4.0 transmitter, as shown in Table 59.

Table 59. Remote ID, sUAS vs sUAS following RoW rules, Overtaking, Vertical-only.

Overtaking 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	BT 4.0			
500fpm				
750fpm				
1000fpm				

Overtaking 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Overtaking 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				BT 4/5
500fpm				
750fpm				
1000fpm				

Overtaking 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				BT 5.0
500fpm				
750fpm				
1000fpm				

Like the other geometries, the unrestricted maneuver had the best performance of the restricted maneuvers with the 0.2s update rate requiring 460-558ft, the 1s update rate requiring 493-575ft, the 3s update rate requiring 542-673ft, and the 5s update rate requiring 591-771ft. Again, a Bluetooth 4.0 transmitter would be required to maintain a safe distance, as show in Table 60..

Table 60. Remote ID, sUAS vs sUAS following RoW rules, Overtaking, Unrestricted.

Overtaking 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	BT 4.0			
500fpm				
750fpm				
1000fpm				

Overtaking 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Overtaking 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm	BT 4.0			
500fpm				
750fpm				
1000fpm				

Overtaking 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Unlike the head-on and converging geometries, the overtaking geometry can function with a Bluetooth 4.0 transmitter due to the fast divergence of the encounter when both aircraft follow the proposed right-of-way rules.

1.4.1.1.4 Discussion

In the case of sUAS vs sUAS interactions following the proposed right-of-way rules, the tested aircraft were able to effectively keep a safe separation distance between each other using the proposed transmitters and ranges defined in ASTM F3411.

Of the three tested maneuver types, unrestricted performed the best for each tested configuration, as good as or better than the best distance for the restricted maneuvers. For each of the tested geometries, the horizontally and vertically restricted maneuvering produced different required ranges but had similar recommended transmitters for the tested configurations. The vertical restricted maneuvering had a larger spread on the required transmitters compared to the horizontal-only restricted maneuvering with the lowest vertical performance potentially requiring a longer-range RID transmitter while the higher vertical performance configurations could get by with a lower range RID transmitter.

For all tested geometries, a Bluetooth 5.0 or WiFi 14dBm transmitter will provide sufficient range to allow the aircraft to maintain a safe distance in sUAS vs sUAS interactions where both aircraft follow the proposed right-of-way rules. The only exception to this recommendation is the lowest vertical performance and GPS accuracy configuration required a 20dBm transmitter when restricted to vertical-only maneuvering. In the case of a sUAS with low vertical performance of 250fpm or less, horizontal-only maneuvering would be best. However, a climb-descent performance of 250fpm is unusually low, representing a very low end of realistic bounding scenarios. Overtaking geometries could use a Bluetooth 4.0 transmitter but would not work the best for other geometries and therefore likely cannot be recommended.

1.4.2 sUAS vs Crewed (UND)

1.4.2.1 Following Right-of-Way Rules

sUAS vs Crewed scenarios represent an entirely theoretical set of stress tests that assume there is similar RID technology on both aircraft. It is noted that this is not a realistic scenario in terms of rulemaking but is included for completeness and as an additional aid to help inform potential rule development of reserved airspace and the evaluation of sUAS vs sUAS interactions with a higher performance delta than discussed earlier.

As in the sUAS vs sUAS scenarios, this simulation set uses the same setup, configuration (Table 15), and safety volumes of the corresponding scenarios within the general interactions section of the report. It also uses the same Remote ID transmitters and update rates as the sUAS vs sUAS scenario with the same color coding shown in Figure 53. As stated, this will remain theoretical and in assistance to other separation evaluations. For these tests, the last updated position information is used as is without any projection or filtering of the intruder's track based off its previous locations.

The below results only look at the 5s pilot response time and the full set of results can be found in the appendix.

1.4.2.1.1 Head-on

In the case of head-on geometries for sUAS vs Crewed interactions, both aircraft will deviate right while passing as defined by the proposed right-of-way rules. The results below assume both aircraft deviate at the moment of detection following a pilot response delay of 5s.

In the case of horizontal-only maneuvering, the required detection range is 7,875-7,924ft for a 0.2s update rate, 7,924ft for a 1s or 3s update rate, and 8,317 ft for a 5s update rate. This distance is much larger than the sUAS vs sUAS scenarios due to the larger performance delta and safety volume. The required ranges are larger and would require at least a WiFi 26dBm transmitter to meet the required ranges for all tested configurations, as shown in Table 61.

Table 61. Remote ID, sUAS vs Crewed following RoW rules, head-on, Horizontal-only.

Head-on	RTK	WAAS	SPS	MAX
0.2s Update Rate	WiFi 26dBm			
1s Update Rate				
3s Update Rate				
5s Update Rate				

For vertical-only maneuvering, the required ranges were much larger depending on the vertical performance of the sUAS. In the case of all 250fpm vertical performance configurations and the 500fpm and MAX GPS uncertainty configuration, none of the tested Remote ID transmitters ranges are larger enough to allow the aircraft to maintain a safe distance. The 250fpm configurations were unable to maintain a safe distance for all ranges tested while the 500fpm configuration was able to maintain a safe distance, but it was larger than evaluated Remote ID transmitters. If the 250fpm configuration is ignored, then the required ranges varied from 7,776-13,436ft for a 0.2s update, 7,924-13,583ft for a 1s update rate, 7,924-13,780ft for a 3s update rate, and 8,317-13,977ft for a 5s update rate. For this geometry, a low vertical performance sUAS would be unable to maintain a safe distance while performing a vertical-only maneuver while sUAS with higher vertical performance would be able to maintain a safe distance if they used at least a WiFi 26dBm transmitter, the longest range proposed transmitter, as shown in Table 62.

Table 62. Remote ID, sUAS vs Crewed following RoW rules, head-on, Vertical-only.

Head-on 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	>13,123ft			
500fpm	WiFi 26dBm			
750fpm				
1000fpm				

Head-on 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Head-on 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Head-on 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

In the same manner as the sUAS vs sUAS interactions, using an unrestricted maneuver produced results that were better than or as good as the best restricted maneuver for the tested configurations. For this maneuver type, the required ranges were 6,349-7,973ft for a 0.2s update rate, 6,497-8,121ft for a 1s update rate, 6,890-8,563ft for a 3s update rate, and 6,890-8,367ft for a 5s update rate. The required ranges and transmitters for the unrestricted maneuver was better than the restricted maneuvers and some of the highest vertical performance configurations were even able to barely get by with a WiFi 20dBm transmitter, as shown in Table 63. In these cases, the required range was still within 5% of the maximum range of a 20dBm transmitter so a 26dBm transmitter would be best. For this type of maneuvering with a conservative assumption, a 26dBm transmitter would be required and the sUAS would need reasonable vertical performance when vertical maneuvering is used.

Table 63. Remote ID, sUAS vs Crewed following RoW rules, head-on, Unrestricted.

Head-on 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	WiFi 26dBm			
500fpm				
750fpm				
1000fpm				

Head-on 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Head-on 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Head-on 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

For this geometry and scenario, a WiFi 26dBm transmitter is needed to maintain a safe distance for all tested configurations assuming the sUAS has a reasonable vertical performance. This is the longest-range transmitter proposed in ASTM F3411 and shows the Remote ID system would be potentially feasible for this geometry but the performance of the transmitter at these large ranges might suffer in performance and could potentially change these recommendations, especially in the case of lower vertical performance and high GPS uncertainty.

1.4.2.1.2 Converging from Left

In the case of converging from left geometries for sUAS vs Crewed interactions, the crewed aircraft has right-of-way so the sUAS will give way to pass behind the crewed aircraft.

Like the head-on geometry, larger detection ranges are required for the sUAS vs Crewed interactions and when restricted to horizontal-only maneuvering, a detection range of 7,235-7,284ft for a 0.2s update rate, 7,235-7,382ft for a 1s update rate, 7,382ft for a 3s update rate, and 7,628ft for a 5s update rate is required. Again, a WiFi 26dBm transmitter is required to maintain a safe distance for all tested configurations due to the same reasons as the head-on geometries, as shown in Table 64.

Table 64. Remote ID, sUAS vs Crewed following RoW rules, Converging from Left, Horizontal-only.

Converging From Left	RTK	WAAS	SPS	MAX
0.2s Update Rate	WiFi 26dBm			
1s Update Rate				
3s Update Rate				
5s Update Rate				

When restricted to vertical-only maneuvering, a similar pattern as the head-on geometries emerges where the 250fpm configurations were unable to maintain a safe distance for any of the ranges tested and the 500fpm configurations range was larger than the ranges of the proposed transmitters. Ignoring the 250fpm configurations, the required detection ranges are 7,727-13,288ft for a 0.2s update rate, 7,825-13,436ft for a 1s update rate, 7,825-13,632ft for a 3s update rate, and 8,219-13,829ft for a 5s update rate. A similar conclusion to the head-on geometry is found where a WiFi 26dBm transmitter would potentially work for this scenario but would require the sUAS to have a decent vertical performance to maintain a safe distance, as shown in Table 65.65.

Table 65. Remote ID, sUAS vs Crewed following RoW rules, Converging from Left, Vertical-only.

Converging From Left 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	>13,123ft			
500fpm	WiFi 26dBm			
750fpm				
1000fpm				

Converging From Left 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging From Left 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging From Left 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

When using an unrestricted maneuver, a similar result as that of the head-on geometry can be observed where the required ranges are as good as or better than the restricted maneuvering with some of the highest tested vertical performance configurations being able to get by with a WiFi 20dBm transmitter but again being within 5% of their max range so a WiFi 26dBm transmitter would be best. The required ranges are 6,447-7,382ft for a 0.2s update rate, 6,546-7,382ft for a 1s update rate, 6,939-7,382ft for a 3s update rate, and 7,284-7,628ft for a 5s update rate. For the same reasoning as the head-on geometry, a 26dBm transmitter would be required and the sUAS would need to have decent vertical performance, as shown in Table 66.66.

Table 66. Remote ID, sUAS vs Crewed following RoW rules, Converging from Left, Unrestricted.

Converging From Left 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	WiFi 26dBm			
500fpm				
750fpm				
1000fpm				

Converging From Left 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging From Left 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging From Left 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

As with head-on geometry, a WiFi 26dBm transmitter is needed to maintain a safe distance for all tested configurations if a reasonable vertical performance is assumed and the 250fpm results are ignored. Again, this is the longest-range transmitter proposed in ASTM F3411 and would have the same potential issues mentioned in the head-on geometry section.

1.4.2.1.3 Converging from Right

As with the converging from left geometries, the Crewed aircraft has right-of-way so the sUAS will give way and pass behind. The following results are like the converging from left results but with some variance in the required ranges due to the changes in geometry and maneuver response.

When restricted to horizontal-only maneuvering, the same general results as the head-on and converging from left geometries can be observed with the required ranges being 7,235-7,333ft for a 0.2s update rate, 7,382ft for a 1s update rate, 7,382-7,628ft for a 3s update rate, and 7,628ft for a 5s update rate. This range would again require a WiFi 26dBm transmitter to maintain a safe distance for the tested configuration, as shown in Table 67.67.

Table 67. Remote ID, sUAS vs Crewed following RoW rules, Converging from Right, Horizontal-only.

Converging From Right	RTK	WAAS	SPS	MAX
0.2s Update Rate	WiFi 26dBm			
1s Update Rate				
3s Update Rate				
5s Update Rate				

The same general transmitter recommendation and exceptions as the head-on and converging from left geometries are present where the 250fpm configurations were unable to maintain a safe distance for all tested ranges and the single 500fpm configuration required a range larger than the longest-range transmitter. Ignoring the 250fpm configurations, the required ranges were 7,678-13,288ft for a 0.2s update rate, 7,875-13,485ft for a 1s update rate, 7,875-13,682ft for a 3s update rate, and 8,268-13,878ft for a 5s update rate. A similar conclusion as the other geometries is found where a WiFi 26dBm transmitter would be needed to potentially maintain a safe distance assuming the sUAS has decent vertical performance, as shown in Table 68.68.

Table 68. Remote ID, sUAS vs Crewed following RoW rules, Converging from Right, Vertical-only.

Converging From Right 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	>13,123ft			
500fpm	WiFi 26dBm			
750fpm				
1000fpm				

Converging From Right 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging From Right 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging From Right 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

As similar result as the converging from left geometries is found for the unrestricted maneuver where the required range is as good or better than the restricted maneuvers with the highest performance configuration being able to get by with a WiFi 20dBm transmitter but again being within 5% so a WiFi 26dBm transmitter would be better. The required ranges for this maneuver type are 6,447-7,382ft for a 0.2s update rate, 6,497-7,530ft for a 1s update rate, 6,890-7,924ft for a 3s update rate, and 7,284-8,268ft for a 5s update rate. For all tested configurations, a WiFi 26dBm transmitter would be required for the sUAS to maintain a safe distance assuming it has decent vertical performance, as shown in Table 69.69.

Table 69. Remote ID, sUAS vs Crewed following RoW rules, Converging from Right, Unrestricted.

Converging From Right 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	WiFi 26dBm			
500fpm				
750fpm				
1000fpm				

Converging From Right 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging From Right 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Converging From Right 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

As with the other above geometries, a WiFi 26dBm transmitter is needed to maintain a safe distance assuming a reasonable vertical performance and in the case of the above results means ignoring the 250fpm configurations. Again, this is the longest-range transmitter would have the same potential issues described above.

1.4.2.1.4 Overtaking

In the case of overtaking, the Crewed aircraft has right-of-way and the sUAS needs to maneuver to maintain a safe distance. This is a demanding maneuver for the sUAS compared to the sUAS vs sUAS scenarios due to the much larger performance delta between the aircraft. In the following simulations, the intruder does not deviate while approaching the sUAS from behind and the sUAS deviates to the left.

For horizontal-only maneuvering, none of the tested configurations were able to maintain a safe distance within the maximum range tested. No tested range allowed the tested geometry scenarios to maintain a safe distance using the standard avoidance maneuver discussed above. This was primarily due to the stress/edge cases tested within the geometry set combined with the avoidance maneuver requiring a detection range larger than the maximum range tested. This is not true for all individual overtaking geometries; some of them were able to properly maintain a safe distance within the maximum range tested but since no single detection range allowed all of the individual geometries to maintain a safe distance, no required transmitter is found for the tested configurations, as shown in Table 70.

Table 70. Remote ID, sUAS vs Crewed following RoW rules, Overtaking, Horizontal-only.

Overtaking	RTK	WAAS	SPS	MAX
0.2s Update Rate	>13,123ft			
1s Update Rate				
3s Update Rate				
5s Update Rate				

When restricted to vertical-only maneuvering, the vertical performance has a large effect on the ability of the sUAS to maintain a safe distance and the required Remote ID transmitter for a given configuration. For the tested configurations, the required detection range was 5,611-15,355ft for a 0.2s update rate, 5,709-15,453ft for a 1s update rate, 5,758-15,453ft for a 3s update rate, and 6,447-15,650ft for a 5s update rate. The required transmitter varied depending on the vertical performance and using a conservative assumption the following transmitters were required for each of the tested vertical performances. No transmitter worked for 250fpm, 500fpm and 750fpm required a WiFi 26dBm transmitter, and 1000fpm required a WiFi 20dBm transmitter, as shown in Table 71. The only exception to this is the 1000fpm configuration was within 5% of the maximum range for the 5s update rate configurations and some of the 3s update rate configurations and could benefit from moving up to a WiFi 26dBm transmitter.

Table 71. Remote ID, sUAS vs Crewed following RoW rules, Overtaking, Vertical-only.

Overtaking 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	>13,123ft			
500fpm	WiFi 26dBm			
750fpm				
1000fpm	WiFi 20dBm			

Overtaking 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Overtaking 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Overtaking 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

In the case of unrestricted maneuvering, the results again were as good as or better than the restricted maneuvering and resulted in similar required ranges and recommendation as the vertical-only results. The required detection ranges were similar to the vertical-only results with the required ranges of 5,562-15,158ft for a 0.2s update rate, 5,611-15,256ft for a 1s update rate, 5,906-15,601ft for a 3s update rate, and 6,300-15,995ft for a 5s update rate. The recommended transmitter results shown in Table 72. is almost the same as the results for the vertical-only maneuver type shown above.

Table 72. Remote ID, sUAS vs Crewed following RoW rules, Overtaking, Unrestricted.

Overtaking 0.2s Update Rate	RTK	WAAS	SPS	MAX
250fpm	>13,123ft			
500fpm	WiFi 26dBm			
750fpm				
1000fpm	WiFi 20dBm			

Overtaking 1s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Overtaking 3s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

Overtaking 5s Update Rate	RTK	WAAS	SPS	MAX
250fpm				
500fpm				
750fpm				
1000fpm				

The results for this geometry varied more than the other tested geometries but using a conservative assumption a WiFi 26dBm could potentially allow the sUAS to maintain a safe distance from the crewed aircraft with a few assumptions and exceptions.

The primary assumption is that the sUAS has decent vertical performance since the tested 250fpm configurations were unable to maintain a safe distance using the proposed transmitters. The main exception is that the horizontal-only maneuver was unable to maintain a safe distance due to some of the stress/edge cases being unable to maintain a safe distance for all detection ranges tested but a decent amount of the individual geometries tested were able to maintain a safe distance that would work with the proposed transmitter ranges.

1.4.2.1.5 Discussion

As mentioned before, sUAS vs Crewed interactions are provided for completeness and should not be read as remote ID recommendations. The primary distinction in these simulations is the higher performance envelopes of the crewed aircraft. Yet it remains possible that there might be higher performance sUAS aircraft interacting with lower performance aircraft. The results, then, expose potential weaknesses of lower performing Remote ID categories.

Following the proposed right-of-way rules, the tested aircraft were able to maintain a safe distance between each other for most of the tested configurations and maneuver restriction types but required the longest-range transmitter defined in ASTM F3411, WiFi 26dBm. Depending on the actual range, update rate, and performance of the transmitters at these ranges the sUAS may not be able to properly maintain a safe distance.

Out of the three maneuver types, unrestricted performed the best for all tested geometries and configurations with results that were usually as good as or better than the restricted maneuvering. The horizontal-only results provided consistent result for the head-on and converging geometries, but the overtaking results were unable to reach a detection range that works for all individual geometries, especially edge/stress ones. The vertical performance had a significant effect on the vertical-only results with the lowest vertical performance configurations being unable to maintain a safe distance. As the vertical performance increased the required ranges and transmitters improved and at the highest tested vertical performance, the sUAS required a detection range similar to or better than the horizontal-only results depending on the GPS uncertainty.

Remote ID is not intended to be used for sUAS vs Crewed interactions, but the results show that it is feasible for Remote ID to provide enough range to allow a sUAS to maintain a safe distance from the crewed aircraft depending on the vertical performance and type of avoidance maneuver the sUAS would use to avoid the crewed aircraft. It is not realistically feasible to require Crewed aircraft to equip Remote ID systems to help in these situations but there could be some benefit for Crewed aircraft that will be interacting with sUAS frequently or primarily flying in areas with sUAS traffic. A better option for the sUAS vs Crewed interactions would be the equipage of a detect and avoid system or another type of cooperative system used by Crewed aircraft, such as ADS-B.

1.4.3 Remote ID Conclusions and Recommendations

In the case of sUAS vs sUAS interactions the proposed Remote ID transmitters in ASTM F3411 appear to provide enough range to allow the sUAS to properly follow the proposed right-of-way rules and maintain a safe distance. Using a conservative assumption a Bluetooth 5.0 or WiFi 14dBm Remote ID transmitter would allow the aircraft to maintain a safe distance assuming the sUAS has reasonable vertical performance, greater than 250fpm, and GPS accuracy.

In the case of sUAS vs Crewed, Remote ID is not intended to be used for deconfliction in this case but the results show that a) it would be feasible to allow for deconfliction of UAS vs Crewed where one aircraft has a much higher performance delta. In these cases, using the longest-range transmitter defined in ASTM F3411 may be necessary. Otherwise, segregating either high performance UAS or crewed aircraft will be necessary. In that case, these data may help inform the reserved airspace question.

2 FLIGHT TEST PLANS

2.1 Flight Test Objectives

2.1.1 Primary Objective(s)

The primary objective of these flight tests is to capture data for safety analysis and to capture encounter parameters (geometries, altitudes, distances, separation, etc.). This data will be analyzed to address FAA knowledge gaps and are intended to support final recommendations on RoW rules.

Each flight card generated will link to one or more of the following test objectives:

- Based on Simulations conducted – what existing questions must be validated through flight tests, or new questions need to be answered through flight testing to further advance understanding of General Interactions, Reserved Airspace, and RID as it directly informs the FAA in regard to RoW rules?
- Answer additional questions that could not be demonstrated during simulations but can be answered during flight tests.

2.1.2 Round 1 (Head-on, Converging, and Overtaking) Objectives

- Identify pilot reaction times from reaching pre-determined avoidance distance and initiate the avoidance maneuver specified in the flight test card.
- Determine the best avoidance maneuver for given interactions (head-on, converging, and overtaking encounters).
    - o Identify factors including the type of maneuver (vertical or horizontal) that may delay or inhibit reaction time and distance needed to avoid a RoWV.
- Observe execution of avoidance maneuvers to prevent RoWV by identifying unintended consequences.
    - o Validate/identify detection distances that affect deconfliction.
    - o Determine if larger UAS detection distances are required due to lower maneuverability.
    - o Determine if rule changes are needed in these encounters for an intruder not altering course.

NOTE: It is understood that in establishing RoW rules, the researchers must assume detection methods are available (likely DAA systems). Therefore, while neither testing of visual conspicuity of sUAS while in a crewed aircraft nor testing of DAA equipment effectiveness is the focus of this research, it does provide an opportunity for ancillary knowledge related to RoW.

2.1.2.1 Sub-objectives to Flight Testing

1. During RoW testing, identify detection distance for observer in crewed aircraft to see various UAS. Use telemetry and recorded data to determine actual distances. Note, many variables affect conspicuity such as various environmental conditions, aircraft configurations, and time of day. Weather data will also be collected to identify any commonalities between various flight-testing scenarios.
2. Identify if the UAS DAA equipment graphic interface can be used to help prevent a RoWV by identifying aircraft and determining distance remaining between UAS and crewed aircraft.
3. Related to RoW, identify latency on autonomous UAS using DAA (KU).

2.1.3 Round 2 (Reserved Airspace Concepts) Objectives

- While conducting a variety of Round 1 encounters, identify the usefulness of RAC on sUAS(s) and Crewed aircraft operating in the RAC to inform RoW rules.
- Identify ability for the UAS pilot to initiate an avoidance maneuver with a crewed aircraft with ADS-B out while remaining within the RAC.
- Determine the best avoidance maneuver for given interactions in the RAC with UAS and/or crewed intruders to inform RoW rules.
- Identify impact of RAC boundaries that may delay or inhibit reaction time and distance needed to avoid a RoWV.

2.1.4 Round 3 (RID) Objectives

- While conducting a variety of encounters, (head-on and converging geometries) identify the usefulness of RID devices on sUAS(s) to inform ROW rules.
    - o Collect RID data and analyze its usefulness for sUAS to identify position (i.e. head-on & converging) in relation to another sUAS.
    - o Analyze if the RID data provides the sUAS operator(s) the necessary information to determine what path to comply with when following proposed RoW rules.

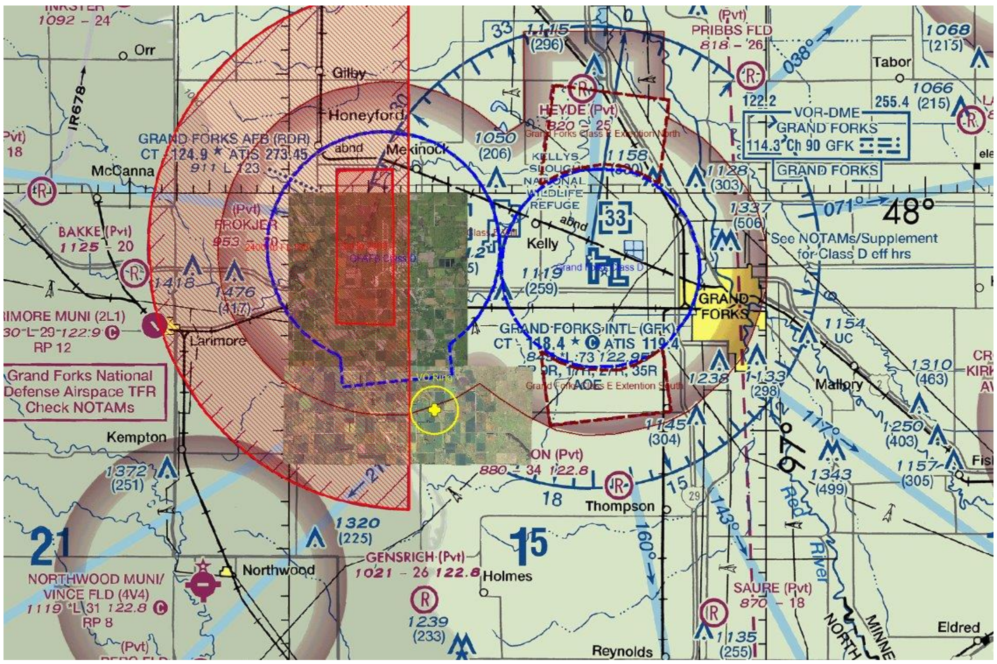
- Evaluate the data received, including update rate, from RID equipment installed on sUAS and determine its impact on sUAS operator actions to identify a possible sUAS encounter or decide what RoW rule will be performed.
    - Evaluate the change of the update rate as you get closer to the sUAS intruder to determine its usefulness on RoW decision making for UAS interactions between two unmanned aircraft.

2.2 UND

2.2.1 Location

The location used for UAS operations was the Gorman Field UAS Test Range. This facility provides facilities capable of BVLOS. It is equipped with DeTect HARRIER radar, Air Domain Awareness and Counter UAS S-Band and X-Band Precision Radar, a 300’ aerodrome runway, launch pad for catapult or VTOL aircraft, and an observation deck for visual observers.

Crewed aircraft were housed at and originated from GFK. Crewed aircraft vs UAS activities were held in Gorman Field airspace.



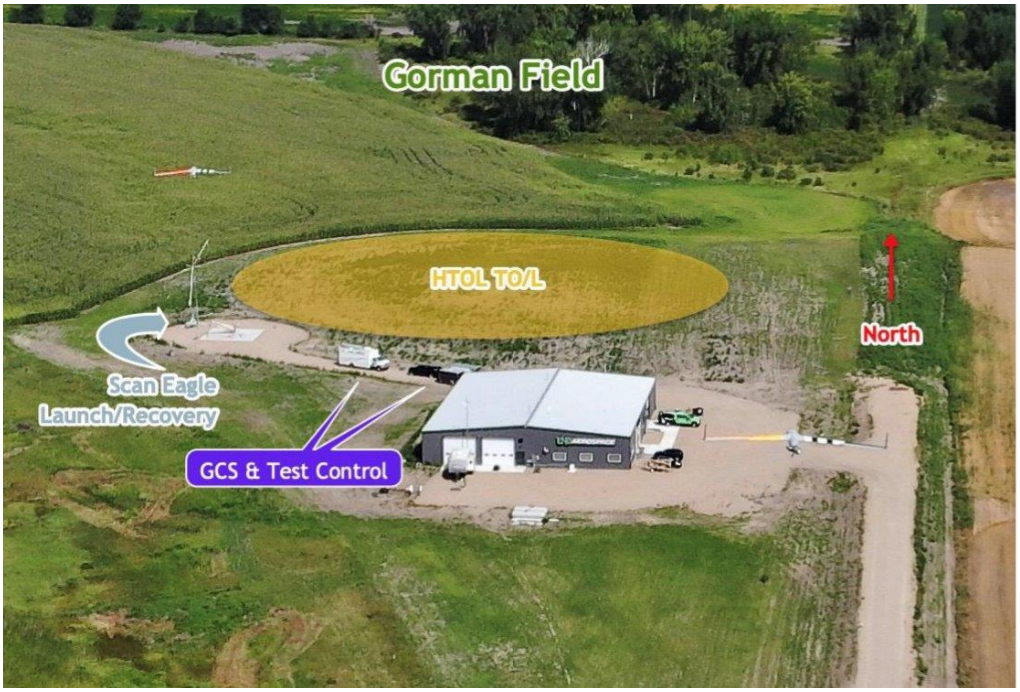


Figure 54. Gorman Field; 47.847794° -97.347316°.

Approximately 5 NM Southeast of Grand Forks AFB. University of North Dakota Property

Figure 55. Crewed launch & recovery airfield layout; Grand Forks International Airport (KGFK).

2.2.2 Date/Schedule

Round 1 (March 24 – March 28, 2024). Details are given in Table 73.

Table 73. Round-1 schedule.

DTG	Event	Notes
Sunday	Local UND Team Deployment	Gorman Field
March 24	Site Prep	Set up from practice run
Monday	General Operations Brief	Cover entire Round 1 test plan
March 25	UND Team/ Rehearsal Day	Walk Thru and then validate flight run telemetry, then do each run airborne
Tuesday	Day 1; Flight test runs	Fly as many test runs as needed
March 26	Day 1; Debrief	All involved offer comment; Plan revisions as needed
Wednesday	Day 2; Flight test runs	Fly as many test runs as needed
March 27	Day 2; Debrief	All involved offer comment; Plan revisions as needed
Thursday	Day 3; Flight test runs	Fly as many test runs as needed
March 28	Day 3; Debrief	All involved offer comment; Plan revisions as needed

Round 2 (July 1 – July 3, 2024). Table 74 gives the Round-2 shedule

Table 74. Round-2 schedule.

DTG	vent	Notes
Monday	Local UND Team Deployment	Gorman Field
July 1	Site Prep (GPS units available?)	Set up from practice run
Monday	General Operations Brief	Cover entire Round 2 test plan
July 1	UND Team/ Rehearsal Day	Walk Thru and then validate flight run telemetry, then do each run airborne
Tuesday	Day 1; Flight test runs	Fly as many test runs as needed
July 2	Day 1; Debrief	All involved offer comment; Plan revisions as needed
Wednesday	Day 2; Flight test runs	Fly as many test runs as needed
July 3	Day 2; Debrief	All involved offer comment; Plan revisions as needed

Round 3 (May 19 – May 22, 2024). Round 3 schedule is shown in Table 75.

Table 75. Round-3 schedule.

DTG	Event	Notes
Sunday	Local UND Team Deployment	Gorman Field
May 19	Site Prep	Set up from practice run
Monday	General Operations Brief	Cover entire Round 1 test plan
May 20	UND Team/ Rehearsal Day	Walk Thru and then validate flight run telemetry, then do each run airborne
Tuesday	Day 1; Flight test runs	Fly as many test runs as needed
May 21	Day 1; Debrief	All involved offer comment; Plan revisions as needed
Wednesday	Day 2; Flight test runs	Fly as many test runs as needed
May 22	Day 2; Debrief	All involved offer comment; Plan revisions as needed

2.2.3 Test plan overview

In this test campaign, the focus was on the impacts of Right of Way when UAS encounters with other UASs or crewed aircraft. The round 1 test performed had CA flying at 120 knots executed against UAS flying at 50 knots. The day 2 experiments involved a UAS flying at 50 knots and were executed against another UAS flying at 40 knots. In Round 2, two UASs were used to test the execution of the RoW rules in an RAC scenario. UASs were flying at different speeds, varying from 50 knots to 70 knots to test. In round 3, two UASs were used to detect the probability of detection using RID. Both of the UASs fly at the same speed, 50 knots, with a RID module and a receiver in it.

2.2.4 Sample test cards

2.2.4.1 Round-1 : sUAS-sUAS

Test Card 1 - Round 1 - Run 1-1a; Head-on Aspect

Thor Cruise Speed (50kts +/- 10) vs. Loki (35 kts).
Both aircraft banks right upon reaching 1,800 ft separation. Test Horizontal avoidance maneuver.

Test Run 1-1a	Head-On-Aspect, Cruise Speeds	
Date	Start Time	Actual Start Time
Scheduled Time	10:00 am	
Objective	Head-on-Aspect. UAS vs. UAS. Both UAS **bank right** at 1,800 distance.	
Description	Refer to Flt Graphic. Both aircraft will turn right	
UAS #1 Thor	ScanEagle (Callsign - Thor)	
Parameters	300 AGL (1211 MSL)	50 kts
UAS #2 Loki	AA Albatross (Callsign Loki)	
Parameters	225 AGL (1136 MSL)	35 kts
Waypoint Locations	Thor Start Orbit: 47.848152°, -97.353297° Loki Start Orbit: 47.853333°, -97.340633°	
Flight Crew Flight Director J. Moe RPIC - UAS #1 Thor D. Myles RPIC - UAS #2 Loki K. Ketola Analyst-VO#1. - UAS Assoc. Analyst-VO#2 - UAS Assoc. RoW Obsvr - UAS Assoc.	Head-on All GPS – 1,493ft Observer notes:	

Notes:
Observer and/or PIC
- Complete tracking log provided
- Announce any aircraft in area, assist in avoiding aircraft

RoW Observer
- Primary responsibility to ensure aircraft turn at or before distance specified on test card
- Inform Flight Director when to initiate collision avoidance maneuver.

Flight Events

1. Both sUA launch and establish orbits (Green) prior to Run 1-1a
2. Flight Director radios "Start Flight Test # 1-1a"
3. Both UAs exit orbit simultaneously turning Thor radios "departing orbit , 300AGL" and Loki radios "departing orbit 225 AGL'
4. Thor PIC calls "established on track northbound," continues northbound down wind
5. Loki PIC calls "established on track, southbound," continues southbound down wind
6. Thor PIC calls "turning final approach , southbound,"
7. Loki PIC calls " turning final approach , northbound,"
8. At 1,800ft apart –Flight Director, states "Thor and Loki– "Turn right 90 degrees for horizontal avoidance maneuver"
9. Upon completely 90 degree turn, Thor and Loki – return to Launch Orbit (green).
10. Thor and Loki when reaching start orbit, announce, "Established in Start Orbit"
11. Flight Director radios for repeat flight, modifications, or calls to move to next test

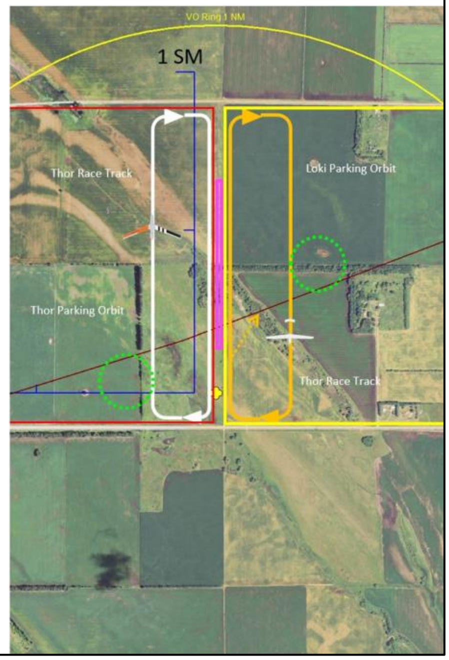


Figure 56. Sample test card of Round-1, sUAS-sUAS showing Head-On aspect.

2.2.4.2 Round-1 : CA-sUAS

Test Card 10 - Round 2 - Run 2-2a; Converging Aspect

Thor Cruise Speed (50kts +/- 10) vs. Zeus (120 kts).
Thor banks right upon identification of Thor at 8,000 ft . Test horizontal avoidance maneuver.

Test Run 2-2a	Converging-Aspect, UAS vs. UAS, Cruise Speeds	
Date	Start Time	Actual Start Time
Scheduled Time	10:00	
Objective	Converging Aspect. Loki **banks right** at 8,000 ft distance upon Thor ID.	
Description	Refer to Flt Graphic. Thor has right of way.	
UAS #1 Thor	ScanEagle (Callsign - Thor)	
Parameters	400 AGL (1311 MSL)	
FWCA Zeus	Cessna 150 (Callsign Zeus)	
Parameters	1000 AGL (1911 MSL)	
Waypoint Locations	Thor Start Orbit: 47°51'34"N 97°21'04"W Zeus Start Orbit: 47°50'56"N 97°18'41"W	
Flight Crew Flight Director J. Moe RPIC - UAS #1 Thor D. Myles RPIC - UAS #2 Loki K. Ketola Analyst-VO#1. - UAS Assoc. Analyst-VO#2 - UAS Assoc. RoW Obsvr - UAS Assoc. C150 – CFI#1 C150 – CFI#2 Obsvr	Converging All GPS , detection range simulated -7,727ft Observer notes:	

Notes:
Observer and/or PIC
- Complete tracking log provided
- Announce any aircraft in area, assist in avoiding aircraft

RoW Observer
- Primary responsibility to ensure aircraft turn at or before distance specified on test card
- Inform Flight Director when to initiate collision avoidance maneuver.

Flight Events

1. Both sUA launch and establish orbits (Green circle) prior to Run 1-2a
2. Flight Director radios "Start Flight Test # 2-2a"
3. Both Aircraft exit orbit simultaneously turning Zeus radios "departing orbit , 1000AGL" and Thor radios "departing orbit 400 AGL'
4. Zeus PIC calls 'established on track westbound' and enters west bound downwind
5. Thor PIC calls "turning final approach , southbound,"
6. At 8,000 ft apart –Flight Director, states "Thor – "Turn right 90 degrees for horizontal avoidance maneuver"
7. Conflict resolved, Thor and Loki – return to Launch Orbit (green).
8. Thor and Loki when reaching start orbit, announce, "Established in Start Orbit"
9. Flight Director radios for repeat flight, modifications, or calls to move to next test

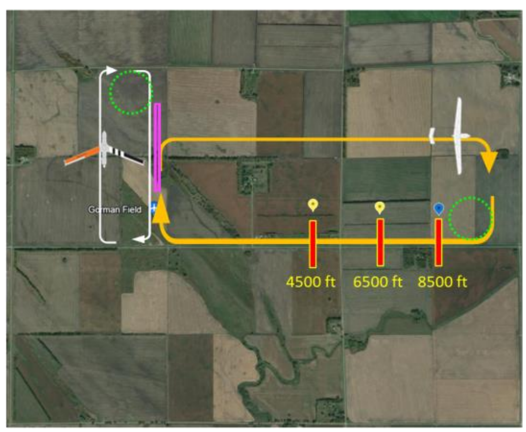


Figure 57. Sample test card of Round-1, CA -sUAS showing converging aspect.

2.2.4.3 Round-2: sUAS-sUAS in RAC

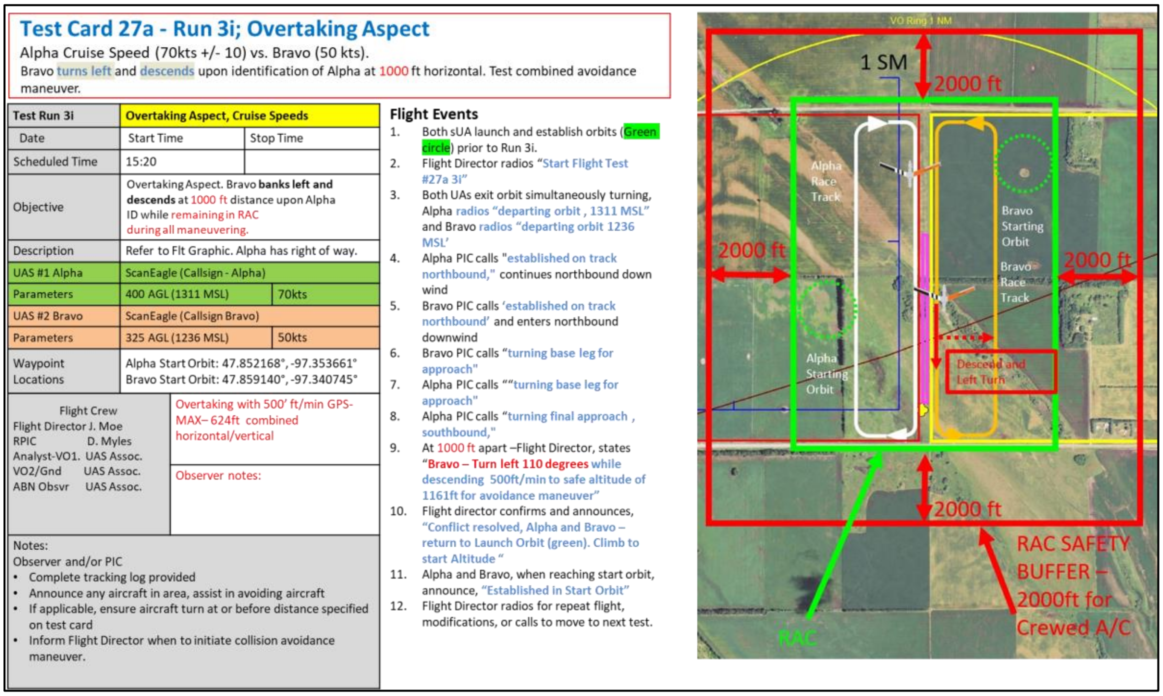


Figure 58. Sample test card of Round-2 (RAC) sUAS-sUAS showing Overtaking aspect. The RAC and RAC buffuer boundaries are displayed in the figure.

2.2.4.4 Round-3 : sUAS-sUAS (RID)

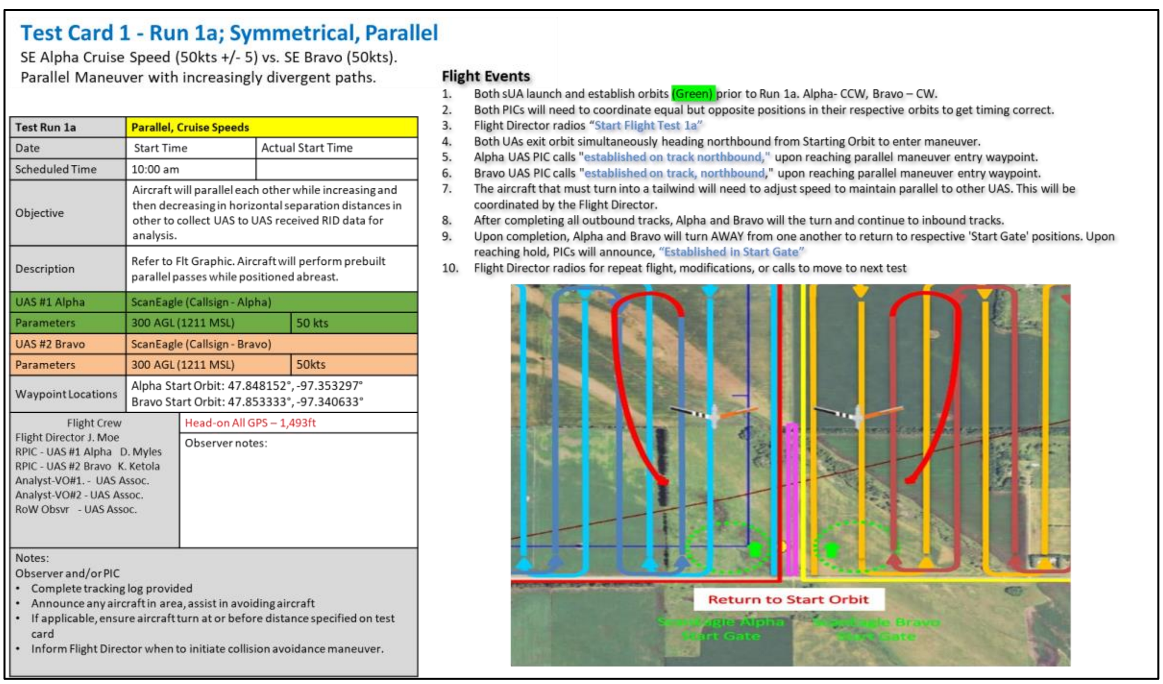


Figure 59. Sample test card of Round-3, sUAS-sUAS showing Symmetric and Parallel aspect.

2.2.5 *Data Analysis*

The data preprocessing stage focused on standardizing units and representations across various datasets. To achieve consistency, GPS and timecard timings were synchronized to UAS Traffic Control reference time. Speed measurements were unified and presented in knots. Furthermore, all distance-related parameters, including surface distance, three-dimensional distance, and altitudes, were converted and expressed in feet.

2.2.5.1 Encounter events

The following parameters were used in the encounter event analysis for the risk volumes:

- Well Clear Violation: A static cylindrical volume with a 2,000-foot horizontal radius and a 250-foot vertical height from the center.
- Horizontal-well clear violation: A surface distance of 2000 ft from the center.
- Vertical well-clear violation: An altitude separation of 250 ft from the center
- Packet detection rate (Round 3) : A minimum horizontal separation of 300 ft, where sUASs are in parallel, then increase in horizontal separation.
- Probability of detection (Round 3): Calculate the probability of a receiver receiving packets send from a RID transmitter. The value depends on the number of packets received with the number of packets transmitted.
- sNMAC Volume: A static cylindrical volume with a 100-foot horizontal radius and a 25-foot vertical height from the center.

A violation of the Well Clear or sNMAC volume occurs when an intruder aircraft enters their respective risk volume.

2.2.5.2 Encounter description

All tests in Round 1 of the simulation were conducted using an Insitu ScanEagle X200 UAS (Thor) and an Applied Aeronautics Albatross Fixed Wing UAS (Loki). Following the initial simulation phase, actual test flights are recommended to assess real-world interactions. The tests encompassed three encounter types: Head-on, Converging, and Overtaking.

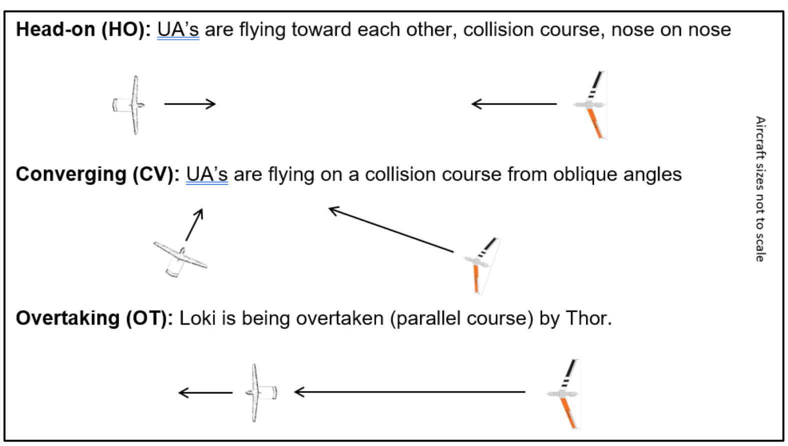


Figure 60. Round 1 Encounter - General Interaction.

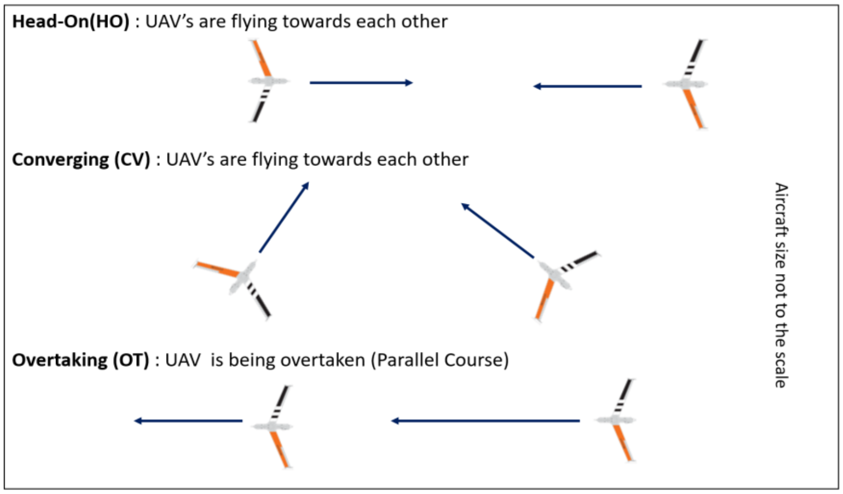


Figure 61. Round 2 Encounter- Reserved Airspace Concept.

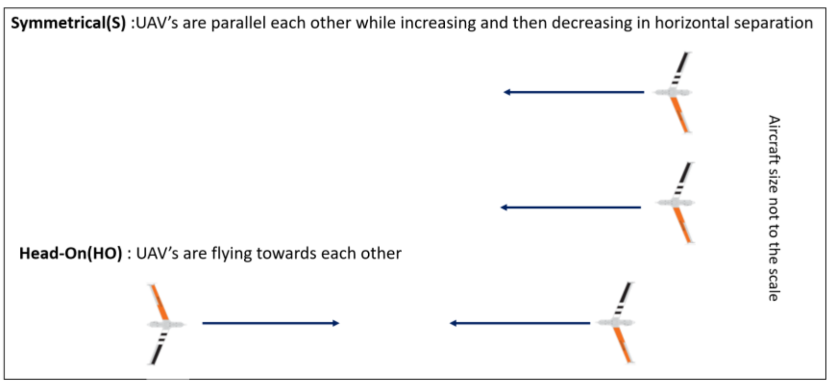


Figure 62. Round 3 Encounter- Remote ID.

Each encounter type involved the UA avoiding the other upon contact confirmation or at specified distances, with three runs using horizontal avoidance (banking right) and three runs using descent avoidance. The UA maintained well-clear distances of 300 feet horizontally and 75 feet vertically. Round 3 encounter type includes symmetrical, which is where UASs fly parallel to each other while increasing the horizontal separation. The minimum horizontal separation in this case is 300ft.The distances for initiating turn maneuvers were determined by simulation data, factoring in GPS accuracy, pilot reaction time, and the need to maintain well-clear distances. The Encounter geometry is shown in figures Figure 60, Figure 61, and Figure 62.

2.2.5.3 Virtual trajectory extension

During flight tests, the aircraft returned to base after executing an avoidance maneuver to prepare for the next test run. However, for data analysis and to calculate representative distances between aircraft, each aircraft's trajectory was virtually extended at its pre-maneuver speed and heading. In other words, a timestamp was identified where the aircraft deviated from its original trajectory after the avoidance maneuver. From that point, a virtual trajectory was generated as if the aircraft had continued on its original course. An example of this analysis is presented in the Figure 63.

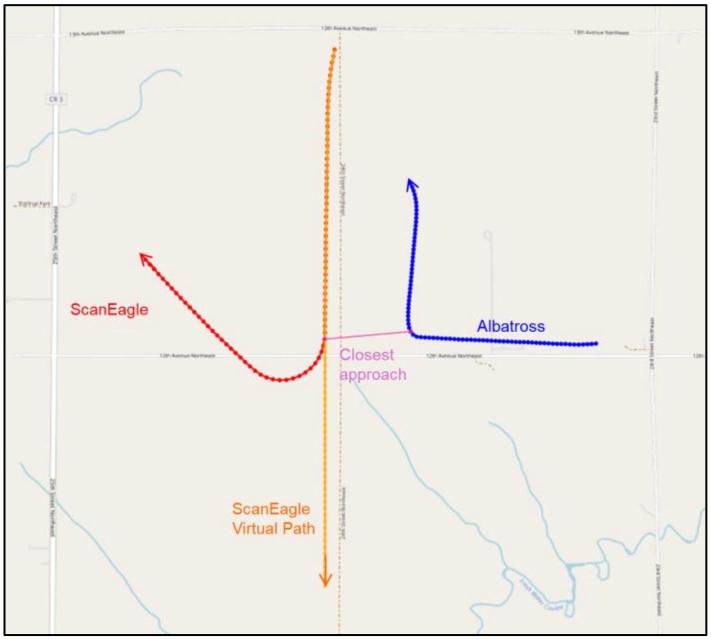


Figure 63. Virtual trajectory extension.

In Figure 63. Virtual trajectory extension. , convergent scenario trajectories for Albatross (blue) and ScanEagle (red) sUASs. Ideally, ScanEagle would maintain a westward course (solid red line). To assess representative inter-UAS distances, ScanEagle's trajectory was virtually extended based on its pre-maneuver speed and heading (dashed orange line).

2.2.5.4 Rate of turn calculations

Selection of Points: Identify two points on the UAS's trajectory, specifically marking the start and completion of the turn. Let these points be denoted as Point 1 and Point 2, respectively (Figure 64).

Angle Measurement: Measure the heading angles of the UAS at each of these points. Let θ1 be the heading angle at Point 1 (start of the turn), and θ2 be the heading angle at Point 2 (completion of the turn) (Figure 64).

Time Measurement: Record the times at which the UAS is at these points. Let T1 be the time at Point 1 and T2 be the time at Point 2.

Rate of Turn Calculation: Use the measured angles and times to calculate the rate of turn (T) using the following equation:

$$RT = \frac{\theta_2 - \theta_1}{T2 - T1} \quad (9)$$

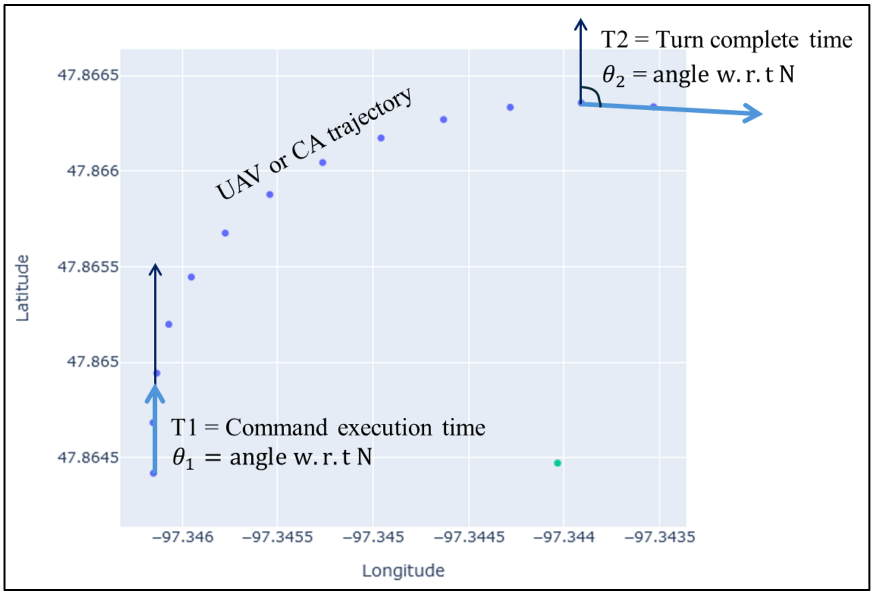


Figure 64. Rate of turn calculations.

2.2.5.5 Distance Calculation

The surface distance between the control point and the UAS is determined using the geodesic function from the *geopy* library. This function calculates distances based on the WGS-84 ellipsoid, a standard reference for Earth's shape and size. The geodesic distance calculation incorporates Earth's curvature, ensuring accurate measurements over small and large distances. The vertical separation is obtained by computing the absolute difference in altitude between the two points. To find the total three-dimensional distance, the function applies the Pythagorean theorem by combining the squared surface distance with the squared altitude difference and then taking the square root of the sum.

2.2.5.6 Vertical speed calculation

To calculate the vertical speed for a UAS trajectory, specific steps are followed. First, two points on the UAS's trajectory are identified. At each point, the altitudes (H1 at Point 1 and H2 at Point 2) are measured, and the times at which the UAS is at these points (T1 and T2) are recorded. The vertical speed V_s is then calculated using the equation

$$V_s = \frac{H2 - H1}{T2 - T1} \tag{10}$$

2.2.5.7 DAA steps

During flight testing, a variety of annotations were added to the graphic user interface of ground control stations, and sUAS telemetry data was integrated into the QGround Control to allow pilots to use the Albratross UAS as a single point of reference to determine vertical and horizontal distances from the ScanEagle UAS as well as crewed aircraft equipped with ADS-B. The annotations (i.e. range rings) as well as data fusion provided an additional level of safety, acting as a method for detecting and avoiding other aircraft. Radar and fused ADS-B data was also integrated into the electronic observation station to provide location information for crewed aircraft in the vicinity.

2.2.5.8 Softwares/Programs

2.2.5.8.1 Python Packages

Due to the urgency of producing results swiftly and the extensive collection of publicly-available software, Python 3 (Van Rossum and Drake, 2009) was chosen as the programming language. Its comprehensive suite of software modules significantly help the development process. Various modules were employed, which mainly include, Pandas, Numpy, Plotly, Matplotlib, Cartopy. They are used for data manipulations, static and interactive data visualization and performing great circle calculations, which were essential for the project's success. These tools allowed for efficient handling of complex computations and the presentation of data in an accessible and interpretable manner.

2.3 University of Kansas

2.3.1 Location

All flight testing has been accomplished in the vicinity of the Clinton International AMA Field, just southwest of Lawrence, Kansas, 7 NM southwest of the Lawrence Regional Airport (LWC). The field is the property of Jayhawk Model Masters, Inc, a club with which KU has a membership. All crewed aircraft flights originate at the Lawrence Regional Airport, which is owned by the City of Lawrence.

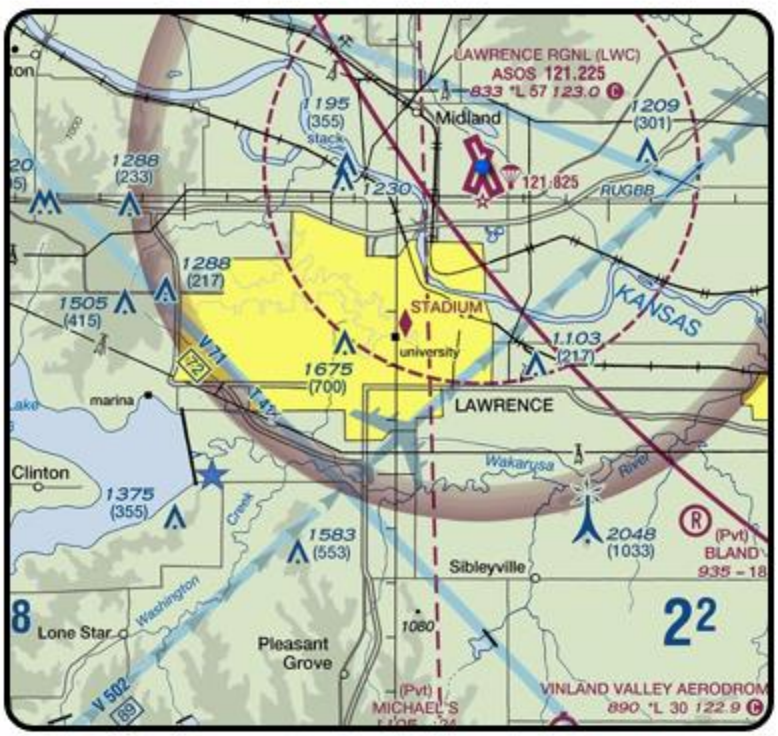


Figure 65. Air Chart showing LWC (upper right) and the AMA field (star at lower left).

At the AMA field, the KU team used two grass runways and a pavilion under which the ground station is set up at the AMA field.

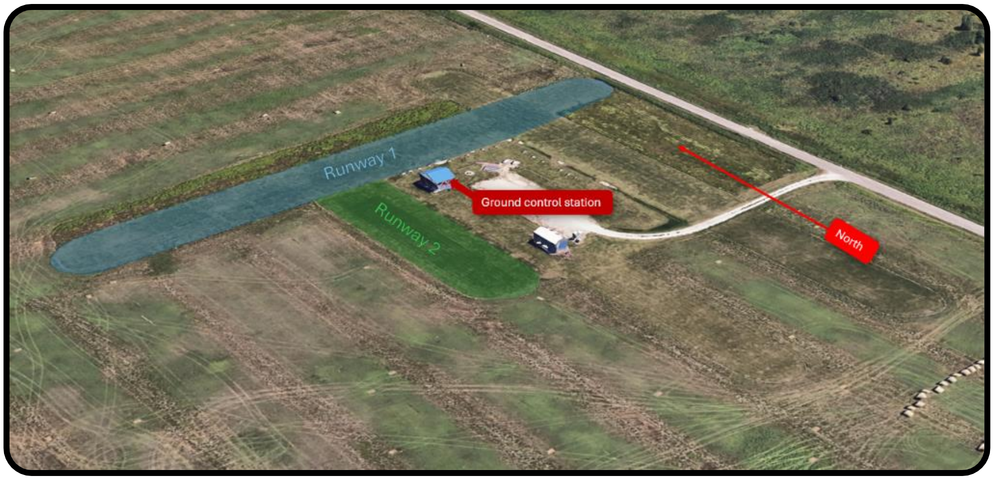


Figure 66. Clinton International AMA Airport.

2.3.2 Flight Test Aircraft and Ground Station

The sUAS used for all flight tests is the SkyHunter UAS, a "kit" sUAS which has been outfitted with the most recent KU Automated Flight System (AFS) and an ADS-B receiver. The KU AFS includes:

- a PixHawk with Orange Cube IMU and GPS receiver
- 2.4 GHz Spektrum AR8020T 8-channel receiver
- MicroHard P900 900 MHz transceiver
- NVIDIA Jetson Nano computer
- Ping RX Pro ADS-B receiver
- Here 3 GPS receiver
- SDP 33 airspeed sensor
- MRO 915 MHz telemetry module
- PPM encoder

Figure 67. SkyHunter sUAS.

The command ground station includes:

- Laptop with a customized version of QGroundControl ground station software
- Microhard P900 900 MHz transceiver
- L-Com HGV 906U dipole antenna on a tripod

The auxiliary ground station includes:

- Laptop with a standard QGroundControl ground station software
- Here + RTK system

The secondary pilot uses:

- 2.4 GHz Spektrum ix20SE transmitter
- DJI FPV goggles

The crewed aircraft is a Cessna 172 certified in the Experimental Category and outfitted with:

- KU AFS (described above)
- L-Com HGV 906U dipole antenna fixed to the left-wing strut
- (FAA-mandated) ADS-B transmitter

Figure 68. Dipole antenna attached to Cessna 172 strut.

A unique feature of the KU flight test setup is that the ground station, the Cessna 172 and the SkyHunter are connected by a “mesh network” wherein these three systems have 2-way connectivity via the 900 MHz MicroHards. This mesh network allows all three systems to have knowledge of the position of the Cessna 172 and the SkyHunter. As a backup to this communications network for providing situational awareness, the ADS-B broadcast from the Cessna is received by the SkyHunter and can be displayed on the auxiliary ground station computer.

2.3.3 Nominal Flight Test Operations

The sUAS operation is under the direction of the Pilot in Command (PIC) who oversees all operations. The secondary pilot launches the sUAS, commanding the sUAS with the ix20SE transmitter, during which time the sUAS is controlled by the commands received by the Spektrum receiver and sent to the PixHawk via the PPM encoder. This is a standard operational concept used by the R/C community. During all phases of flight, the Jetson Nano computer logs GPS location, airspeed, and inertial data provided by the PixHawk.

When commanded, the secondary pilot switches control from the Spektrum transmitter to the Jetson Nano. Until control is switched by the secondary pilot back to the Spektrum transmitter, the sUAS operates in autonomous mode with control commands provided by software installed on the Jetson Nano. The autonomous control software receives information on the crewed aircraft position from either the ADS-B receiver or via the 900 MHz mesh network. The avoidance maneuvers of the SkyHunter are then computed autonomously using the position and velocity vector of the Cessna using either the ADS-B broadcast or the information from the mesh network. The algorithm also includes various “failsafes” which return the control of the sUAS to control by the secondary pilot. For this reason, when the secondary pilot does not see the sUAS, he wears FPV goggles to immediately alert him to any off-nominal behavior.

The Cessna is flown with a KU AFS installed, which provides only two functions. Once turned on, the system logs the inertial and GPS data from the PixHawk onto an SD card in the Jetson Nano. Simultaneously, the MicroHard transceiver broadcasts inertial and GPS data to the “mesh network”.

2.3.4 Test Plan Overview

During all flight tests, the primary goal is two-fold: to determine the degree to which the simulations faithfully predict actual flight performance; and to determine if there are other considerations—like hardware and software performance—necessary to conduct future simulations.

Round 1, General Interactions flights will test the ability of the sUAS to avoid the Cessna 172 for selected General Interactions, to include head-on, converging or overtaking encounters.

Table 76. Round 1 Test Matrix.

Subcase	**Encounter angle**	**Crewed aircraft maneuvers**	**Crewed aircraft doesn’t maneuver**
Head-on	0	A1	A2
Converging	45	B1	B2
Overtaking	180	C1	C2

In all tests, the crewed aircraft flies a racetrack to set up the appropriate encounter angle**.** Figure 69 is the flight test card for the head-on encounter with the crewed aircraft pilot not maneuvering. With these flights being flown within 0.5 NM of the ground station, the complete avoidance maneuver cannot be accomplished in this airspace. Therefore, as the sUAS approaches the 0.5 NM range limit, the sUAS will be recovered by the secondary pilot and readied for the next encounter or landed to refresh batteries. Success in these flights will be judged by the degree to which the avoidance maneuver is following the path expected from simulations.

Test Card A2*.1.1		
Head-on/SkyHunter sUA/Mesh Network DAA		
Date	**start time**	**end time**
Crewed aircraft	Cessna 172 (N1KU)	
alt/speed	900 AGL(1750 MSL)	100 kts
sUAS	SkyHunter	
alt/speed	300 AGL (1150 MSL)	40 fps
flight crew		
Director		
Remote Pilot In Command (RPIC)1		
RPIC 2		n/a
Grnd Station Operator (GSO)		
Ground visual observer (GVO)		
Crewed aircraft pilot		
Crewed flight test engineer (FTE)		

Notes:	practice run for 2 sUA vs Crewed (not maneuvering)
	Radio comms on _____ MHz
Flight events	
1. Cessna launches, approach test area (red trajectory)	
2. sUA launch, establish orbit (yellow)	
3. FTE radios "ready for encounter"	
4. GSO activates DAA system	
5. Pilot and FTE radio "UAS in sight, estimated range ___"	
6. RPIC recovers sUA if necessary to stay in VLoS	
7. GSO radios "sUA maneuver terminated"	
8. Director radios one of the following:	
	"move to next encounter"--go to event 3.
	"sUA land, recharge batteries"--aircraft orbits
	" end of test, sUA and crewed aircraft land"
sky: start	
sky: end	

Pilot/FTE Notes:

Figure 69**.** Sample Flight Test Card: Head-on Encounter, Crewed Aircraft Doesn't Maneuver.

Round 2, Reserved Airspace flights will be of two types.

Round 2.1 flights will be similar to the Round 1 head-on encounters, however, the encounters will be set up such that the head-on avoidance maneuver will progress to the point that the full maneuver can be observed which will allow an assessment of how far off the flight path the sUAS goes. This distance allows for determination of the required width of a reserved airspace corridor. Figure 70 shows the flight test area for these flights. Figure 71 is a sample flight test card.

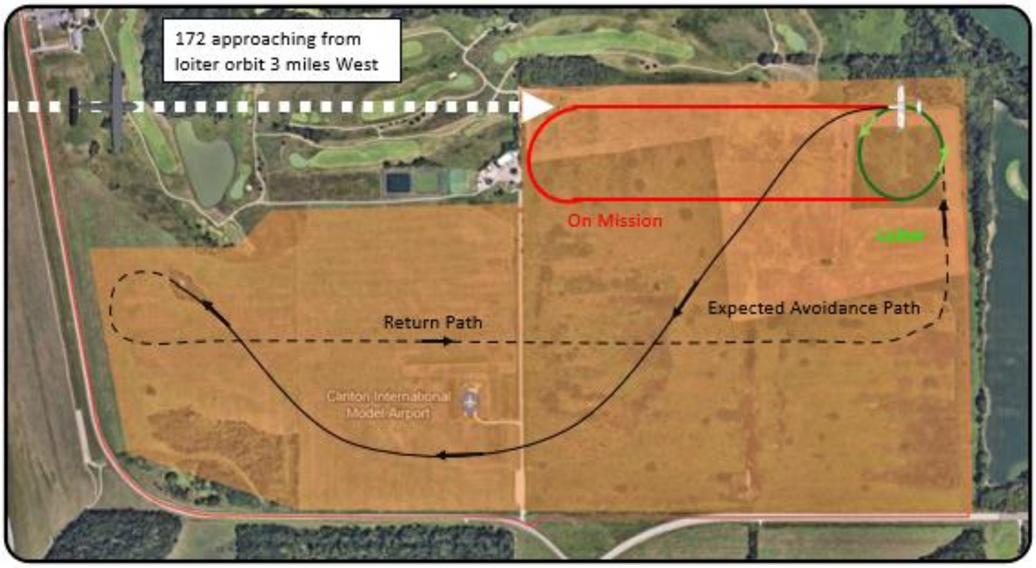
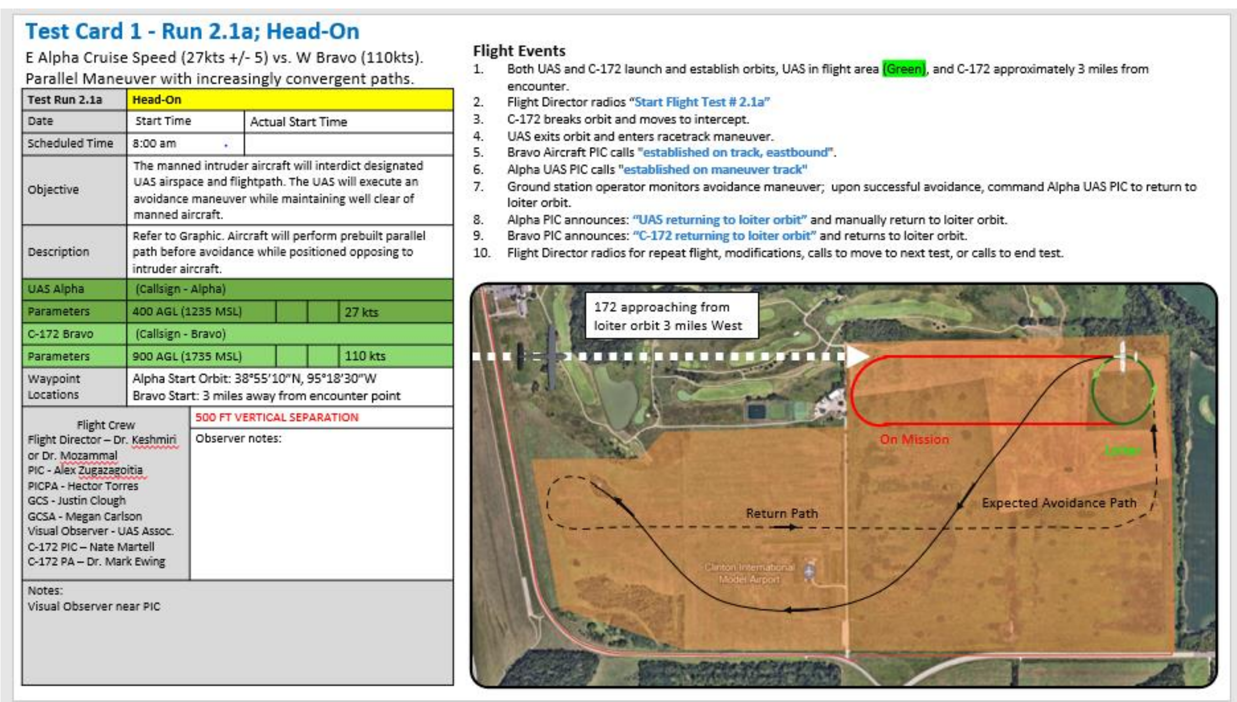


Figure 70. Round 1/2.1 Supporting Flight In a Corridor Analysis.



Test Card 1 - Run 2.1a; Head-On

E Alpha Cruise Speed (27kts +/- 5) vs. W Bravo (110kts).
Parallel Maneuver with increasingly convergent paths.

Test Run 2.1a	Head-On	
Date	Start Time	Actual Start Time
Scheduled Time	8:00 am	
Objective	The manned intruder aircraft will interdict designated UAS airspace and flightpath. The UAS will execute an avoidance maneuver while maintaining well clear of manned aircraft.	
Description	Refer to Graphic. Aircraft will perform prebuilt parallel path before avoidance while positioned opposing to intruder aircraft.	
UAS Alpha	(Callsign - Alpha)	
Parameters	400 AGL (1235 MSL)	27 kts
C-172 Bravo	(Callsign - Bravo)	
Parameters	900 AGL (1735 MSL)	110 kts
Waypoint Locations	Alpha Start Orbit: 38°55'10"N, 95°18'30"W Bravo Start: 3 miles away from encounter point	
Flight Crew Flight Director – Dr. Keshmiri or Dr. Mozammal PIC - Alex Zugazagoitia PICPA - Hector Torres GCS - Justin Clough GCSA - Megan Carlson Visual Observer - UAS Assoc. C-172 PIC – Nate Martell C-172 PA – Dr. Mark Ewing	500 FT VERTICAL SEPARATION Observer notes:	
Notes: Visual Observer near PIC		

Flight Events

1. Both UAS and C-172 launch and establish orbits, UAS in flight area (Green), and C-172 approximately 3 miles from encounter.
2. Flight Director radios "Start Flight Test # 2.1a"
3. C-172 breaks orbit and moves to intercept.
4. UAS exits orbit and enters racetrack maneuver.
5. Bravo Aircraft PIC calls "established on track, eastbound".
6. Alpha UAS PIC calls "established on maneuver track"
7. Ground station operator monitors avoidance maneuver; upon successful avoidance, command Alpha UAS PIC to return to loiter orbit.
8. Alpha PIC announces: "UAS returning to loiter orbit" and manually return to loiter orbit.
9. Bravo PIC announces: "C-172 returning to loiter orbit" and returns to loiter orbit.
10. Flight Director radios for repeat flight, modifications, calls to move to next test, or calls to end test.

Figure 71. Sample Round 2.1 Flight Test Card (for a Head-on Maneuver).

Round 2.2 flights will involve interactions with the crewed aircraft while the sUAS is conducting a grid surveying mission. These flights will require and expanded flight test area to include Clinton Lake and the use of multiple visual observers positioned on the dam located between the AMA field and the lake. The flight tests will start with encounters over the lake to, as in Round 2.1, allow enough space for the sUAS to perform complete avoidance maneuvers. The first few tests will be encounters when the sUAS is approaching a turn-around and in a turn on a racetrack pattern. During these flights, the visual observers will determine the maximum distance the sUAS can be allowed to continue on an avoidance maneuver and still remain within line of sight. Figure 72 shows a head-on encounter scenario. Figure 73 is a sample flight test card.

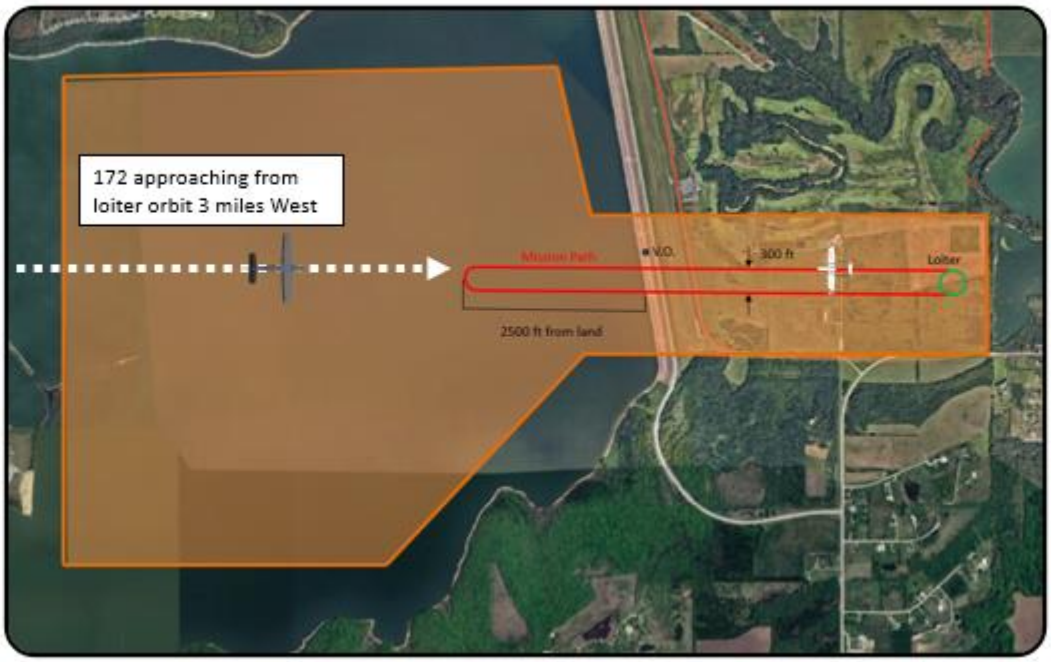
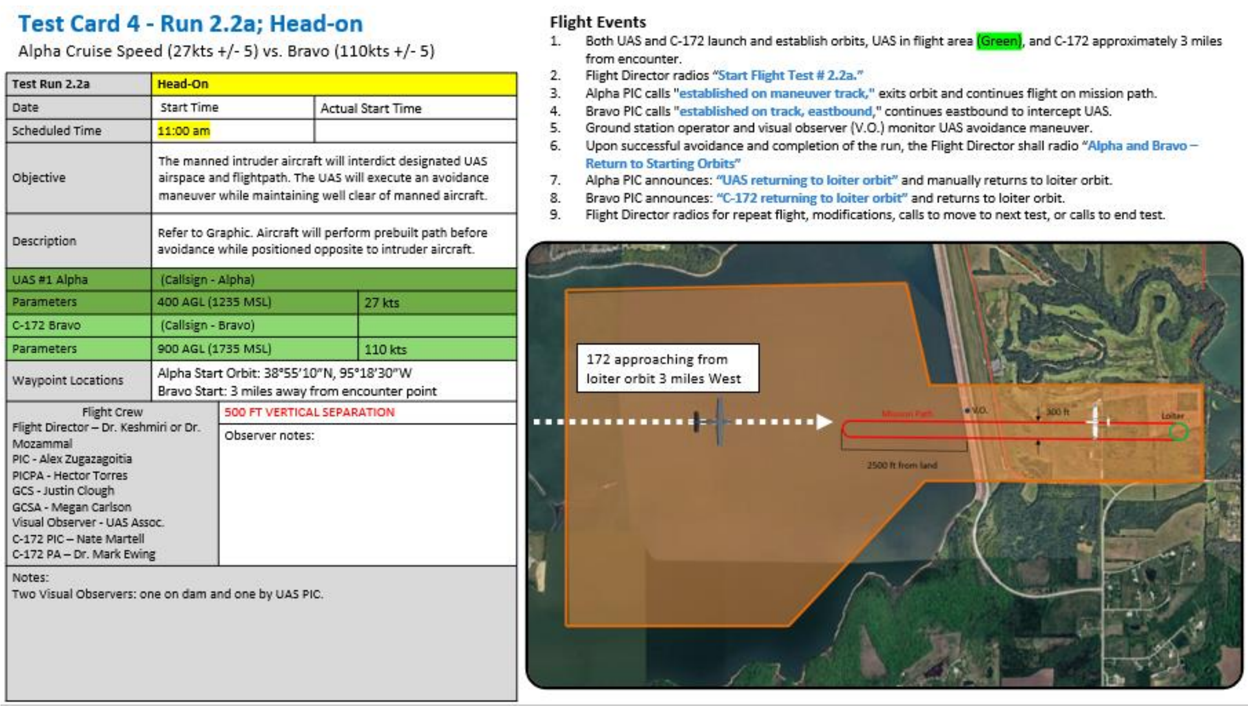


Figure 72. Head-on Encounter over Clinton Lake.



Test Card 4 - Run 2.2a; Head-on

Alpha Cruise Speed (27kts +/- 5) vs. Bravo (110kts +/- 5)

Test Run 2.2a	Head-On	
Date	Start Time	Actual Start Time
Scheduled Time	11:00 am	
Objective	The manned intruder aircraft will interdict designated UAS airspace and flightpath. The UAS will execute an avoidance maneuver while maintaining well clear of manned aircraft.	
Description	Refer to Graphic. Aircraft will perform prebuilt path before avoidance while positioned opposite to intruder aircraft.	
UAS #1 Alpha	(Callsign - Alpha)	
Parameters	400 AGL (1235 MSL)	27 kts
C-172 Bravo	(Callsign - Bravo)	
Parameters	900 AGL (1735 MSL)	110 kts
Waypoint Locations	Alpha Start Orbit: 38°55'10"N, 95°18'30"W Bravo Start: 3 miles away from encounter point	
Flight Crew Flight Director – Dr. Keshmiri or Dr. Mozammal PIC - Alex Zugazagoitia PICPA - Hector Torres GCS - Justin Clough GCSA - Megan Carlson Visual Observer - UAS Assoc. C-172 PIC – Nate Martell C-172 PA – Dr. Mark Ewing	500 FT VERTICAL SEPARATION Observer notes:	
Notes: Two Visual Observers: one on dam and one by UAS PIC.		

Flight Events

1. Both UAS and C-172 launch and establish orbits, UAS in flight area (Green), and C-172 approximately 3 miles from encounter.
2. Flight Director radios "Start Flight Test # 2.2a."
3. Alpha PIC calls "established on maneuver track," exits orbit and continues flight on mission path.
4. Bravo PIC calls "established on track, eastbound," continues eastbound to intercept UAS.
5. Ground station operator and visual observer (V.O.) monitor UAS avoidance maneuver.
6. Upon successful avoidance and completion of the run, the Flight Director shall radio "Alpha and Bravo – Return to Starting Orbits"
7. Alpha PIC announces: "UAS returning to loiter orbit" and manually returns to loiter orbit.
8. Bravo PIC announces: "C-172 returning to loiter orbit" and returns to loiter orbit.
9. Flight Director radios for repeat flight, modifications, calls to move to next test, or calls to end test.

Figure 73. Sample Flight Test Card for Head-on Encounter over Clinton Lake.

After gaining experience with flight testing with forward-place visual observers, encounters during a grid survey mission will be conducted. Figure 74 shows a planned encounter during such a mission. Figure 75 is the associated flight test card.

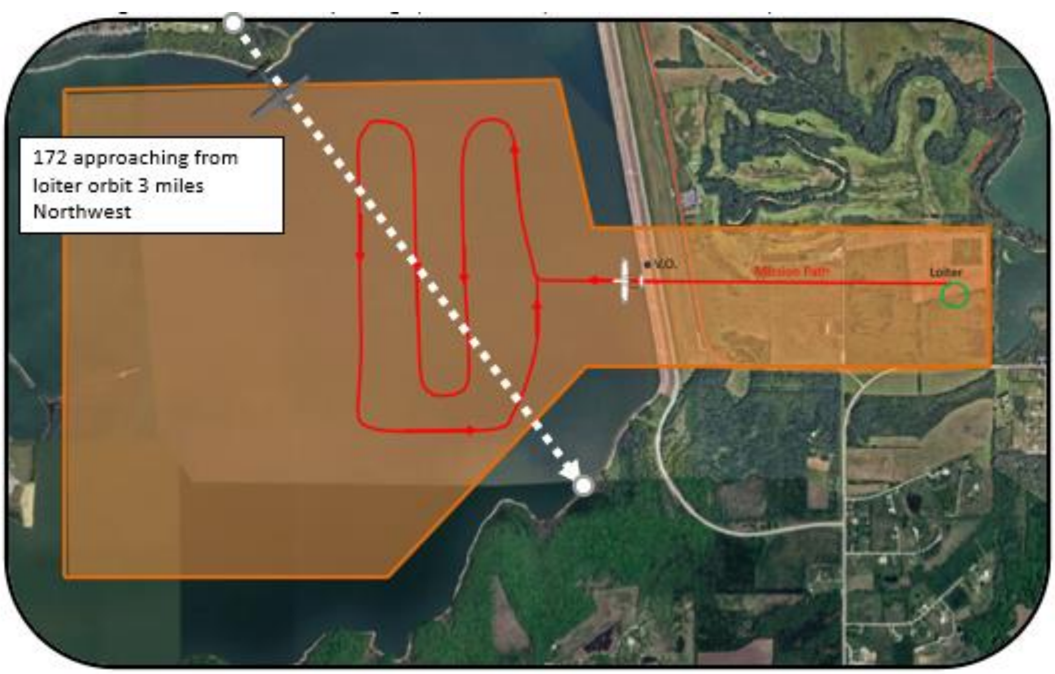
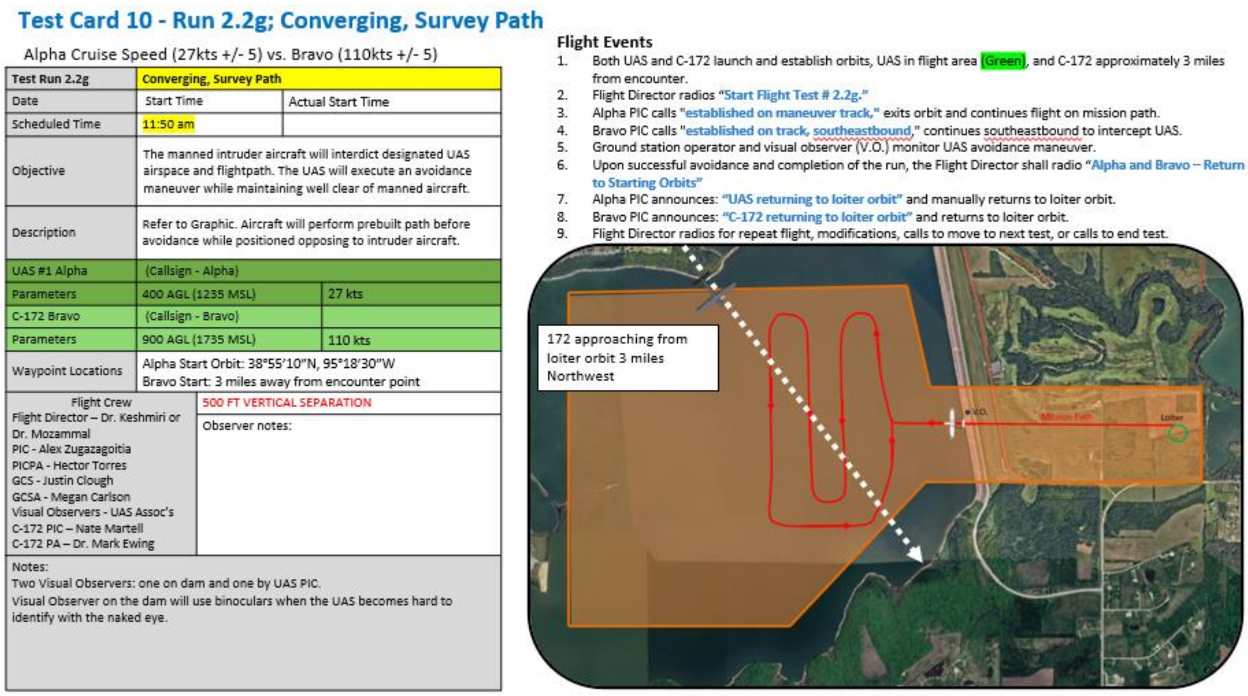


Figure 74. Encounter Scenario During a Grid Survey Mission.



Test Card 10 - Run 2.2g; Converging, Survey Path

Alpha Cruise Speed (27kts +/- 5) vs. Bravo (110kts +/- 5)

Test Run 2.2g	Converging, Survey Path	
Date	Start Time	Actual Start Time
Scheduled Time	11:50 am	
Objective	The manned intruder aircraft will interdict designated UAS airspace and flightpath. The UAS will execute an avoidance maneuver while maintaining well clear of manned aircraft.	
Description	Refer to Graphic. Aircraft will perform prebuilt path before avoidance while positioned opposing to intruder aircraft.	
UAS #1 Alpha	(Callsign - Alpha)	
Parameters	400 AGL (1235 MSL)	27 kts
C-172 Bravo	(Callsign - Bravo)	
Parameters	900 AGL (1735 MSL)	110 kts
Waypoint Locations	Alpha Start Orbit: 38°55'10"N, 95°18'30"W Bravo Start: 3 miles away from encounter point	
Flight Crew Flight Director – Dr. Keshmiri or Dr. Mozammal PIC - Alex Zugazagoitia PICPA - Hector Torres GCS - Justin Clough GCSA - Megan Carlson Visual Observers - UAS Assoc's C-172 PIC – Nate Martell C-172 PA – Dr. Mark Ewing	500 FT VERTICAL SEPARATION Observer notes:	
Notes: Two Visual Observers: one on dam and one by UAS PIC. Visual Observer on the dam will use binoculars when the UAS becomes hard to identify with the naked eye.		

Flight Events

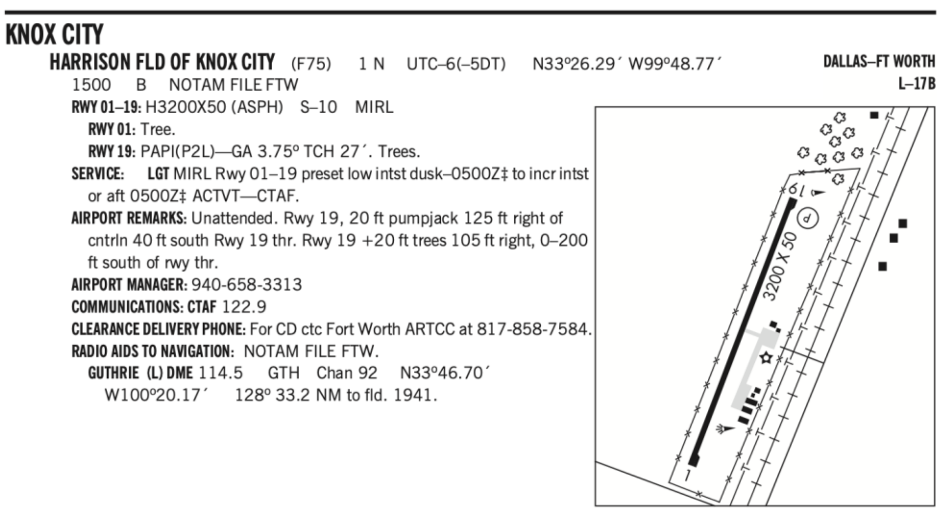
1. Both UAS and C-172 launch and establish orbits, UAS in flight area (Green), and C-172 approximately 3 miles from encounter.
2. Flight Director radios "Start Flight Test # 2.2g."
3. Alpha PIC calls "established on maneuver track," exits orbit and continues flight on mission path.
4. Bravo PIC calls "established on track, southeastbound," continues southeastbound to intercept UAS.
5. Ground station operator and visual observer (V.O.) monitor UAS avoidance maneuver.
6. Upon successful avoidance and completion of the run, the Flight Director shall radio "Alpha and Bravo – Return to Starting Orbits"
7. Alpha PIC announces: "UAS returning to loiter orbit" and manually returns to loiter orbit.
8. Bravo PIC announces: "C-172 returning to loiter orbit" and returns to loiter orbit.
9. Flight Director radios for repeat flight, modifications, calls to move to next test, or calls to end test.

Figure 75. Sample Flight Test Card for Encounter During a Grid Survey Mission over Clinton Lake.

2.4 Embry-Riddle Aeronautical University

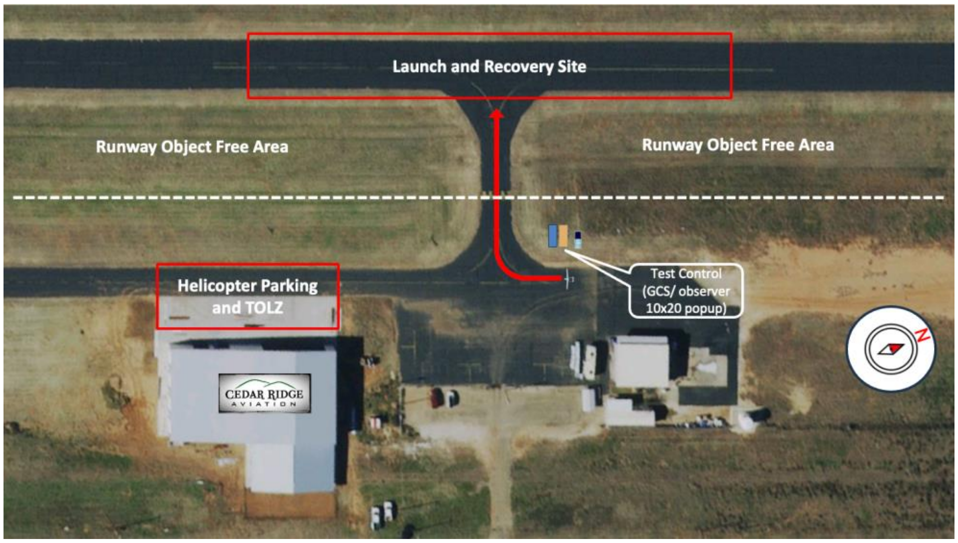
2.4.1 Location

The location used was the airport of Knox City Texas (F75). This facility was approved for use by the City Council in 2022. There is one permanent operator on the airport (Cedar Ridge Aviation) and they also supported our flight testing.

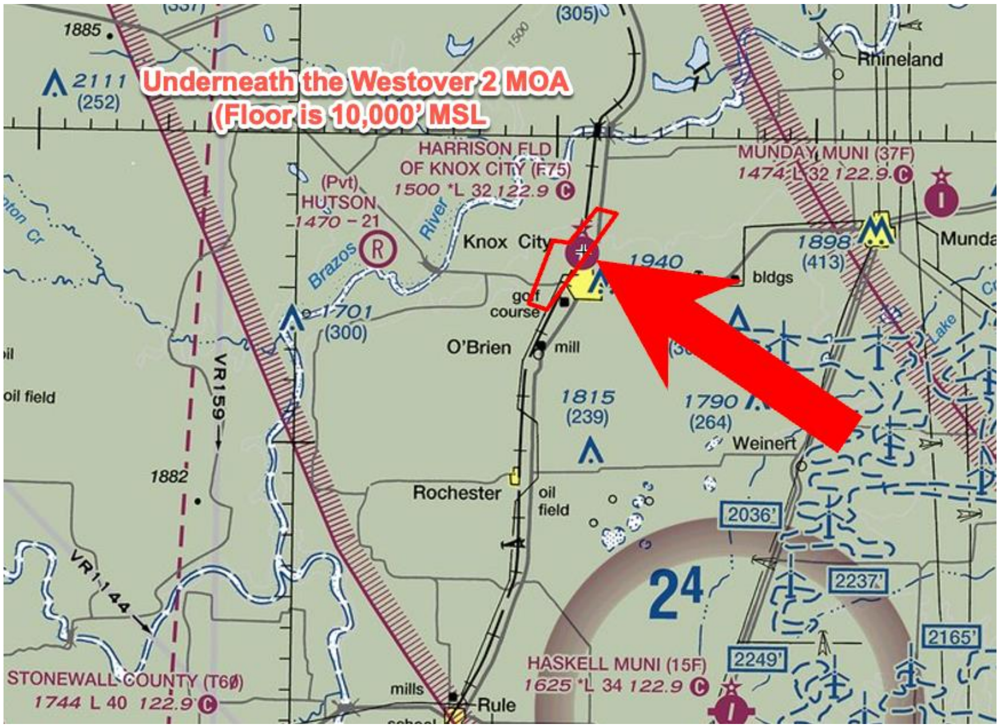


KNOX CITY

HARRISON FLD OF KNOX CITY (F75) 1 N UTC–6(–5DT) N33°26.29´ W99°48.77´ **DALLAS–FT WORTH**
1500 B NOTAM FILE FTW **L–17B**
RWY 01–19: H3200X50 (ASPH) S–10 MIRL
RWY 01: Tree.
RWY 19: PAPI(P2L)—GA 3.75° TCH 27´. Trees.
SERVICE: **LGT** MIRL Rwy 01–19 preset low intst dusk–0500Z‡ to incr intst or aft 0500Z‡ ACTVT—CTAF.
AIRPORT REMARKS: Unattended. Rwy 19, 20 ft pumpjack 125 ft right of cntrln 40 ft south Rwy 19 thr. Rwy 19 +20 ft trees 105 ft right, 0–200 ft south of rwy thr.
AIRPORT MANAGER: 940-658-3313
COMMUNICATIONS: CTAF 122.9
CLEARANCE DELIVERY PHONE: For CD ctc Fort Worth ARTCC at 817-858-7584.
RADIO AIDS TO NAVIGATION: NOTAM FILE FTW.
GUTHRIE (L) DME 114.5 GTH Chan 92 N33°46.70´ W100°20.17´ 128° 33.2 NM to fld. 1941.



Operations were conducted fully within Class G airspace, below 400' AGL, during daylight hours, and VLOS of the airport facility.



2.4.2 Date/Schedule

Table 77. General Interactions Round 1 Timeline.

DTG	Event	Notes
Sunday	Transport UAS GCS Trailer to F75	.308 to F75
4FEB24		Establish Operations location

Monday	Site Setup	
5FEB24	AA from Austin / ERAU from Seattle / Sagetech from AZ	Walk Thru, validate flight run telemetry
Tuesday	Day 1; General Operations Brief/Safety/ Systems Checks and Troubleshooting	Initial Flights with avionics tests and troubleshooting followed by Rehearsal flights. Fly as many test runs as needed. No Helicopter.
6FEB24	Day 1; Debrief	All involved offer comment; Plan revisions as needed
Wednesday	Day 2; General Operations Brief/Safety/ Flight test run plans	Brief with Helicopter PIC. Test runs with helicopter to calibrate test cards. Fly as many test runs as time allows
7FEB24	Day 2; Debrief	All involved offer comment; Plan revisions as needed
Thursday	Day 3; General Operations Brief/Safety/ Flight test runs	Brief with Helicopter PIC. Test runs with helicopter to calibrate test cards. Fly as many test runs as time allows
8FEB24	Day 3; Debrief	All involved offer comment; Plan revisions as needed
Friday		
9FEB24	Recover from Field Site	

Table 78. RAC Round 2 and RID Round 3 Timeline.

DTG	**Event**	**Notes**
Sunday 19 May 24	Transport UAS GCS Trailer to F75	.308 to F75. Establish location
	Some Travel	
Monday 20 May 24	Site Setup	
	SB setup of GCS; Travel Day for DT, JC from WA State & PA; RJ from Austin	Walk Thru, conduct flight test run rehearsals
Tuesday 21 May 24	0800-1600 Day 1; General Operations Brief/Safety/	Round 3 (RID) Data Collection Flights with avionics tests and troubleshooting followed by Rehearsal flights.

	Systems Checks and Troubleshooting	Fly as many test runs as needed. No Helicopter.
	Completion; Post Flight Debrief (GCS Post Flt)	All involved offer comment; Plan revisions as needed
Wednesday 22 May 24	0800-1600 Day 2; General Operations Brief/ Safety/ Flight test run plans	Round 2 (RAC) Brief with Helicopter PIC. Test runs with helicopter to calibrate test cards. Fly as many test runs as time allows
	Completion; Post Flight Debrief (GCS Post Flt)	All involved offer comment; Plan revisions as needed
Thursday 23 May 24	0800-1600 Day 3; General Operations Brief/ Safety/ Flight test runs	Clean Up and fly any repeats with Helo from Rounds 1 & 2. Brief with Helicopter PIC. Test runs with helicopter to calibrate test cards. Fly as many test runs as time allows
	Completion; Post Flight Debrief (GCS Post Flt)	All involved offer comment; Plan revisions as needed
	Travel; Departures	
Friday 24 May 24	Transport UAS GCS Trailer to Rule	
	Travel & Recovery	

2.4.3 Sample test cards

The following are a sample of test cards used in each ERAU test Round;

Round 1

Test Card 1 - Round 1 - Run 1-1a; Head-on Aspect w/ Turn

Helicopter Cruise Speed (100kts +/- 10) vs. FW UAS (33 kts).

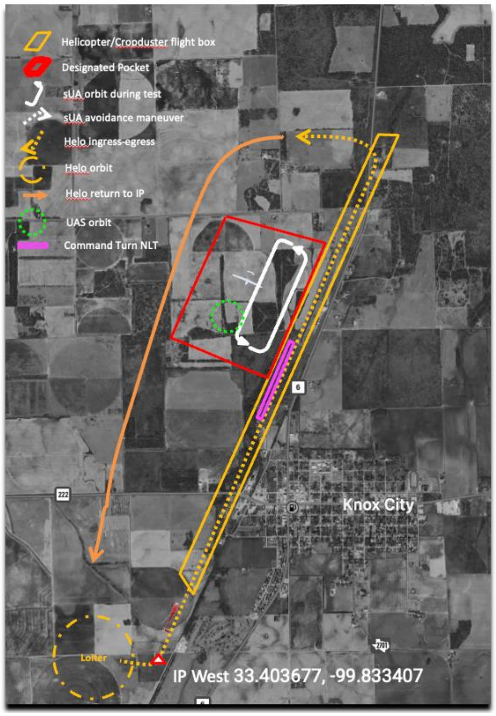
UAS banks away upon identification of Helo. Test Horizontal avoidance maneuver.

Test 1-1a	**Head-On-Aspect, Cruise Speeds**	
Date	Start Time	Stop Time
Start Time		Actual Start
Objective	Head-on-Aspect. Helo vs. UAS. UAS **bank right** at 7900' distance.	
Description	Refer to Flt Graphic. Helo has right of way.	
Crewed Acft	R44 Helicopter (Callsign - Cedar Ridge)	
Parameters	800 AGL (2300 MSL)	100 kts
sUA Acft	AA Albatross (Callsign Riddle 1)	
Parameters	300 AGL (1800MSL)	33 kts
Waypoint Locations	IP West: 33.408858, -99.840568 Rwy TH No.: 33.441054°, -99.813941° Rwy TH So.: 33.433003°, -99.817813°	
GPS Time Intruder ID'd:		
Observer notes:		
Notes: A maneuver distance of 7900' ft to 10000' ft, regardless of GPS receiver, is required depending on pilot response time. UAS turns right based on AAGS flight plan: Helo RTN to IP West at end of ingress corridor. Helicopter PIC • Announce visual Drone Tally or No Tally • Log weather influence to ID		

Flight Events

1. sUA launch and establish UAS orbit (Green) prior to Run 1-1a
2. Helicopter launches and/or returns to establish orbit (Gold) at IP West
3. Flight Director radios "**Start Flight Test # 1-1a**"
4. Helo PIC radios "**IP Inbound at 100kts, 800AGL**"
5. Helo PIC radios "**Cedar Ridge entering Flt Box**" and would turn North
6. RPIC exits orbit simultaneously turning south **radios 'Riddle 1 departing orbit , 300AGL'**
7. Helo PIC radios when UAS is ID'd (Tally Drone) [or] no Tally observed
8. RPIC announces "right turn initiated' @ **7900'** horizontal distance
9. RPIC radios **"Riddle 1 exiting track"** returns to resume orbit @ UAS Orbit
10. Flight Director radios for repeat flight, modifications, or calls to move to next test

Note; Flt Director is at sUA Launch & Recovery Site (LRS), and Intruder (Helicopter) launches. Gnd Crew announces/verifies all recording devices are on. No Comms plan: Albatross lands, R44 fly over >1000' observe RWY activity, land as applicable.
Term 'radio' is a VHF transmission on 122.9
Term 'announces' is verbal at LRS



Test Card 8 - Round 1 - Run 1-2b; Converging Aspect

Helicopter Cruise Speed (100kts +/- 10) vs. FW UAS (33 kts).

UAS banks away upon identification of Helicopter. Test horizontal avoidance maneuver

Test Run 1-2b	**Converging-Aspect, Helo vs. UAS, Cruise Speeds**	
Date	Start Time	Stop Time
Scheduled Time		Actual Start
Objective	Converging Aspect. UAS **banks away** at 3000' distance upon Helo ID	
Description	Refer to Flt Graphic. Helo has right of way	
Crewed Acft	R44 Helicopter (Callsign - Cedar Ridge)	
Parameters	800 AGL (2300 MSL)	100 kts
sUA Acft	AA Albatross (Callsign Riddle 1)	
Parameters	300 AGL (1800MSL)	33 kts
Waypoint Locations	IP Brazos: 33.403940°, -99.871287° Rwy TH No.: 33.441054°, -99.813941° Rwy TH So.: 33.433003°, -99.817813°	
GPS Time Intruder ID'd:		
Observer notes:		
Notes: A maneuver distance of 3000' ft to 5100' ft, regardless of GPS receiver, is required depending on pilot response time. UAS turns right based on AAGS flight plan: Helo RTN to IP West at end of ingress corridor. Helicopter PIC • Announce visual Drone Tally or No Tally • Log weather influence to ID		

Flight Events

1. sUA launch and establish orbit (Green circle) prior to Run 1-2b
2. Helicopter launches and/or returns to establish orbit at IP Brazos
3. Flight Director radios "**Start Flight Test # 1-2b**"
4. Helo PIC radios **"IP Inbound at 100kts, 800AGL"**
5. Helo PIC radios **"Cedar Ridge entering Flt Box"** and would turn North
6. RPIC exits orbit simultaneously turning south calls **'Riddle 1 departing orbit, 300AGL'**
7. Helo PIC calls out when UAS is ID'd (Tally Drone)
8. RPIC announces 'right turn initiated' @ **3000'** horizontal distance
9. RPIC radios **"Riddle 1 exiting track"** returns to resume @ UAS Orbit
10. Flight Director calls for repeat flight, modifications, or calls to move to next test

Notes: Callsigns- UAS is 'Riddle 1'. R44 is 'Cedar Ridge'. Helo exits flight box upon UAS ID. Flt Director is at sUA Launch & Recovery Site (LRS), and Intruder (Helicopter) launches. Gnd Crew announces/verifies all recording devices are on. No Comms plan: Albatross lands, R44 fly over >1000' observe RWY activity, land as applicable.

Round 2

Test Card 1 - Round 2 - Run 2-1a; Head-on Aspect w/ Avoidance
Helicopter Cruise Speed (100kts +/- 10) vs. FW UAS (33 kts).
UAS relocates within rectangular RAC (red pocket) upon identification of Helo.

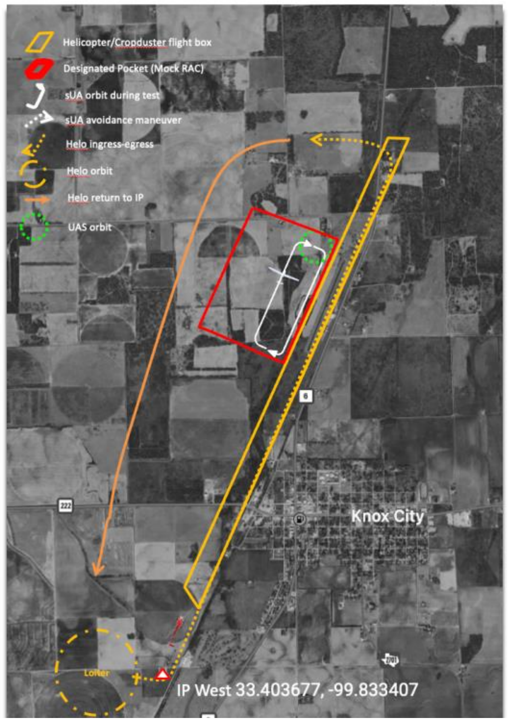
Test 2-1a	Head-On-Aspect	
Date	Start Time	Stop Time
Start Time		Actual Start
Objective	Test relocating to best location within RAC.	
Description	Refer to Flt Graphic. Helo has right of way.	
Crewed Acft	R44 Helicopter (Callsign - Cedar Ridge)	
Parameters	800 AGL (2300 MSL)	100 kts
sUA Acft	AA Albatross (Callsign Riddle 1)	
Parameters	300 AGL (1800MSL)	33 kts
Waypoint Locations	IP West: 33.408858, -99.840568 Rwy TH No.: 33.441054°, -99.813941° Rwy TH So.: 33.433003°, -99.817813°	
GPS Time Intruder ID'd:		
Observer notes:		

Notes:
This RAC mimics a rectangular inspection. UAS turns based on Intruder aspect to a location in the RAC that provides greatest separation.
Decision to descend or turn first based on RPIC.
Helo RTN to IP West at end of ingress corridor.
Helicopter PIC
- Announce visual Drone Tally or No Tally
- Log weather influence to ID

VHF Traffic may be present periodically. Albatross RPIC communicates with local traffic. Flight Director communicates with participating R44

Flight Events
1. sUA launch and establish UAS orbit (Green) prior to Run 1-1a
2. Helicopter launches and/or returns to establish Loiter (Gold) at IP West
3. Flight Director radios "Start Flight Test # 2-1x"
4. Helo PIC radios "IP Inbound at 100kts, 800AGL"
5. Helo PIC radios "Cedar Ridge crossing 222"
6. RPIC exits orbit simultaneously turning south radios 'Riddle 1 departing orbit , 300AGL'
7. Helo PIC radios if UAS is ID'd (Tally Drone) [or] no Tally observed
8. RPIC announces "Riddle 1 Avoiding"
9. Flight Director radios "End of Run, Reset for 2-2x"
10. Cedar Ridge returns to Loiter, Riddle 1 returns to UAS Orbit

Note; Flt Director is at sUA Launch & Recovery Site (LRS), Intruder (Helicopter) launches. Gnd Crew announces/verifies all recording devices are on.
No Comms plan: Albatross lands, R44 fly over >1000' observe RWY activity, land as applicable.
Term 'radio' is a VHF transmission on 122.9
Term 'announces' is verbal at LRS



Test Card 3 - Rnd 2 - Run 2-3a; Converging Aspect Avoidance
Helicopter Cruise Speed (100kts +/- 10) vs. FW UAS (33 kts).
UAS relocates within Polygonal RAC (red pocket) upon identification of Helo.

Test Run 2-3a	Converging Aspect	
Date	Start Time	Stop Time
Start Time		Actual Start
Objective	Test relocating to best location within RAC.	
Description	Refer to Flt Graphic. Helo has right of way.	
Crewed Acft	R44 Helicopter (Callsign - Cedar Ridge)	
Parameters	800 AGL (2300 MSL)	100 kts
sUA Acft	AA Albatross (Callsign Riddle 1)	
Parameters	300 AGL (1800MSL)	33 kts
Waypoint Locations	IP West: 33.408858, -99.840568 Rwy TH No.: 33.441054°, -99.813941° Rwy TH So.: 33.433003°, -99.817813°	
GPS Time Intruder ID'd:		
Observer notes:		

Notes:
This RAC mimics a large RAC area with a converging intruder. UAS turns based on Intruder aspect to a location in the RAC that provides greatest separation.
Decision to descend or turn first based on RPIC.
Helo RTN to IP West at end of ingress corridor.
Helicopter PIC
- Announce visual Drone Tally or No Tally
- Log weather influence to ID

VHF Traffic may be present periodically. Albatross RPIC communicates with local traffic. Flight Director communicates with participating R44

Flight Events
1. sUA launch and establish UAS orbit (Green) prior to Run 1-1a
2. Helicopter launches and/or returns to establish Loiter (Gold) at IP West
3. Flight Director radios "Start Flight Test # 2-3x"
4. Helo PIC radios "IP Inbound at 100kts, 800AGL"
5. Helo PIC radios "Cedar Ridge crossing 222"
6. RPIC exits orbit simultaneously turning south radios 'Riddle 1 departing orbit , 300AGL'
7. Helo PIC radios if UAS is ID'd (Tally Drone) [or] no Tally observed
8. RPIC announces "Riddle 1 Avoiding"
9. Flight Director radios "End of Run, Reset for X-X"
10. Cedar Ridge returns to Loiter, Riddle 1 returns to UAS Orbit

Note; Flt Director is at sUA Launch & Recovery Site (LRS), Intruder (Helicopter) launches. Gnd Crew announces/verifies all recording devices are on.
Departing/Inbound cropduster/s may be present. Radio all Taxi's/ Departures, pattern locations as applicable, and Landing indications.
No Comms plan: Albatross lands, R44 fly over >1000' observe RWY activity, land as applicable.
Term 'radio' is a VHF transmission on 122.9
Term 'announces' is verbal at LRS

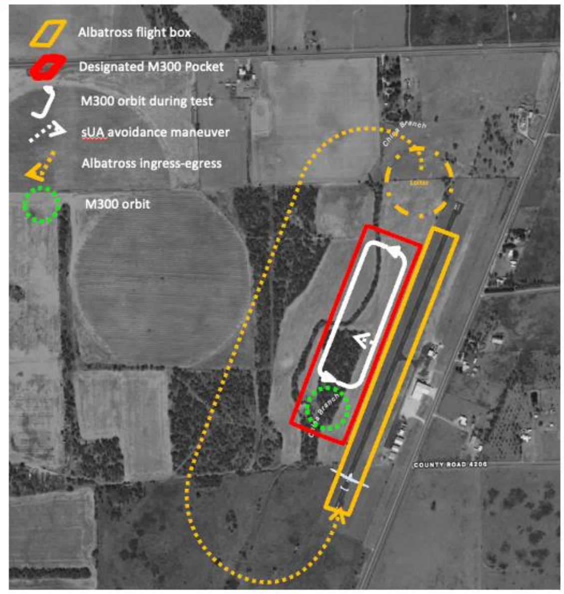
Round 3

Test Card 4 - Round 3 RID - Run 3-2a; Head-on Aspect
Albatross Cruise Speed (33kts) vs. M300 UAS (20 kts).

Test 3-2a	Head-On-Aspect, Cruise Speeds	
Date	Start Time	Stop Time
Start Time		Actual Start
Objective	Pattern to attain data for Post Flight Analysis. Maintain safe separation.	
Description	Refer to Flt Graphic. Maintain safe, separated flight for data collection.	
FW UA Acft	Albatross (Callsign – Riddle 1)	
Parameters	300 AGL	33 kts
M300 UA Acft	Matrice M300 (Callsign Riddle 2)	
Parameters	250 AGL	20 kts
Waypoint Locations	Rwy TH No.: 33.441054°, -99.813941° Rwy TH So.: 33.433003°, -99.817813°	
GPS Time Intruder ID'd:		
Observer notes:		
Notes: Collect Data for post flight analysis. Detect and avoid. WC standard is 100' hztl/25' vert. We will triple this and maintain horizontal separation at 300'.		

Flight Events
1. MC UA launch and establish UAS orbit (Green) prior to Run
2. FW UA launches and/or returns to establish orbit (Gold)
3. Flight Director radios "Start Flight Test #"
4. FW PIC radios "Riddle 1 Inbound at 33kts, 200AGL"
5. Matrice PIC radios "Riddle 2 in hover at 200AGL"
6. FW UA RPIC radios "Riddle 1 exiting track" returns to resume orbit @ FW UA Orbit
7. Flight Director radios for repeat flight, modifications, or calls to move to next test

Note; Flt Director (Albatross safety pilot is at sUA LRS on RWY, M300 RPIC is next to LRS. Albatross RPIC in GCS announces/verifies all recording devices are on. No Comms plan: Albatross lands, M300 descends and RPIC observes Albatross thru landing on RWY, land as applicable.
Term monitors VHF traffic on 122.9
Team Comms on BT vox headsets.

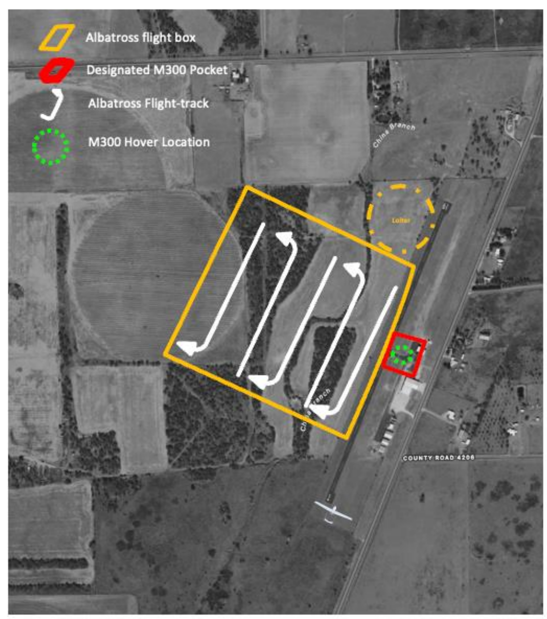


Test Card 1 - Round 3 – RID Run 3-1a; Perpendicular Aspect
FW UA (33kts +/- 5) vs. MC UA (0 kts).

Test Run 3-1a	Perpendicular Aspect, Divergent Speeds	
Date	Start Time	Stop Time
Start Time		Actual Start
Objective	Pattern to attain data for Post Flight Analysis. Maintain safe separation.	
Description	Refer to Flt Graphic. UA maintain safe separation	
FW UA	AA Albatross (Riddle 1)	
Parameters	200 AGL (1700 MSL)	33 kts
MC UA	DJI Matrice M300 (Riddle 2)	
Parameters	200 AGL (1700MSL)	0 kts
Waypoint Locations	Albatross Orbit: 33.435577°, -99.818829° Matrice Hover: 33.437019°, -99.815834°	
GPS Time Intruder ID'd:		
Observer notes:		
Notes: • Maintain safe separation and verify via internal communications • Maintain data integrity and compartmentalization • Tracks will be 300', 1600' and 2900' distance center point from the M300 • Width of each track will be 2500'		

Flight Events
1. MC UA launch and establish UAS orbit (Green) prior to Run
2. FW UA launches and/or returns to establish orbit (Gold)
3. Flight Director radios "Start Flight Test #"
4. FW PIC radios "Riddle 1 Inbound at 33kts, 200AGL"
5. Matrice PIC radios "Riddle 2 in hover at 200AGL"
6. FW UA RPIC radios "Riddle 1 exiting track" returns to resume orbit @ FW UA Orbit
7. Flight Director radios for repeat flight, modifications, or calls to move to next test

Note;
Flt Director is at sUA Launch & Recovery Site (LRS).
MC UA RPIC is collocated with FD.
FW UA RPIC is in GCS.
No Comms plan: FD & MC UA RPIC move to GCS Ramp to colocate.
Maintain VHF 122.9 to monitor and communicate as needed with area traffic



2.4.3.1 Test Plans overview

Each flight test occurred in the prescribed operation. ERAU established an operational base at F75 as shown in the previous section. The general procedure was to prepare for test flights with several rehearsal runs on the first day after aircraft preparation. The following days would include an organized process of test flight runs using the test cards shown in 3.3.4.

In each iteration (Round 1, Round 2, and Round 3) an uncrewed aircraft would launch from its specified Launch and Recovery Site (the F75 runway) and conduct flight testing. The Applied

Aeronautics Albatross is flown to establish and airborne orbit and await the beginning of the particular Test Run. When applicable, a supporting crewed helicopter takes off from their ramp on F75. Time of departure, location to hold until flight testing commences will be identified. The Flight Director will commence all flight testing.

Safe Separation. Two safety volumes were emplaced to maintain airspace safety, and evaluate if an encounter failed, sNMAC and small Well Clear. The standard FAA separation of 500ft horizontal and vertical separation was followed and never penetrated. Using the RTCA sNMAC well clear static volume of 2000ft horizontal and 250ft vertical for this research was used and frequently violated. Additionally, the analysis for this choice can be found in Appendix D.

Tasks. The following general tasks were followed. The Data Collection Plan (Table 79) was established and modified to suit research needs. Some of these tasks were modified as needed or as capabilities or limitations were discovered.

- Crewed Aircraft airborne tasks
    - Follow Flight test card parameters.
    - Maintain constant communications with flight director.
    - Execute emergency procedures per org procedure.
- Uncrewed Aircraft airborne tasks
    - Follow Flight test card parameters.
    - Maintain constant communications with flight director.
    - Execute emergency procedures per org procedure.
- Collective Team Tasks and Methods – (Observers and Data Collectors – on ground and when applicable in crewed aircraft)

Table 79. Data Collection Plan.

Collection Task	Information	Collection Instrument
Response Times	All radio call times (i.e. ‘IP South Inbound’, ‘entering Flt Box’, ‘departing orbit’, Tally calls, exit calls)	GoPro, audio or digital recorder
GUI Data	Note closest distance between aircraft on GUI (vertically and horizontally)	Screen record on laptop/tablet as applicable
Proximity	Note closest distance between aircraft (vertically and horizontally)	Albatross Telemetry files Sagetech sXU telemetry files GPS Receiver (puck) Data

Target Loss	Note any loss of capability to identify where traffic is located – on DAA display or visually	All instruments (audio and telemetry)
Weather	Sky cover / Approx visibility / Winds / Temp	Recorded in preflight brief and periodic PIREPs
Airborne Safety	Unintended hazards or risks associated with each Test Run	All instruments (audio and telemetry)
GPS Data	Collect data from pucks at mid-day and end of day	
Initial Drone Tally	Attempt to capture the distance the UAS is visually acquired; announce. Pilot perceptions.	Airborne PIC and Observer annotation
Tally method	When the UAS does not give way, when does helicopter see the UAS. How is UAS identified? (ADS-B? Visually?)	All instruments (audio and telemetry)
Tally quality	How does the weather conditions impact visual conspicuity of the UAS	Airborne PIC and Observer annotation
	Does the aircraft act as agilely as expected	RPIC

In each test Round, several after action reviews were conducted and the first was there at Knox City (as all participants were from geographically separate areas). Follow-on after action reviews were conducted virtually. Data was processed, analyzed and discussed for each round of data.

As the sponsor required weeks of pre-test notification, a process was established whereby the flight test cards would be sent for approval. In the case of Round 1 – General Interactions, and Round 2 –RAC, ERAU used the same test cards and plan for Round 2 as was used for Round 1. The only difference was that the notional airspace that was used to emulate a block of reserved airspace was implemented. This mock configuration did not change flight paths of the crewed aircraft, nor the well clear separation between the sUAS and the helicopter. The only difference was the space in which the sUAS maneuvered became more confined and did not change aircraft control or stability in any flight.

3 FLIGHT TESTS

The section provides flight test results performed by each performer university. The results are presented for ROW General Interaction, Reserved Airspace Concept and Remote ID.

3.1 General Interactions

3.1.1 sUAS vs sUAS and CA vs sUAS (UND)

3.1.1.1 Flight test Summary

A summary of encounters executed during the test campaign is provided in

Table 80. As indicated in Table, In Round 1 total of 54 encounters were planned, resulting from three tests for each of the 18 different maneuvers for head-on convergence and overtaking encounters. On Day 1, researchers conducted UAS versus crewed encounters, totaling 27, and on Day 2, researchers conducted

UAS versus UAS encounters, also totaling 27. Despite strong winds on March 27, 2024, the goal of completing all 54 encounters was successfully achieved.

Table 80 shows the encounter details for Round 2. A total of 34 encounters were planned. The Day 1 a total of 18 encounters were conducted and the remaining 16 encounters were done on day 2.

Table 80. Summary of flight test encounters. Detailed analysis of all rounds are given in Appendix G.

Round	Days	Number of desired events	Number of acceptable Encounter	Comments
Round 1	Day 1	27	26	Test cards 21g (HO_HD) is not considered because of of inconsistencies in flight path/altitudes/speed.
	Day 2	27	21	Test cards 11g (HO_HD), 13e (OT_D), 12d (CV_D), 12h and 12d (CV_HD) are disregarded because of inconsistencies in flight path/altitudes/speed.
	Total	54	47	
Round 2	Day 1	18	17	Test cards 2g (CV_HD) is disregarded because of inconsistencies in flight profile due to bad weather
	Day 2	14	10	Test cards 3c, 25a, 25b, 26b are disregarded.
	Total	32	27	
Round 3	Day 1	15	15	Symmetric Parallel:3 Headon Horizontal: 6 Headon Vertical: 6
	Total	15	15	
Grand Total		101	89	

Certain flight events detailed in

Table 80 have been excluded from the analysis as anomalies. Telemetry data indicates these flights deviated significantly from standard flight profiles in terms of altitude and airspeed. Potential contributing factors include adverse meteorological conditions or other external influences. These anomalous events have been omitted from summary statistics and subsequent analysis to ensure the accuracy and relevance of the findings.

3.1.1.2 sUAS vs sUAS Maneuvering Criteria

For Round-1, sUAS-sUAS, the RoW flight test approach includes Head-On, Convergent, and Overtaking scenarios. For each scenario, the objective is to test horizontal avoidance, vertical avoidance, and a combined horizontal and vertical avoidance. **Table 81** provides the abbreviations and maneuver initiation distances. The sUAS-sUAS flight tests were conducted using various initiation distances, carefully determined based on the results obtained from simulations.

Table 81.Abbreviations and maneuver initiation distances for Round-1, sUAS-sUAS encounters.

Approach	**Objective**	**Abbreviation**	**Maneuver Initiation Distance (ft)**	**Maneuvering UAS***
Head-On	Horizontal avoidance	HO_H	1800	Loki banks right upon identification of Thor.
	Vertical avoidance	HO_D	2000	Loki descends upon identification of Thor.
	Combined Horizontal/Vertical avoidance	HO_HD	1800	Loki descends and turns right upon identification of Thor
Convergent	Horizontal avoidance	CV_H	1800	Loki banks right upon identification of Thor.
	Vertical avoidance	CV_D	2600	Loki descends upon identification of Thor.
	Combined Horizontal/Vertical avoidance	CV_HD	1800	Loki descends and turns right upon identification of Thor
Overtaking	Horizontal avoidance maneuver	OT_H	1000	Thor banks right upon identification of Loki.
	Vertical avoidance	OT_D	1500	Thor descends upon identification of Loki.
	Combined Horizontal/Vertical avoidance	OT_HD	1000	Thor descends and turns right upon identification of Loki

*ScanEagle's call sign is Thor, AA Albatross's call sign is Loki

3.1.1.3 CA vs sUAS Maneuevring Criteria

For Round-1, CA-sUAS, the Rules of the Road (RoW) flight test approach includes Head-On, Convergent, and Overtaking scenarios. For each scenario, the objective is to test horizontal avoidance, vertical avoidance, and a combined horizontal and vertical avoidance. Table 82 provides the abbreviations and maneuver initiation distances. The CA-sUAS flight tests were conducted using various initiation distances, carefully determined based on the results obtained from simulations. The distance was varied from 6200 ft – 8000ft.

Table 82. Abbreviations and maneuver initiation distances for Round-1, sUAS-sUAS encounters.

Encounters	Objective	Abbreviation	Maneuver Initiation Distance (ft)	Maneuvering UAS*
Head-On	Horizontal avoidance	HO_H	8000	Thor banks right upon the identification of Zeus.
	Vertical avoidance	HO_D	8000	Thor descends upon the identification of Zeus.
	Combined Horizontal/Vertical avoidance	HO_HD	6500	Thor descends and turns right upon identification of Zeus
Convergent	Horizontal avoidance	CV_H	8000	Thor banks right upon the identification of Zeus.
	Vertical avoidance	CV_D	8500	Thor descends upon the identification of Zeus.
	Combined Horizontal/Vertical avoidance	CV_HD	7300	Thor descends and turns right upon identification of Zeus
Overtaking	Horizontal avoidance	OT_H	6200	Thor banks right upon the identification of Zeus.
	Vertical avoidance	OT_D	6200	Thor descends upon the identification of Zeus.
	Combined Horizontal/Vertical avoidance	OT_HD	6200	Thor descends and turns right upon identification with Zeus

*ScanEagle's call sign is Thor, Crewed Aircraft's (Cessena 150) call sign is Zeus

3.1.1.4 Flight Test Results - UAS vs sUAS

- The implemented avoidance maneuver was successful. The Closest Point of Approach (CPA) distances during the maneuver, along with the DAA radius, are presented in Figure 76. In all cases, the maneuvering was efficient, and well clear distances were maintained. This was accomplished by having additional safety buffers verticallly and horizontally between sUAS, other sUAS, and crewed aircraft. Additionally, radar and ADS-B data was used to ensure separation from non-cooperative aircraft.

- No potential collision risk , well clear violations or sNMAC, were observed.
- Sensor data integrity and update rates were sufficient.
- The average turn rate profile of the ScanEagle and Albatross for each flight test and scenario is plotted in Figure . The average turn rate of the Albatross varied between 8.9-11.3 degrees per second. The average turn rate of the ScanEagle varied between 5.6-8.5 degrees per second.
- The vertical speed profile of the ScanEagle and Albatross for each flight test and scenario is plotted in Figure 80. During the 'descent' and 'horizontal and descent' maneuver scenarios, the Albatross approached a vertical speed of 315-381 feet per minute (fpm), while the ScanEagle achieved a vertical speed of 429.8-483.1 fpm. The target vertical speed for both aircraft was 500 fpm.
- Vertical speeds were not constant throughout the descent, exhibiting fluctuations.
- Vertical descent performance, defined as the vertical distance descended by the maneuvering UAS from its original altitude by the time of closest approach, was calculated. The average vertical descent achieved by the Albatross was approximately 73 feet, and the ScanEagle 193 feet. The lower value for the Albatross is attributed to its lower-than-target vertical speed.
- The average ground speed profile of the ScanEagle and Albatross for each flight test and scenario is plotted in Figure 81, with averaged values presented in Figure 80. The results indicate that maintaining target ground speeds was difficult due to environmental conditions. The target ground speed for the ScanEagle was 50 knots (± 10 knots), while the target for the Albatross was 35 knots. The ScanEagle consistently exceeded 50 knots with a mean value of 57.7 knots and a standard deviation of 5.4 knots. The Albatross had a mean value of 39.1 knots and a standard deviation of 1.3 knots.
- The altitude profile of the ScanEagle and Albatross for each flight test and scenario is plotted in Figure 79 and Figure . Two observations were made: 1) In the horizontal-only scenario, where altitude variation was not necessary for maneuvering, there was significant variation in maintaining altitude. 2) During descent, the sUAS altitude variation was not smooth, sometimes showing a sudden increase, which is undesirable and poses a potential risk of well clear violation.
- The average human reaction times for each scenario shows that operator reaction time varied between 1 second to 6.3 seconds. Additionally, no specific correlation was observed between human reaction time and the maneuvering criteria. It should be noted that statistically significant data is not available to draw conclusive values on human reaction times. However, it was observed that the operator's graphical user interface (GUI) had a significant impact on reaction time.
- As later described, the GUI incorporated annotations in the form of concentric distance rings as a spatial reference system this enhanced the operator's ability to detect and respond to potential collisions. Additional GUI information was provided by QGround Control software fusing sUAS telemetry data and ADS-B data from the crewed aircraft to provide visual references of vertical and horizontal distances of all participating aircraft from the Albratross aircraft. These modification signficant assisted the pilots ability to react to

sitations and use to assisting in remaining well clear and not violating sNMAC specifications.

- GPS Discrepancy: A 30-minute comparison flight between uBlox M9N and QStratZ GPS systems on the Albatross UAS revealed an average difference of ~19 feet in horizontal distance and ~6 ft in altitude. The maximum difference in horizontal distance is ~36.2 ft and maximum difference in altitude is 17.2 ft.
- Weather data on the flight test day indicated wind speeds of 5-10 mph in varying directions, daytime temperatures between 20-42 degrees Fahrenheit, and pressure of 29.11-29.18 inches of mercury (source: wunderground.com).

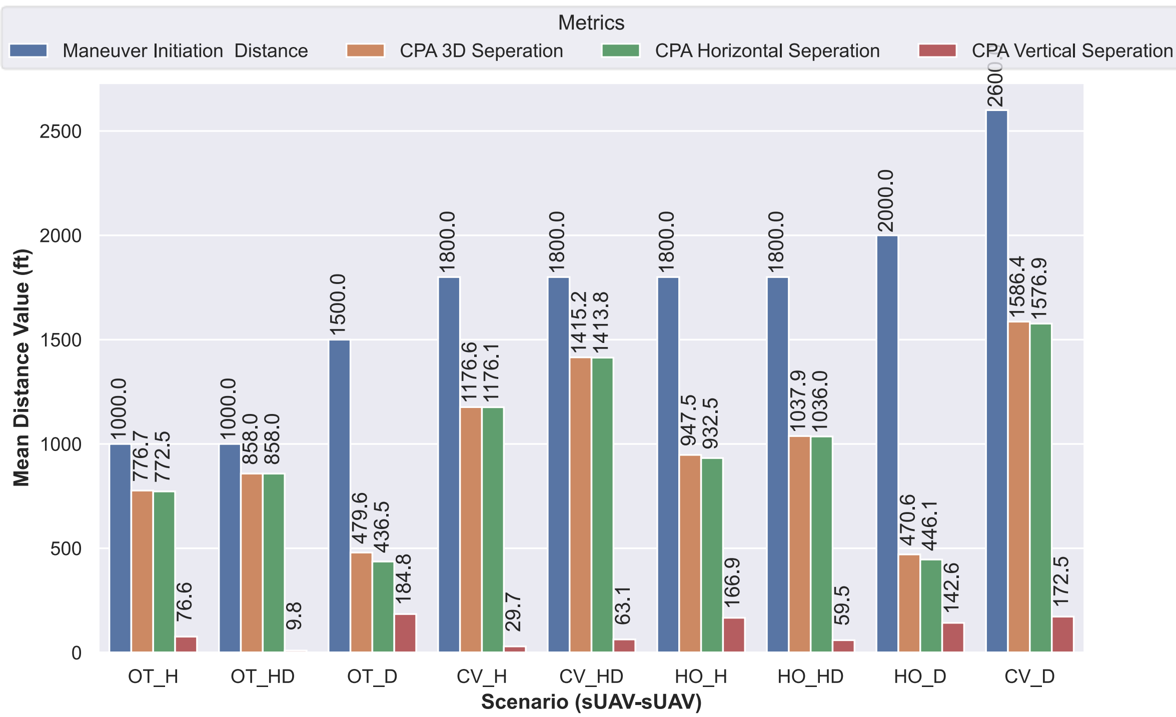


Figure 76. Round-1, sUAS-sUAS overall analysis.

In Figure 76, Round-1, sUAS-sUAS overall analysis shows the bar plot illustrates the DAA encounter distance, along with CPA 3D, CPA horizontal, and CPA vertical separation distances at the time of the CPA of the two UASs, for various maneuvering scenarios. Each bar represents the average outcome of multiple repeated flight tests within the respective scenario.

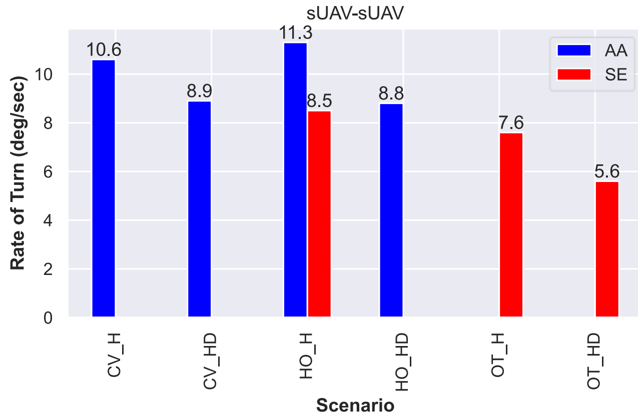


Figure 77. Round-1, sUAS vs CA.

This bar chart shown in Figure 77. Round-1, sUAS vs CA., illustrates the average Rate Of Turn (ROT) performance of sUASS: the Albatross (AA) and the ScanEagle (SE). Each bar represents the average ROT achieved in Round 1 of a specified flight scenario. Note that the 'Descent Only' criterion does not involve a rate of turn maneuver, and thus, no data is presented for this condition.

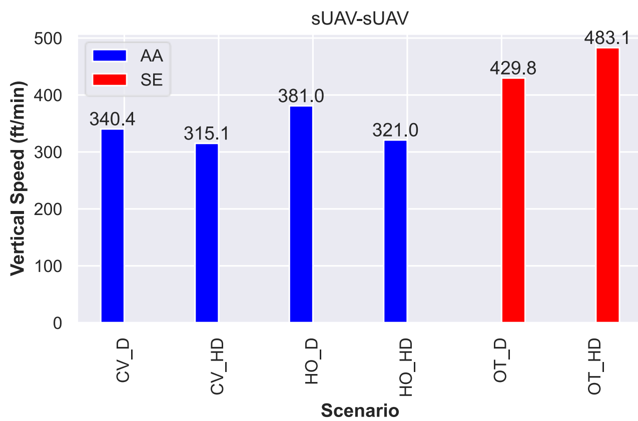


Figure 78. Round-1, sUAS vs sUAS.

This bar chart shown in Figure 78, Round-1, sUAS vs sUAS, illustrates the vertical speed performance of sUASS: the Albatross (AA) and the ScanEagle(SE). Each bar represents the average vertical speed of a specified flight scenario. Note that the ‘Horizontal Only' criterion does not involve a descent maneuver, and thus, no data is presented for this condition.

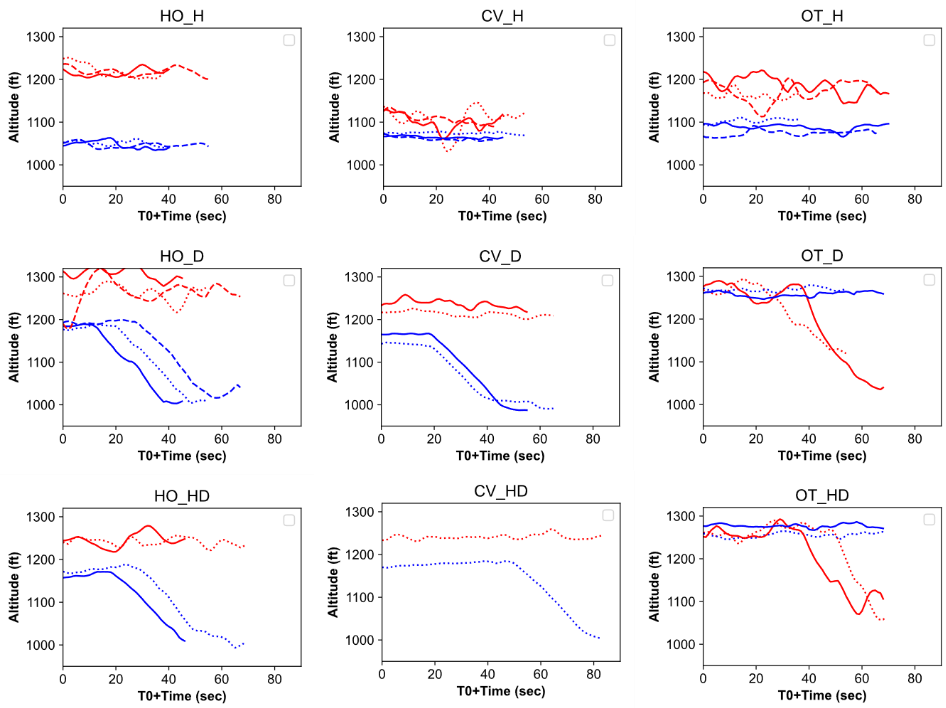


Figure 79. Round-1, sUAS-sUAS, Altitude data.

In Figure 79. Round-1, sUAS-sUAS, Altitude dataeach subplot depicts the flight profile variations in altitude of ScanEagle (red) and Albatross (blue) across repeated flight tests for each scenario, commencing at the on-track time and concluding at the completion maneuver time.

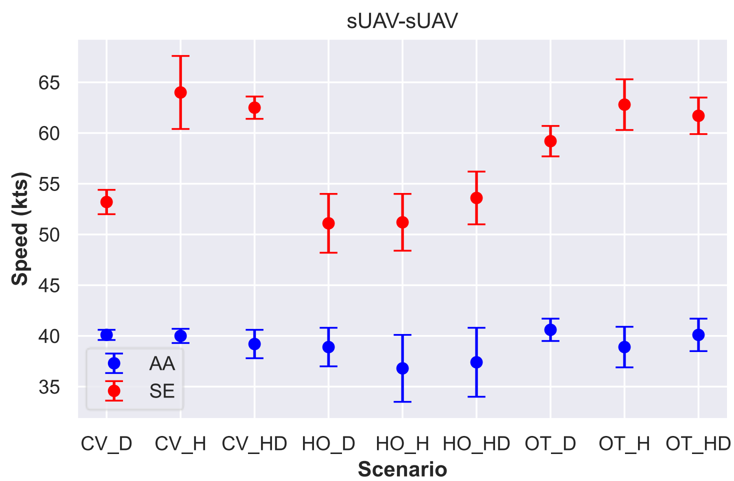


Figure 80. Ground Speed, Round-1, sUAS-sUAS.

The plot in Figure 80. Ground Speed, Round-1, sUAS-s shows the ground speed maintained during the flight testing by two sUASS, the ScanEagle (SE) and the Albatross (AA). Each line represents the mean ground speed achieved in a specific scenario, with vertical error bars indicating the standard deviation derived from repeated flight tests within that scenario. The target ground speed for the SE is 50 knots (± 10 knots), while the target for the Albatross is 35 knots.

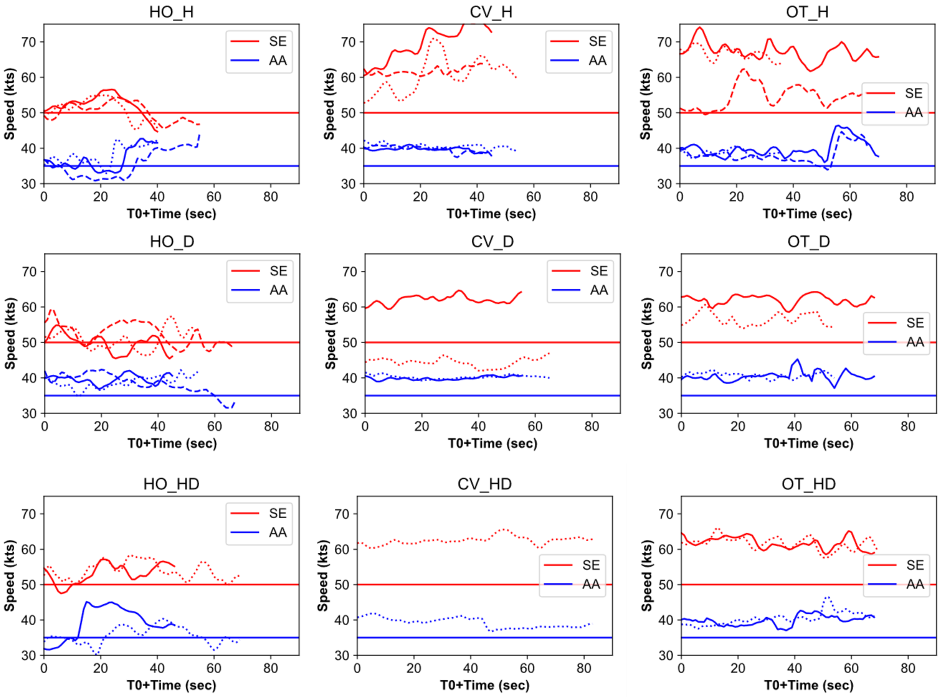


Figure 81. Round-1, sUAS-sUAS, Ground speed data.

Each subplot shown in Figure 81. Round-1, sUAS-sUAS, Ground speed data. depicts the flight profile variations in ground speeds of ScanEagle (red) and Albatross (blue) across repeated flight tests for each scenario, commencing at the on-track time and concluding at the completion maneuver time. The target ground speed for the SE is 50 knots (± 10 knots) (indicated in a solid red horizontal line), while the target for the Albatross is 35 knots (indicated in a solid blue horizontal line).

3.1.1.5 Flight Test Results CA-sUAS

- The avoidance maneuver was successful. The CPA distances and the DAA radius are shown in Figure 82. Round-1, CA-s The maneuvers were efficient, maintaining well-clear distances in all cases.
- The crewed aircraft has the right of way; therefore, ScanEagle UAS underwent all maneuvers in all scenarios.
- No potential collision risk was detected.
- Sensor data integrity and rate were adequate.
- The average turn rate profiles of the ScanEagle UAS and the scenario are shown in Figure . The ScanEagle had an average turn rate of 6.4-11.4 degrees per second.
- The vertical speed profiles of the ScanEagle UAS and the Crewed aircraft for each flight test and scenario are plotted in Figure 83Figure 84. In the 'descent' and 'horizontal and descent' maneuver scenarios, the ScanEagle reached a vertical speed of 264.7-548.2 feet per minute (fpm). The target vertical speed of ScanEagle 500 fpm.
- Vertical speeds varied during descent, showing fluctuations.

- Vertical descent achieved, defined as the vertical distance descended from the original altitude by the time of closest approach, was calculated. The ScanEagle achieved an average vertical descent of 73 feet. The UAS's lower descent is due to its lower-than-target vertical speed.
- The average ground speed profiles of the ScanEagle and Albatross for each flight test and scenario are shown in Figure 87, with averaged values in Figure 86. Environmental conditions made maintaining target ground speeds challenging. The ScanEagle, targeting 50 knots (± 10 knots), averaged ~50.72 knots with a standard deviation of ~7.2 knots. The crewed aircraft, targeting 120 knots, averaged ~92.3 knots with a standard deviation of ~3.3 knots.
- The altitude profiles of the ScanEagle and Crewed Airctaft for each flight test and scenario are plotted inFigure 85. Similar to the sUAS-sUAS scenarios, it was observed that: 1) Significant altitude variation in the horizontal-only scenario where altitude change was unnecessary. 2) During descent, altitude changes were sometimes abrupt, posing a potential risk of well clear violation.
- The average human reaction times for each scenario show that reaction times scenario are presented in **Error! Reference source not found.**. Reaction times ranged from 2.7 to 7.0 seconds, with no specific correlation to maneuvering criteria. Statistically significant data on human reaction times is lacking, but the operator's graphical user interface (GUI) significantly impacted reaction times.
- Figure presents the frequency of CA sighting UAS. Out of 31 instances, the UAS was seen 11 times and not seen 20 times. All the sightings were occurred after sUAS passing the CA.
- Weather data on 03/27/2024, the flight test day, showed wind speeds of 6-27 mph in varying directions, wind gusts are up to 30mph, daytime temperatures between 14-33 degrees Fahrenheit, and pressure of 29.00-29.11 inches of mercury (source: wunderground.com).

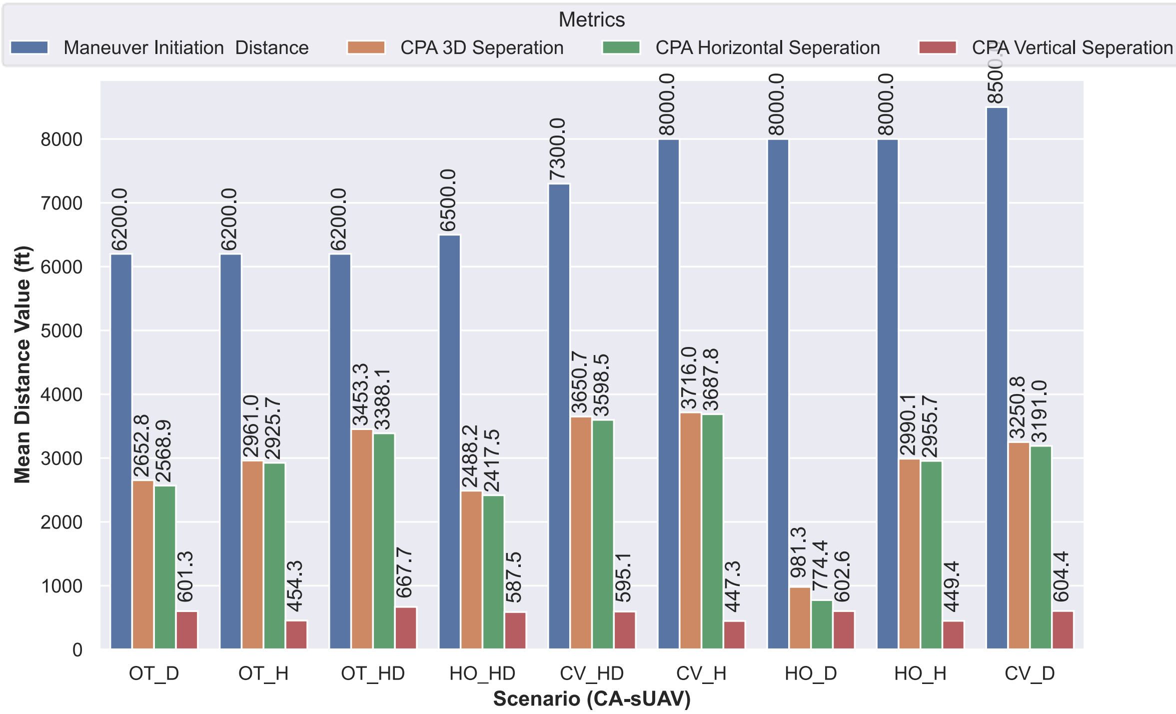


Figure 82. Round-1, CA-sUAS.

The bar plot showin in Figure 82 Figure 82. Round-1, CA-sillustrates the DAA encounter distance, along with 3D, horizontal, and vertical separation distances at the time of the closest approach of the CA and UAS, for various maneuvering scenarios. Each bar represents the average outcome of multiple repeated flight tests within the respective scenario.

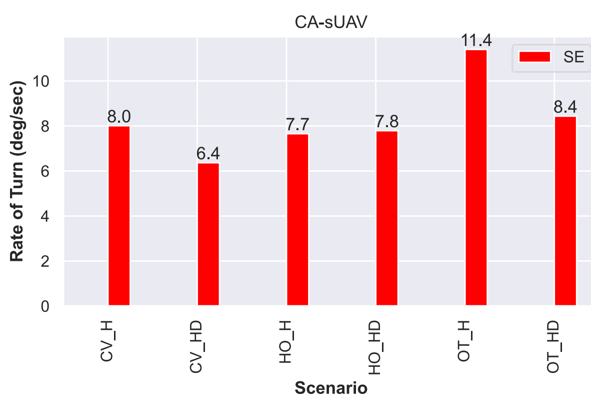


Figure 83. Round-1, CA-sUAS.

The above bar chart Figure 83. Round-1, CA-sillustrates the average ROT performance of ScanEagle(SE) UAS. Each bar represents the average ROT achieved in Round 1 of a specified flight scenario. Note that the 'Descent Only' criterion does not involve a rate of turn maneuver, and thus, no data is presented for this condition.

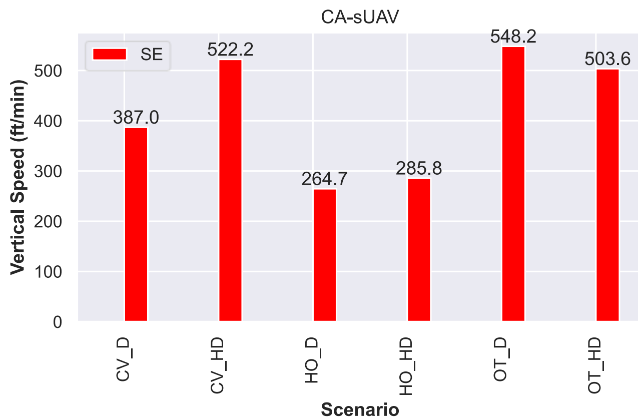


Figure 84. Round-1, CA-sUAS.

This bar chart shown in Figure 84. Round-1, CA-sUAS. illustrates the vertical speed performance ScanEagle(SE). Each bar represents the average vertical speed of a specified flight scenario. Note that the 'Horizontal Only' criterion does not involve a descent maneuver, and thus, no data is presented for this condition.

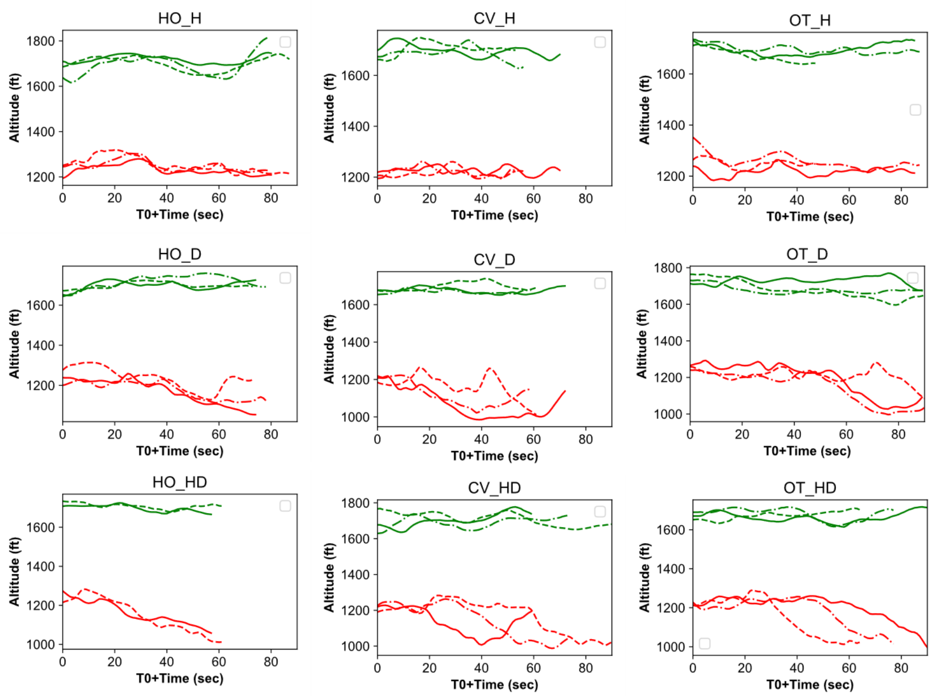


Figure 85. Round-1, CA-sUAS, Altitude data.

Each subplot in Figure 85Figure 85. Round-1, CA-sUAS, Altitude data depicts the flight profile variations in altitude of ScanEagle UAS (red) and Crewed Aircraft (green) across repeated flight tests for each scenario, commencing at the on-track time and concluding at the completion maneuver time.

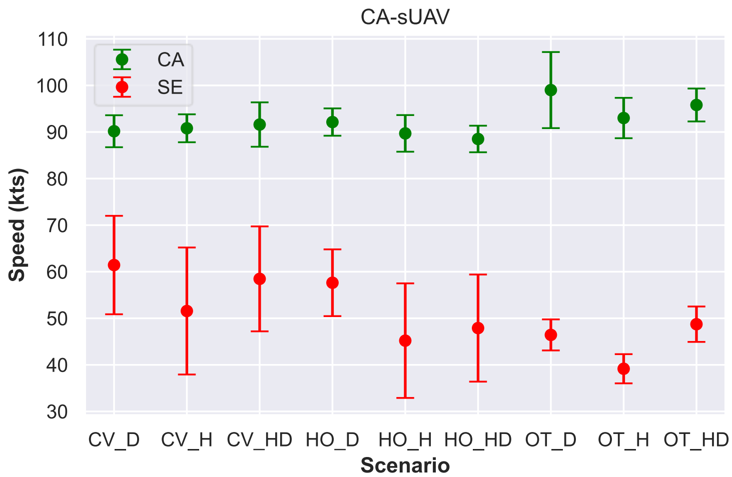


Figure 86. Ground Speed, Round-1, CA-sUAS.

Figure 86Figure 86. Ground Speed, Round-1, CA-s shows the ground speed maintained during the flight testing by CA and the UAS ScanEagle (SE). Each line represents the mean ground speed achieved in a specific scenario, with vertical error bars indicating the standard deviation derived from repeated flight tests within that scenario. The target ground speed for the SE is 50 knots (± 10 knots), while the target for the CA is 120 knots.

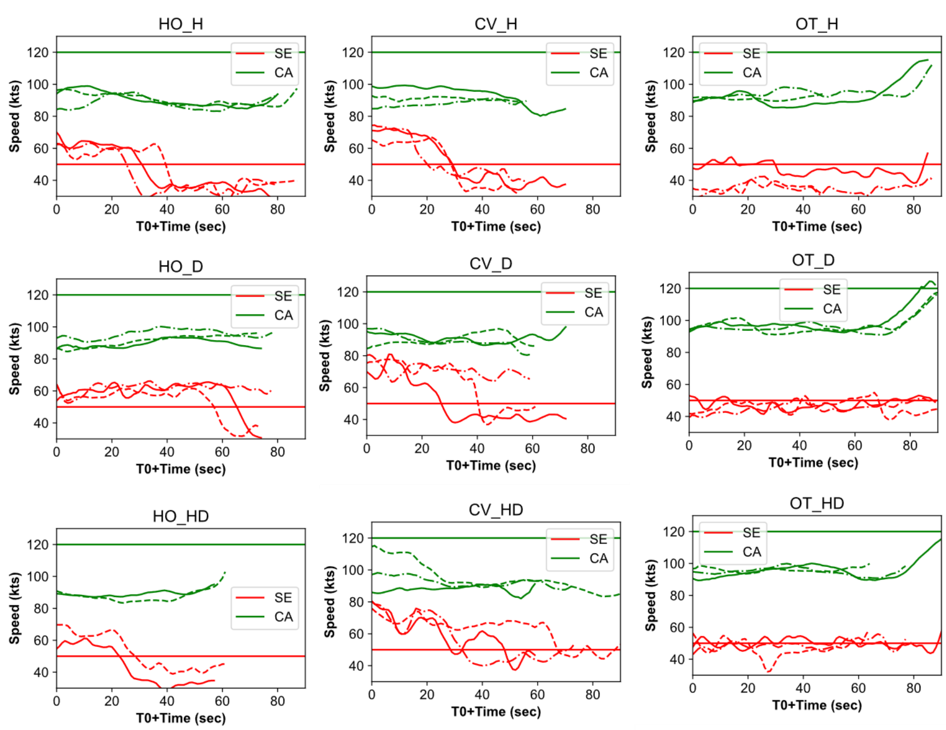


Figure 87. Round-1, CA-sUAS, Ground speed data.

Each subplot in in the above figure Figure 87. Round-1, CA-sUAS, Ground speed datadepicts the flight profile variations in ground speeds of ScanEagle sUAS(red) and CA (green) across repeated flight tests for each scenario, commencing at the on-track time and concluding at the completion maneuver time. The target ground speed for the SE is 50 knots (± 10 knots) (indicated in a solid red horizontal line), while the target for the CA is 120 knots (indicated in a solid green horizontal line).

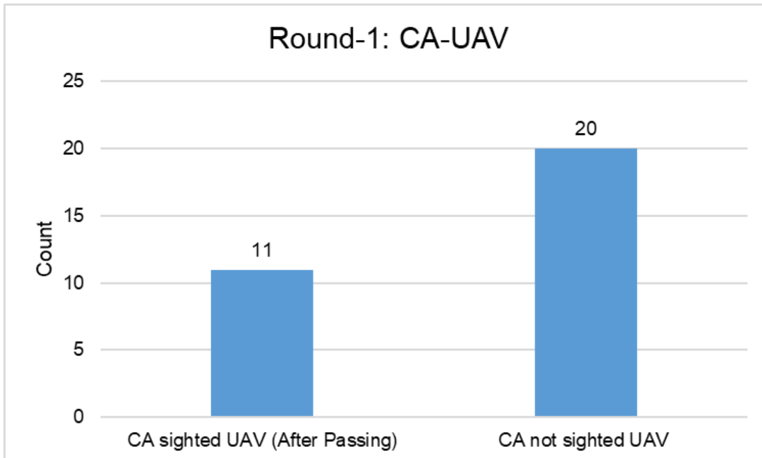


Figure 88. Frequency of CA sighting UAS sightings during Round 1 for CA-sUAS.

3.1.2 Assessment of Flight Test Objectives (UND)

The following discussion is presented to assess the flight test objectives mentioned in Section 3.1

Primary Objectives

Objective: The primary objective of these flight tests is to capture data for safety analysis and to capture encounter parameters (geometries, altitudes, distances, separation, etc.). This data will be analyzed to address FAA knowledge gaps and are intended to support final recommendations on RoW rules.

- Objectives Met:
  - Data Capture for Safety Analysis: The observations indicate successful data capture on encounter parameters, including geometries, altitudes, distances, separation, operator reaction time, conspicuous of sUASs, as well as avoidance maneuvers.
  - Successful Avoidance Maneuvers: The flight test observations indicate that the implemented avoidance maneuver was successful in all cases in Round 1, and with well-clear distances maintained and no potential collision risk observed. In Round 2, while the avoidance maneuver was successful, the maneuvering UAS moved beyond RAC.
  - During flight testing, we identified a variety of unexpected results. These results have been documented and provide insight to further research needed or policy established regarding aircraft maneuverability standards, GUI ergonomics, human reaction time and defining airspeed limitations (i.e. ground speed, IAS, or GPS airspeed).

Objective: Based on Simulations conducted – what existing questions must be validated through flight tests, or new questions need to be answered through flight testing to further advance understanding of General Interactions, Reserved Airspace, and RID as it directly informs the FAA in regard to RoW rules? Answer additional questions that could not be demonstrated during simulations but can be answered during flight tests.

- Round-1 flight tests are designed considering the simulation insights.
- Impact of Environmental Conditions
    - Observation: "The results indicate that maintaining target ground speeds was difficult due to environmental conditions."
    - Unanswered Question (from simulations): How do varying wind speeds and directions affect the ability of UASs to execute precise avoidance maneuvers, especially at different altitudes? How the unpredicted altitude variations in UAS affect the potential for well-clear violation.
    - Observation Helps: Real-world wind can hinder a UAS's speed, affecting avoidance maneuvers. This highlights the need to study wind thresholds and develop adaptive algorithms. Real-world data must be incorporated into simulations to refine models.
- Human-in-the-Loop Performance
    - Observation: "The data shows that operator reaction time varied between 1 second to 7.0 seconds. Additionally, no specific correlation was observed between human reaction time and the maneuvering criteria. It should be noted that statistically significant data is not available to draw conclusive values on human reaction times. However, it was observed that the operator's graphical user interface (GUI) had a significant impact on reaction time."
    - Unanswered Question (from simulations): How does the design of the operator interface influence reaction time and decision-making during critical avoidance maneuvers, and what is the optimal interface design to minimize reaction times? This is a topic of future research.
    - How Observation Helps: This observation directly highlights the need to investigate the GUI's impact on reaction time, a factor not typically accounted for in simulations. It suggests that further research is needed to determine the specific GUI elements that either help or hinder operators and to design interfaces that optimize human performance in real-world scenarios.
- System Performance Limits
    - Observation: "During descent, the sUAS altitude variation was not smooth, sometimes showing a sudden increase, which is undesirable and poses a potential risk of well-clear violation."
    - Unanswered Question (from simulations): How do the UAS's control systems and avoidance algorithms perform under rapid descent maneuvers, and are there any limitations or potential failure modes that could compromise safety?
    - How Observation Helps: Observation indicates a potential issue with the UAS's descent control or interaction between descent and avoidance algorithms. This wasn't easily identified in simulations, highlighting the need for further investigation into the altitude fluctuations and potential refinements to the control systems or algorithms.

Objective: Round 1 (Head-on, Converging, and Overtaking) Objectives. Identify pilot reaction times from reaching pre-determined avoidance distance and initiate the avoidance maneuver specified in the flight test card.

Table 83. Flight Test Results.

Scenario	Averaged Range (min-max) (Sec)	Average (sec)	Standard deviation (sec)
Round-1, sUAS-sUAS	1.0-6.3	4.71	2.57
Round-1, CA-sUAS	2.7-7.0	4.38	2.00
Round-2, sUAS-sUAS	1.0-6.0	2.19	1.72
Combined	1.0-7.0	3.43	2.62

Objective: Determine the best avoidance maneuver for given interactions (head-on, converging, and overtaking encounters).

- Results between simulations and flight tests show significant results. Interpretations within will assist in providing a rationale for proposed RoW rules.

Objective: Identify factors including the type of maneuver (vertical or horizontal) that may delay or inhibit reaction time and distance needed to avoid a RoWV.

- Environmental conditions: Wind speed, gusts
- Visibility of sUAS was difficult.
- GCS does not have proper displays and situational awareness to inform the pilot
- Varied handling characteristics or maneuverability of different sUAS
- Speed
- Rate of closure (or) Net speed: Faster closure rates require quicker reactions; therefore, avoidance maneuvers should consider the speed of both the sUASS when estimating the DAA radius.
- Complexity of the Maneuver
- Predictability of maneuver, whether the pilot is expected to a particular action during testing or must react with no prior knowledge.

Objective: Observe execution of avoidance maneuvers to prevent RoWV by identifying unintended consequences.

- Secondary Conflicts: The maneuver itself might, by mistake, put the UAS in a position where it violates the RoW of another aircraft that was not initially a threat.
- Deviation from Flight Path: The new maneuvers might force a UAS to deviate significantly from its intended flight path, causing delays.
- Safety Risk: The maneuvering UAS might enter unintended operational areas, endangering people and property on the ground.
- Aircraft Handling Characteristics – Crewed aircraft under instrument rules turn at ROT of 3 degrees per second. sUAS turn at a variety of speeds, bank angles and consquently ROT as well. The Remote Pilot in Command (RPIC) may be unaware of how fast or slow a turn may take to avoid another aircraft. Airspeeds and Altitudes of aircraft also varied depending on other factors, such as wind gusts and thermals causing updrafts over portions of the flight.

Objective: Validate/identify detection distances that affect deconfliction.

- The detection distances were calculated based on simulations that included an additional safety buffer. It was observed that deconfliction was mostly successful in all cases during Round 1, and successful in head-on and descent scenarios during Round 2. However, it should be noted that a few *potential* well-clear violation instances were identified due to uncertainties in altitudes and speeds, which were influenced by wind speed and turbulence (*Only potential, well clear violation was not observed*). Additionally, during vertical descents, the sUASs did not achieve the target vertical speeds. This suggests a need to refine the detection range based on the actual descent rates of the sUASs.

Objective: Determine if larger UAS detection distances are required due to lower maneuverability.

- Yes, during vertical descent, the sUASs are not achieving the desired speeds. Therefore, the vertical descent procedure needs to be re-evaluated with realistic vertical speeds, taking into account the effects of environmental conditions.

Objective: Determine if rule changes are needed in these encounters for an intruder not altering course.

- Determination of rule changes will be described in the final report. The data shows that if an intruder is unable to or choses not to alter course greater distances must be anticipated for the other aircraft to successfully avoid the other aircraft.

3.1.3 Single and Multiple sUAS vs Crewed (KU)

Initial flight tests for Round 1 were accomplished on 8 Nov 2023. During these flights, the sUAS avoided the Cessna in head-on encounters, but did not complete the maneuver due to the size of the flight test area, as expected.

Once it was determined that Round 2.1 encounters were actually the same as Round 1, all further head-on, converging and overtaking encounters were conducted in the Round 2.1 campaign. Therefore, all successful General Interactions encounters are reported in the Round 2.1 section.

3.1.4 Helicopter vs sUAS (ERAU)

This section reports on Round 1 General Interactions. Embry-Riddle Aeronautical University-Worldwide Campus, Department of Flight, conducted the Round 1 A54 flight tests at F75, Harrison Field of Knox City Texas on 6-7 February 2024. For context, please refer to Figure below.

<u>ERAU Flight Test Encounter General Information</u>

- There are three rounds of testing
  - Round 1 is fixed wing sUAS vs. Crewed Aircraft (helicopter) in General Encounters (Head-on, Converging, and Overtaking)
  - Round 2 is sUAS vs. Crewed Aircraft where the sUAS is confined to avoid within a notionally reserved block of airspace
  - Round 3 is sUAS vs. sUAS in Head-on and Converging encounters.
- All Round 1 and 2 tests were run using Robinson R-44 Helicopter and an Applied Aeronautics Albatross Fixed Wing (FW) UAS.

- All Round 3 tests were run using the Applied Aeronautics Albatross FW UAS and the DJI Matrice M300RTK.
- Test runs were designed using initial simulation recommendations.
- Each test intended to include three types of encounters; Head-on, Converging, and Overtaking. Head-on and Overtaking were combined as the reactions would be the same.
- Each type of encounter included the UA avoiding a helicopter upon contact confirmation / by specified distances with three runs avoiding horizontally (turning right) and three runs avoiding with a descent.
- UA remains WC with the volume at 2000’ horizontally and 250’ vertically.
- Flight altitudes were designed to place both UA and Helicopter by at least a 540’ distance if passing each other with no maneuver.

Test personnel included;

Dr. Scott Burgess, Flight Director, LRS (runway) RPIC, recovery pilot, lead researcher.
Dr. David Thirtyacre, GCS autonomous RPIC, data collector.
Mr. Ryan Johnston, Applied Aeronautics CEO, Lead Pilot, data collector and processor.
Mr. Rudy Johnson, Sagetech Avionics, Sales Team, acted as Visual Observer when not attempting to configure ACAS/MXS.
Mr. Kevin Curry, Cedar Ridge Aviation, Helicopter PIC.

Test aircraft

Crewed aircraft: 1997 Robinson R-44
Uncrewed aircraft: 2023 Applied Aeronautics Albatross

Aviation Surveillance Equipment

Crewed Aircraft:	UASionix Ping 2020i ADS-B In/Out Sagetech ACAS X (ADS-B Out) Demonstrator (non-functional)
Uncrewed Aircraft:	UASionix pingRX Pro ADS-B In Iris Automation Casia Computer Vision (semi-functional) SSagetech MXS-SXU DAA system (non-functional)

Note: As a caveat to this test, the Sagetech MXS-SXU had never consistently or reliably worked throughout the 18-month integration period. On the week of this test, Sagetech sent a technician to help with both the MXS-SXU and an (ADS-B Out) ACAS X Demonstrator. Neither were successfully operational. For redundancy, the UASionix ADS-B system was acquired and installed and partially successful in use on the helicopter. The helicopter ADS-B data was accurate when the aircraft was inbound toward the encounter area, however, the accuracy of the time stamps could not be considered in the analysis.

Ground Control Station (sUAS)

- 20’ enclosed trailer as hardened Ground Control Station.
- Dell 5430 Latitude Rugged to run the Sagetech UI.
- 1 x monitor for the Applied Aeronautics Ground Station (AAGS) software (uses QGC as backbone).
- AAGS (run by MacBook Pro).

- 1 x GoPro Hero 8 wall mounted
- 1 x iCom IC-T10 handheld VHF Transceiver
- 1 x Kestrel 5000 Anemometer (tripod mounted)
- 4 x Wireless VOX headsets

Test Location. Harrison Field of Knox City, Texas. Airport Identifier F75.

Test Area Run Configurations. The team designed three test area configurations based upon typical commercial sUAS mission sets. Our goal was to design configurations that could support as many encounter geometries as possible.

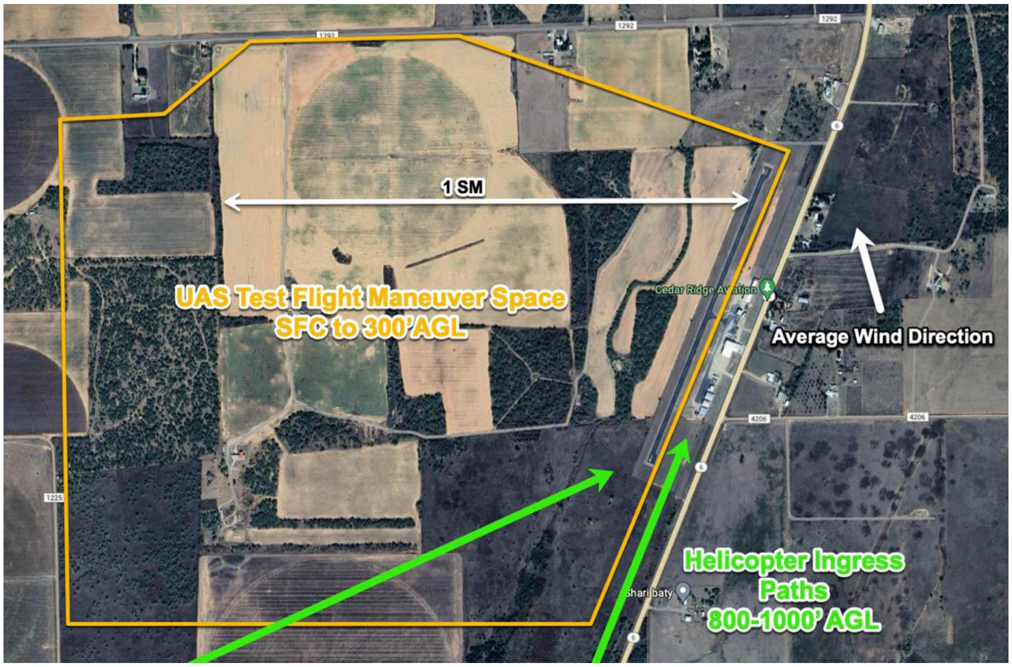


Figure 89. Flight Test Area.

To maintain organizational aviation safety -standards, FAR Part 107.39 (flight over people), and noise abatement considerations (helicopter), and emergency recovery tasks, this test area configuration provided the best total performance.

General Factors Involved in Test and Data Collection

- Flight Test Area:
  - Test parameters (500’ vertical and 500’ horizontal separation between UAS and Helicopter) were established to maintain safe separation.
  - Figure identifies boundaries of areas for safe flight testing which relegated test flight directions to occur as shown in Appendix A.
- Environmental: The sky was clear and visibility beyond 10 miles. Winds were generally from the south at around 20kts at 300AGL’.
  - This affected reaction times and the ability to remain well clear. With the wind approximately 50% of the drone's airspeed, the maneuver timing and distance were significantly different than planned. This needs to be considered when developing automated AMs and should be planned for worst case.

- Regulatory: Adherence to FAR 107.39 (flight over humans) and helicopter noise abatement considerations in this area required the test area maneuvering to occur only to the west of the airfield.
- DAA Equipment: DAA equipment (Casia and Sagetech) was used for the express purpose of maintaining safe separation for the flight tests and not to test and recommend as DAA required equipment. Based upon the Iris and Sagetech system's inability to provide consistent (or any) data, the team additionally focused on the Human Factors elements to address the test objectives.
    - ADS-B Out used in Helicopter was a bundle configured for testing only and affixed to the dashboard, powered with a 3000mAh, 3.3WH battery. No external antenna was fixed to the bundle. When the helicopter was facing away from the test area, the signal was intermittent but as the helicopter faced the test area, the ADSB signal was received.
    - Iris Automation, Casia Computer Vision System: The system was not consistently functional. Additionally, as the velocity of the drone was so much less than the helicopter (especially with wind conditions), the drone could be hit from any direction (e.g., overtaking, beam, converging). Only having a forward looking system is a huge limitation and doesn't account for the majority of collision scenarios.
    - Sagetech Avionics: ACAS/MXS equipment never functioned (on the Albatross or the helicopter). The team acquired a backup system, a UASionics Ping 2020i ADS-B In/Out, which was employed to determine range and trigger planned avoidance maneuvers. The team wasted valuable time (with the company technician) and were unable to make the Sagetech system functional.
- Cockpit recording: The GCS (trailer) had a wall mounted GoPro camera to observe RPIC actions on contact during encounter profiles. This helped to identify pilot reaction times when the RPIC made decisions to maneuver to avoid the oncoming helicopter.

Round 1 objective as given in section 3.1
All objectives were followed. Through simulation, Table 84 identifies avoidance distances to remain well clear based upon the flight parameters identified in Figure .

The distances shown in Table 84. Avoidance Distances to Maintain Well Clear4 were derived from over 16,000 simulation runs using the craft airspeeds identified in Figure . Following FAR 107.51, it was determined to conduct vertical avoidance maneuvers of only a 100' descent to maintain flight safety.

Table 84. Avoidance Distances to Maintain Well Clear.

Horizontal Avoidance	
Scenario	Planned Maneuver Initiation Distance
Head-on Norm Horizontal Violations	7900'
Converging Norm Horizontal Violations	3000'
Overtaking Norm Horizontal Violations	7200'

Vertical Avoidance	
Scenario	Planned Maneuver Initiation Distance
Head-on Norm Vertical Violations	9300’
Converging Norm Vertical Violations	6500’
Overtaking Norm Vertical Violations	5800

Round 1 Objectives Assessment

Identify pilot reaction times from reaching pre-determined avoidance distance and initiate the avoidance maneuver specified in the flight test card. Data collection was captured using a GoPro mounted above and behind the RPIC, and screen recording of AAGS on the MacBook Pro.

Avoidance Maneuvers (AMs) were conducted from autonomous flight. The backbone flight control software behind AAGS is QGroundControl (QGC). QGC (like several available software) has a sequence for avoidance maneuvering steps when in autonomous flight described below. Throughout available commercial off-the-shelf platforms, many are step-based selection/ confirmation avoidance maneuvers, while the more expensive Department of Defense systems are the ‘click and go’ steps. Therefore, reaction times would vary based upon the systems used, the pilot, and environmental conditions.

In this test, RPIC reaction times (decision to avoid to first actual movement of the aircraft) were an average of 5.15 seconds. Observation of RPIC actions show that when a decision to conduct an avoidance maneuver was made, an RPIC verbal command to the crew was followed by a new waypoint selection on the map (instigating a command prompt shown on left pane below) followed by an execution prompt (slide bar shown on right pane below). Upon execution of the command there was an approximate delay of 1-2 seconds before the aircraft began the maneuver commanded.

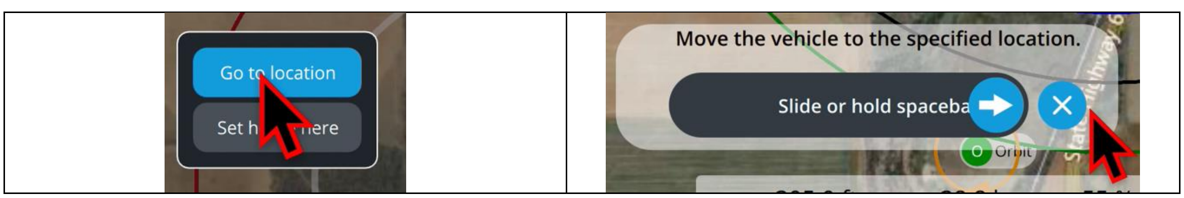


Figure 90. AAGS Pilot GUI for Avoidance Maneuvering.

Data on avoidance maneuvers were extracted from the 6 February screen recording of the AAGS software. There were in excess of 45 total AMs. Approximately 10 maneuvers were not used due to the RPIC pre-selecting the command, then delaying its execution. In some cases, these delays exceeded 10-15 seconds. Data was tallied for only the maneuvers that were sequential steps without delay. These data included 38 avoidance maneuvers and totaled 165 seconds of delay between decision to avoid and aircraft avoidance maneuver movement. In the AAGS software, there is slight delay (approx. 1-2 sec) from the time the turn command is completed and the aircraft appears to begin turning in the GUI. Overall, this yielded an average of 5.15 seconds from the time the RPIC decision was made until the aircraft began maneuvering.

The RPIC, when able, initiated an application of ‘pre-planning’ or ‘pre-loading’ an avoidance maneuver as a crew action in preparation for possible emergency actions (controlled crash landing, avoidance of potential airborne threats, or obstacle avoidance). This is accomplished by selecting a spot on the map (within the AAGS GUI) that is perpendicular to a potential airborne threat. While the RPIC knew the intruder vector ahead of time in this test, in a normal operation, the DAA equipment would potentially forecast the avoidance maneuver requirement, thus enabling the RPIC to pre-load the avoidance direction. This logic coincides with aviation doctrine of being ahead of the aircraft and prepared to conduct avoidance maneuvering for safe separation.

Avoidance maneuvering directions were an in-flight decision by the RPIC in each case. While it was intended to coincide with the test-card, and mostly did, at times when winds or approach vectors dictated a slightly different maneuver. In each case, the test runs were flown safely and remained within the flight test area boundaries.

Determine the best avoidance maneuver for given interactions (head-on, converging, and overtaking encounters).

- Identify factors including the type of maneuver (vertical or horizontal) that may delay or inhibit reaction time and distance needed to avoid a RoWV.

In over 32 iterations of six scenarios, the reaction time averaged approximately 5.15 seconds (refer to Error! Reference source not found. for context):

Head-on encounters – Either left or right turns (depending upon intruder aspect angle) were found most functional and safe. Test factors included maintaining FAR 107.39 and having to turn right (to avoid flight over people), right turn (adhering to FAR 107.37), no terrain or manmade obstacles to the right, as such, a right turn avoidance maneuver performed exceptionally well. However, this highlights the importance of a preflight survey and studying the flight location to increase situational awareness and allow quick contingency decisions.
Note: Vertical AMs were found to require more reaction time to conduct, and altitude limitations were not going to allow for safe separation. Additionally, given the limited altitude for UAS (i.e., 400ft AGL) an altitude avoidance maneuver may increase risk with only marginal avoidance results.

Factors that affect the best avoidance maneuver for this interaction.

- Winds at altitude for the UAS.
- Maneuvers must be preplanned whether manually initiated or automatically executed. In other words, the "correct" maneuver and timing needs to be continually updated based on the situation. What might have been a 90° right turn a few seconds ago, may be a left 135° later based on the other aircrafts heading/maneuvers.
- AMs should also include an altitude change when sufficient altitude exists (which may be possible where an altitude waiver is in place). The flight path of the helicopter is assumed to be constant (as was in this test). When the helicopter changes direction

or altitude, the horizontal avoidance maneuver may not be enough. Altitude away from the helicopter (typically a descent) should accompany a horizontal avoidance maneuver to ensure separation should the helicopter change course.

- UAS flight control software flexibility (ease of changing course immediately during an autonomous flight).
- UAS GUI Situational Awareness (SA) of intruder through DAA equipment interface.
  - ADS-B In interface was exceptional but sometimes intermittent at distances > 1.5 miles or when the helicopter was pointed away from test area (ADS-B Out located on dashboard in cockpit). However, when the helicopter was flying toward the test area, the traffic symbology of the intruder was constantly visible (by visual observers) out to 2.3 miles , and thus it greatly improved SA. Of note was that when combined with the Collision Avoidance Distance Rings (CADR) below, crew SA was significantly enhanced.
  - Computer Vision Sensor System (CVSS). Warnings from the CVSS came as notifications and required access to a separate page by the RPIC and would delay reaction for avoidance by approximately 5 seconds. Additionally, the CVSS forward facing horizontal field of view is 80°, and vertically is 50°. Reliability of intruder data was not 100% accurate. There are no intruder traffic symbols presented on the GCS GUI with this system.
  - CADR. Applied Aeronautics created distance rings that greatly enhanced UAS crew SA. These were variegated at standard short-range distances of 2k’, 2.5k’, 3k’, 3.5k’, and test specific distances (Figure 91). In every case, they became a visual reference to initiating a turn to avoid the well clear horizontal volume. The CADR and the ADS-B In traffic symbol combined were exceptional collision avoidance references. These also were beneficial when head or tail winds were experienced at altitude. Without the addition of CADR, range to the helicopter would be difficult to ascertain.

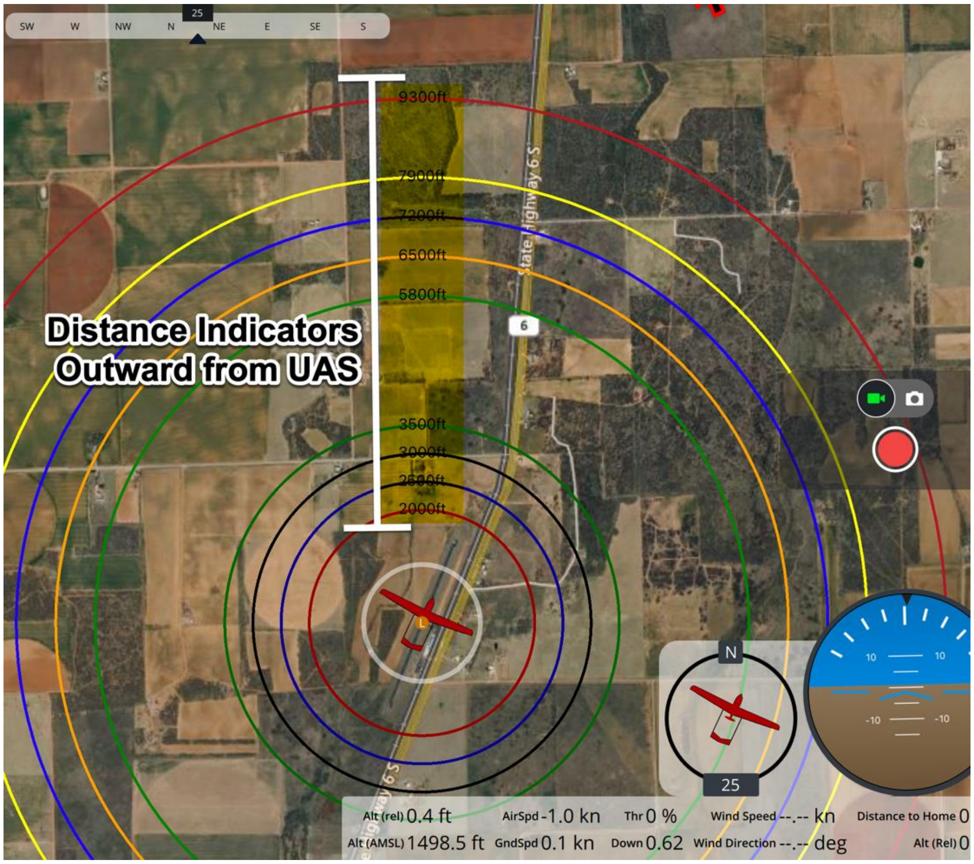


Figure 91. Collision Avoidance Distance Rings (CADR).

In Figure 91. Collision Avoidance Distance Rings (CADR) the distances were derived to reflect basic distances for safety and at AM distances to enhance SA and maintain safe clearances for this test. This was determined necessary by the flight director after 12 months of delay were experienced on the ACAS/MXS integration and redundancy was deemed important. These are not a part of the normal GUI for this aircraft. Applied Aeronautics was committed to our successful testing as a vital partner.

Converging encounters - Turns away from intruders (left or right) to avoid faster rates of closure are best. Due to the converging aspect angle of our test the encounter was always with the intruder (helicopter) approaching from the right. This aspect requires UAS adherence to 107.37 and maneuver left as to turn right would place the encounter in a more dangerous aspect. In this case, a left turn was used in all cases, and initiation distances from simulation were proven effective in maintaining well clear.

Factors that affect the best avoidance maneuver for this interaction.

- Winds at altitude for the UAS.
- Maneuvers must be preplanned whether manually initiated or automatically executed. In other words, the "correct" maneuver and timing needs to be continually updated based on the situation. What might have been a 90° right turn a few seconds ago, may be a left 135° later based on the other aircrafts heading/maneuvers.

- AMs should also include an altitude change when sufficient altitude exists. The flight path of the helicopter is assumed to be constant (like how we did it). When the helicopter changes direction or altitude, the horizontal avoidance maneuver may not be enough. Altitude away from the helicopter (typically a descent) should accompany a horizontal avoidance maneuver to ensure separation should the helicopter change course.
- UAS flight control software flexibility (ease of changing course immediately during an autonomous flight).
- UAS GUI SA of intruder through DAA equipment interface.
    - ADS-B In interface was exceptional but sometimes intermittent at distances > 1.5 miles or when the helicopter was pointed away from test area (ADS-B Out located on dashboard in cockpit). However, when the helicopter was flying toward the test area, the traffic symbology of the intruder was constantly visible (by visual observers) out to 2.3 miles , and thus it greatly improved SA. Of note was that when combined with the CADR below, crew SA was significantly enhanced.
    - Computer Vision Sensor System (CVSS). Warnings from the CVSS came as notifications and required access to a separate page by the RPIC and would delay reaction for avoidance by approximately 5 seconds. Additionally, the CVSS forward facing horizontal field of view is 80°, and vertically is 50°. Reliability of intruder data was not 100% accurate. There are no intruder traffic symbols presented on the GCS GUI with this system.
    - Collision Avoidance Distance Rings (CADR) (Figure 91). Applied Aeronautics created distance rings that greatly enhanced UAS crew SA. These were variegated at standard short-range distances of 2k', 2.5k', 3k', 3.5k', and test specific distances (Table 84). In every case, they became a visual reference to initiating a turn to avoid the well clear horizontal volume. The CADR and the ADS-B In traffic symbol combined were exceptional collision avoidance references. These also were beneficial when head or tail winds were experienced at altitude. Without the addition of CADR, range to the helicopter would be difficult to ascertain.

Overtaking encounters – Turns away from intruders to avoid faster rates of closure are best. Turning right was not performed due to FAR 107.39 (flight over people), and the UAS was being overtaken by the faster helicopter from the right. This aspect also requires the UAS to adhere to FAR 107.37 (RoW yield) with a need to turn left away (left) from an impending encounter thus avoiding a more dangerous aspect because if the helicopter pilot did see the drone prior to a possible impact, the reaction to avoid by the helicopter could potentially place that aircraft in a dangerous and unusual attitude. In this test, a left turn was used in all cases as it was a maneuver away from a passing intruder. AM initiation distances from simulation were proven effective in maintaining well clear.

Factors that affect the best avoidance maneuver for this interaction.

- Winds at altitude for the UAS.

- Maneuvers must be preplanned whether manually initiated or automatically executed. In other words, the "correct" maneuver and timing needs to be continually updated based on the situation. What might have been a 90° right turn a few seconds ago, may be a left 135° later based on the other aircrafts heading/maneuvers.
- Avoidance maneuvers should also include an altitude change when sufficient altitude exists. The flight path of the helicopter is assumed to be constant (like how we did it). When the helicopter changes direction or altitude, the horizontal AM may not be enough. Altitude away from the helicopter (typically a descent) should accompany a horizontal AM to ensure separation should the helicopter change course.
- UAS flight control software flexibility (ease of changing course immediately during an autonomous flight).
- UAS GUI SA of intruder through DAA equipment interface.
    - ADS-B In interface was exceptional but sometimes intermittent at distances > 1.5 miles or when helicopter was pointed away from test area (ADS-B Out located on dashboard in cockpit). However, when the helicopter was flying toward the test AM area, the traffic symbology of the intruder was visible out to 2.3 miles consistently, and thus it greatly improved SA. Of note was that when combined with the CADR below, crew SA was significantly enhanced.
    - Warnings from the CVSS only occurred after the helicopter overtook the UAS since the CVSS forward facing horizontal field of view is 80° and vertical is 50°. Each encounter occurred with the intruder approaching the UAS from the four to five o'clock orientation from the right rear of the UAS Heading. Therefore, the CVSS did not provide any reliable avoidance warning for overtaking encounters. There are no intruder traffic symbols presented on the GCS GUI with this system.
    - Collision Avoidance Distance Rings (CADR). The distance rings (created Applied Aeronautics) greatly enhanced UAS crew SA. These variegated distance rings became a visual reference to initiating a turn to avoid the well clear horizontal volume. The CADR and the ADS-B In traffic symbol combined were exceptional collision avoidance references. These also were beneficial when winds at altitude were experienced.

Observe execution of avoidance maneuvers to prevent RoWV by identifying unintended consequences.

- Validate/identify detection distances that affect deconfliction.
    - Detection distances were identified in Task 3 simulation and validated in testing. The combination of ADS-B In and the CADR became instrumental in positively affecting deconfliction and possibly enhancing pilot avoidance reaction times.
- Determine if larger UAS detection distances are required due to lower maneuverability.
    - Headwinds at altitude for head-on and some in converging were consistently around 20kts and this caused extended reaction time to the UAS crew (see Figure 91).
    - Tailwind conditions created the need to initiate slightly prior to avoidance distances established from simulation.

- Testing found that maneuvers must be preplanned whether manually initiated or automatically executed. In other words, the "correct" maneuver and timing needs to be continually updated based on the situation. What might have been a 90° right turn a few seconds ago, may be a left 135° later based on the other aircrafts heading/maneuvers.

o Determine if rule changes are needed in these encounters for an intruder not altering course.

- All encounter testing indicated that AMs away from crewed aircraft per current doctrine and regulation were able to be followed. RPIC actions to avoid were found to be easier to accomplish with practice and in the notion that the UAS Crew specifically identified a direction to give way based upon intruder convergence vectors, distances, winds, and ground speeds as what is the most expeditious action.
- ADS-B In capability was found beneficial to RPIC actions upon encountering an intruder.
- The addition of the CADR in this test when combined with ADBS-In provided provide the best RoWV combination.

NOTE: It is understood that in establishing RoW rules, the researchers must assume detection methods are available (likely DAA systems). Therefore, while neither testing of visual conspicuity of sUAS while in a crewed aircraft nor testing of DAA equipment effectiveness is the focus of this research, it does provide an opportunity for ancillary knowledge related to RoW.

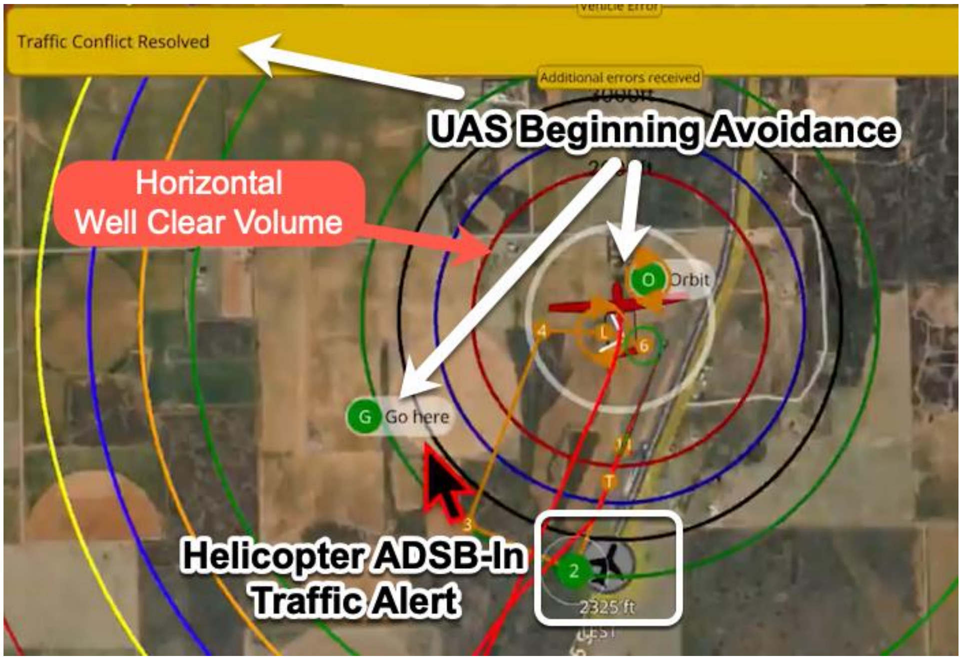


Figure 92. UAS DAA equipment graphic interface with CADR, ADS-B.

Sub-objectives and results to the flight testing include:

- During RoW testing, identify detection distance for observer in crewed aircraft to see various UAS. Use telemetry and recorded data to determine actual distances. Note, many variables affect conspicuity such as various environmental conditions, aircraft configurations, and time of day. Weather data will also be collected to identify any commonalities between various flight-testing scenarios.
  - Due to availability of additional observer in helicopter (1/3rd of the flights had an observer), the conspicuity results were limited to a handful of flights. As predicted in preparatory meetings (Team and TIM), either the pilot or observer became situationally aware the moment they were asked to look for the UAS. Additionally, their view became 'trained' and value to this aspect of the research could be considered diminished accordingly.
  - The weather did not appear to reduce conspicuity of the UAS.
  - Ground vegetation near F75 at this time were seasonal, and are medium to light tan grasses, dark mesquite leafless trees, and dark green cedar. Much of this contrasts well to the gleaming white Albatross from above.
  - Structural masking in the helicopter cockpit can also detract from an ability to view the UAS below.
  - In a head-on (co-altitude) encounter, the Albatross, which has an extremely low visibility profile and would likely not be seen until just prior to impact.
  - Clearly, the ADS-B In performance provided the best SA in identifying distances to the intruder. Additionally, the team, conceived of and Applied Aeronautics developed, additional user interface in the form of range rings to help the RPIC in decision making to begin AMs. These were called Collision Avoidance Distance Rings (CADR) which are detailed below. The CADR in conjunction with ADS-B In, greatly enhanced distance detection. The Computer vision performance did not provide detection distance resolution, only intermittent warnings.

- Identify if the UAS DAA equipment graphic user interface can be used to help prevent a RoWV by identifying aircraft and determining distance remaining between UAS and crewed aircraft.
    - Utilization of multiple UAS DAA systems was intended to provide redundancy and improved reaction time for avoidance maneuvering as well as safe separation for aviation safety. The intent in this test was to utilize the DAA equipment discussed above (specifically Iris and Sagetech components) for safe separation as the primary task, and for SA to assist in prevention of an RoWV. The GCS ADS-B GUI in conjunction with the CADR provided the best SA and ability to predict conflicts and sense and avoid. It was found that multiple GUI indications yielded far superior airspace intelligence/air picture regarding intruders.
    - Figure 93 shows both ADS-B In and CADR graphic interfaces working together for SA. This combination worked exceptionally well with 100% accuracy, in prevention of a RoWV.

Flight Test Run Profiles

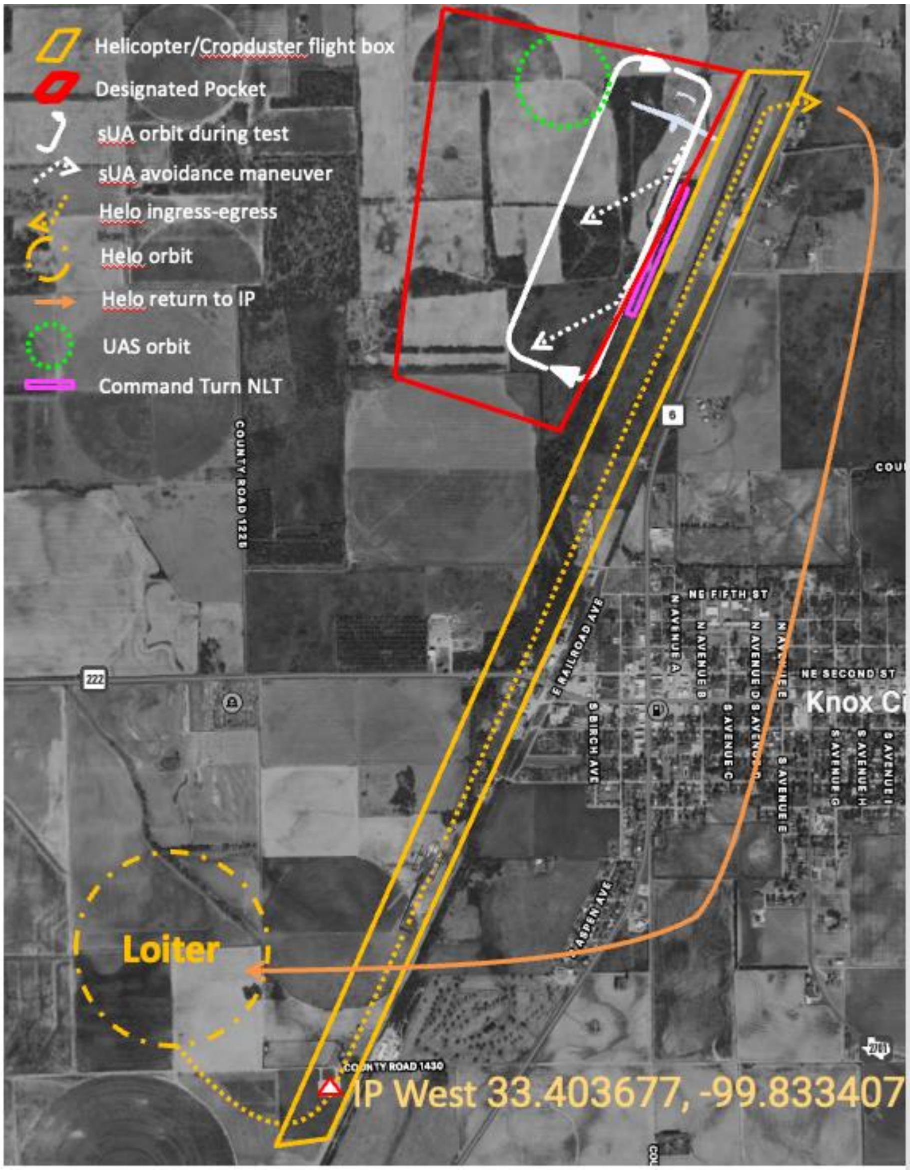


Figure 93. Head-On Encounter.

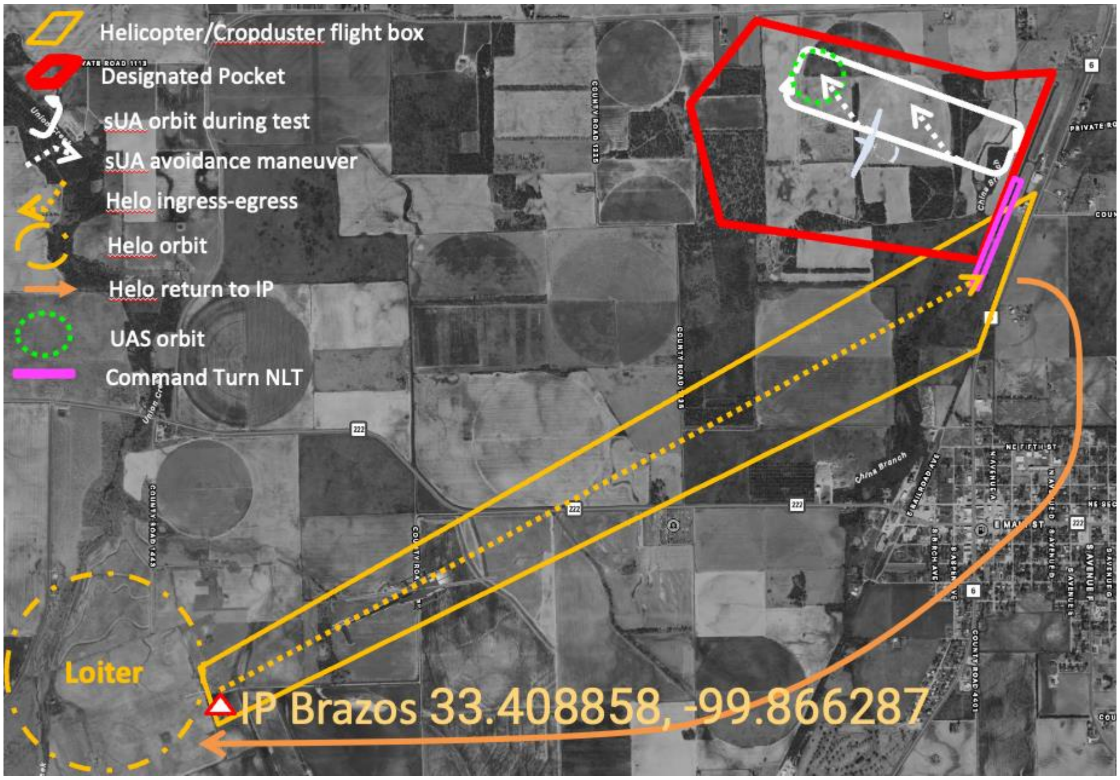


Figure 94. Converging Encounter.

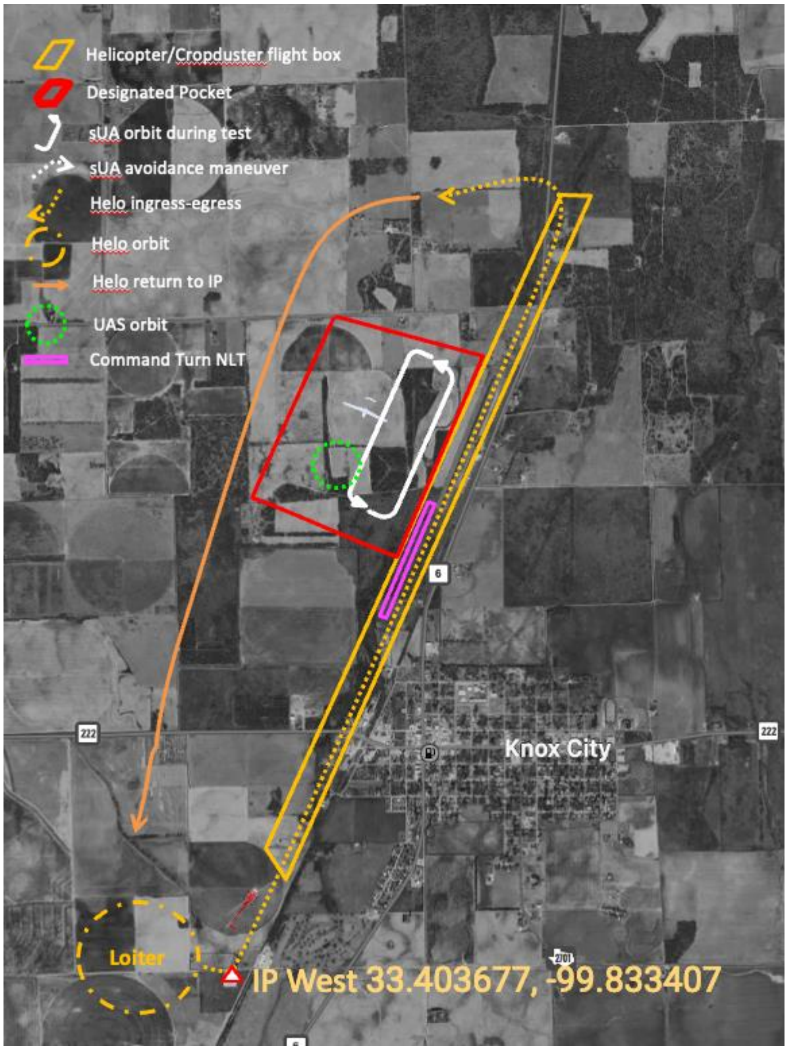


Figure 95. Overtaking Encounter.

3.2 Reserved Airspace Concept

3.2.1 sUAS vs sUAS Maneuevring Criteria (UND)

For Round-2, sUAS vs sUAS, the RoW flight test approach includes Head-On, Convergent, and Overtaking scenarios. For each scenario, the objective is to test horizontal avoidance, vertical avoidance, and a combined horizontal and vertical avoidance. Table 855 provides the abbreviations and maneuver initiation distances. The sUAS-sUAS flight tests were conducted using various initiation distances, carefully determined based on the results obtained from simulations.

Table 85. Abbreviations and maneuver initiation distances for Round-2, sUAS vs sUAS in RAC.

Encounters	**Objective**	**Abbreviation**	**Maneuver Initiation Distance (ft)**	**Maneuvering UAS***
Head-On	Horizontal avoidance	HO_H	1800	Bravo banks right upon identification of Alpha
	Vertical avoidance	HO_D	2000	Bravo descends upon identification of Alpha
	Combined Horizontal/Vertical avoidance	HO_HD	1800	Bravo descends and turns right upon identification of Alpha.
Convergent	Horizontal avoidance	CV_H	1800	Bravo banks right upon identification of Alpha
	Vertical avoidance	CV_D	2600	Bravo descends upon identification of Alpha
	Combined Horizontal/Vertical avoidance	CV_HD	1800	Bravo descends and turns right upon identification of Alpha.
Overtaking	Horizontal avoidance	OT_H	1000	Alpha side steps to right upon identification of Bravo.
	Vertical avoidance	OT_D	1500	Bravo descends upon identification of Alpha.
	Combined Horizontal/Vertical avoidance	OT_HD	1000	Bravo descends AND turns left upon identification of Alpha.

*The two sUASs are ScanEagles, Callsign Alpha, and Callsign Bravo were used.

3.2.1.1 Flight test results - sUAS vs sUAS (UND)

- The implemented avoidance maneuver was successful. The CPA distances during the maneuver, along with the DAA radius, are presented in Figure 97. In all cases, the maneuvering was efficient, and well-clear distances were maintained.
- The flight paths were monitored during avoidance to check if the sUAS was breaching the RAC (see Figure 96). It was observed that most of the time, during overtaking maneuvers, the sUAS violated the RAC boundary.
- No potential collision risk was observed.
- Sensor data integrity and rate were sufficient.
- The average turn rate profile for Alpha and Bravo for each flight test and scenario is plotted in Figure 98. The average turn rate for Bravo varied between 7.9 to 14.8 degrees per second, while Alpha displayed 10.8 degrees per second.
- The vertical speed profile for ScanEagles Alpha and Bravo for each flight test and scenario is plotted in Figure 99. During the 'descent' and 'horizontal and descent' maneuver scenarios, the UASs approached an average vertical speed of 138-408.5 feet per minute (fpm). These vertical speeds are significantly less than the target vertical speed for both UASs (500 fpm).
- Vertical speeds were not constant throughout the descent, exhibiting fluctuations.
- The average ground speed profile for ScanEagles Alpha and Bravo for each flight test and scenario is plotted in Figure 101, with averaged values presented in Figure 100. The results indicate that maintaining target ground speeds was difficult due to environmental conditions. The target ground speed for Bravo varied as 50, 60 and 70 kts, while the target for Alpha was 50 knots. Alpha maintained a mean value of 42.2 knots and a standard deviation of 6 knots. Bravo had a mean value of 42.6 knots and a standard deviation of 9.3 knots (Headon and convergent).
- The altitude profile for ScanEagles Alpha and Bravo for each flight test and scenario is plotted in Figure 102, Two observations were made: 1) In the horizontal-only scenario, where altitude variation was not necessary for maneuvering, there was significant variation in maintaining altitude. 2) During descent, the sUAS altitude variation was not smooth, sometimes showing a sudden increase, which is undesirable and poses a potential risk of well-clear violation.
- The average human reaction times for each scenario show that operator reaction time varied between 1 second to 6.0 seconds with an average value of 2.2 sec. Additionally, no specific correlation was observed between human reaction time and the maneuvering criteria. It should be noted that statistically significant data is not available to draw conclusive values on human reaction times. However, it was observed that the operator's graphical user interface (GUI) had a significant impact on reaction time.
- Weather data on the day1 of flight test day (July 2nd 2024) indicated wind speeds of 8-16 mph in varying directions, wind gusts upto 33 mph, daytime temperatures between 65-78 degrees Fahrenheit, and pressure of 28.68-28.78 inches of mercury (source: wunderground.com).

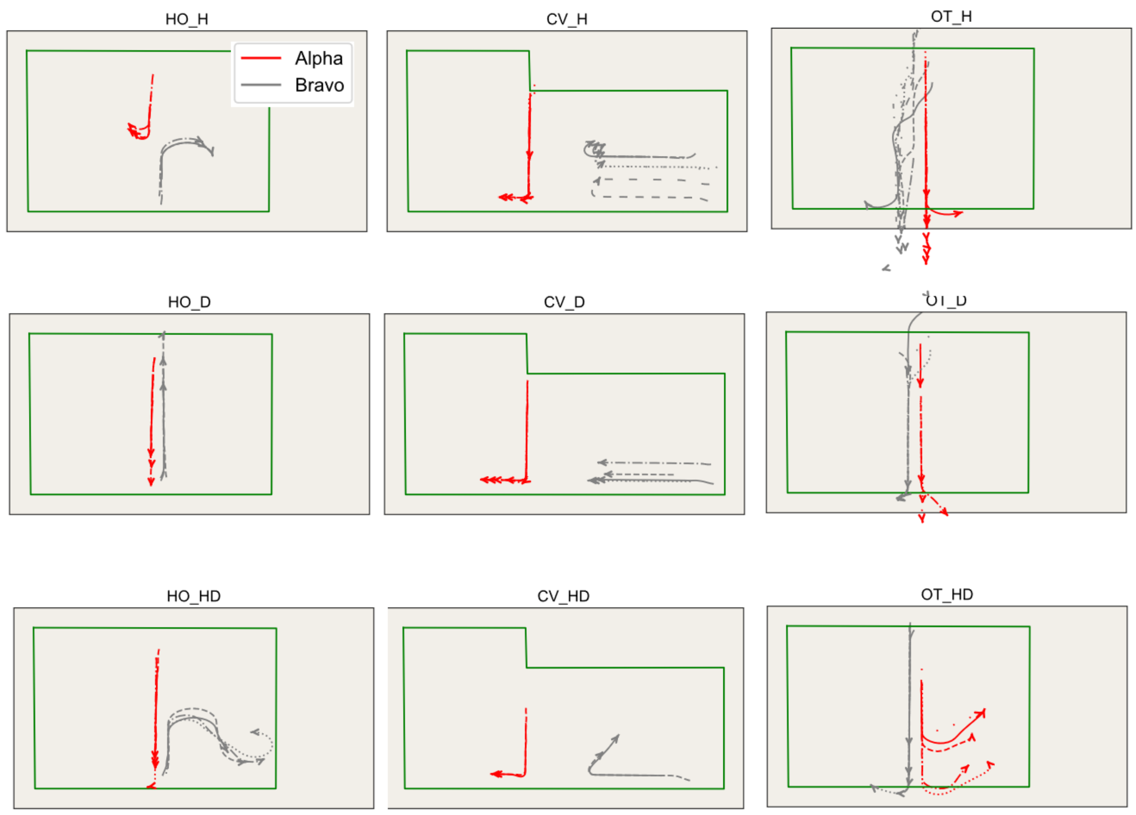


Figure 96. Round 2, sUAS-sUAS in RAC.

Figure 96. Round 2, sUAS-sUAS in RAC, shows the subplot displays the flight trajectories of two UASs, ScanEagle-Alpha (red) and ScanEagle-Bravo (grey). The RAC boundary is depicted as a green box. Different lifestyles represent repeated flight tests for each scenario. The scenario name is indicated at the top of each subplot.

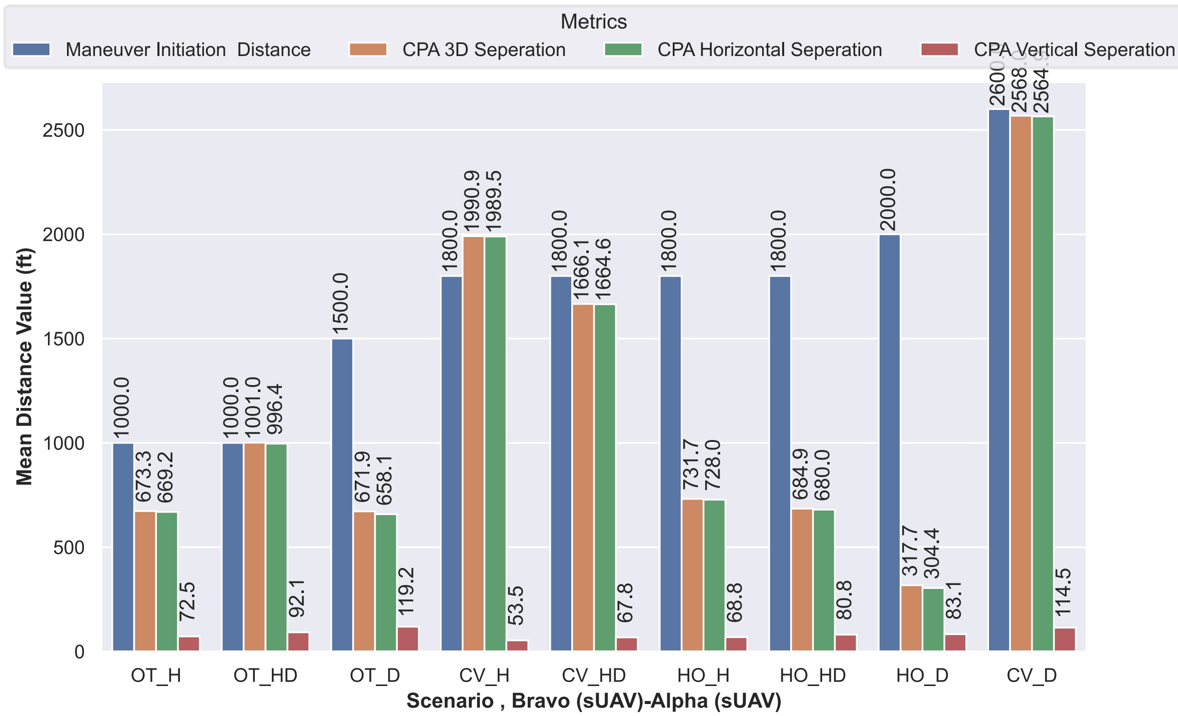


Figure 97. Round-2, sUAS-sUAS,RAC.

The bar plot in Figure 97. Round-2, sUAS-sUAS,RAC illustrates the DAA encounter distance, along with 3D, horizontal, and vertical separation distances at the time of the closest approach of the two UASs, for various maneuvering scenarios. Each bar represents the average outcome of multiple repeated flight tests within the respective scenario.

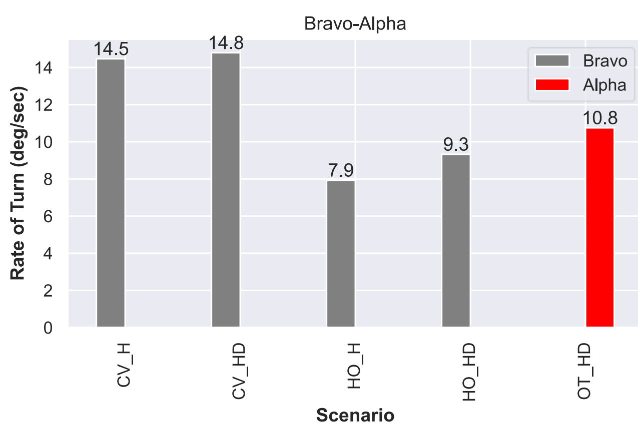


Figure 98. Round-2, sUAS-sUAS, RAC.

The bar chart in Figure 98. Round-2, sUAS-sUAS, RAC illustrates the average ROT performance of two ScanEagle sUASS: Alpha and Bravo. Each bar represents the average ROT achieved in

Round 2 of a specified flight scenario. Note that the 'Descent Only' criterion does not involve a rate of turn maneuver, and thus, no data is presented for this condition.

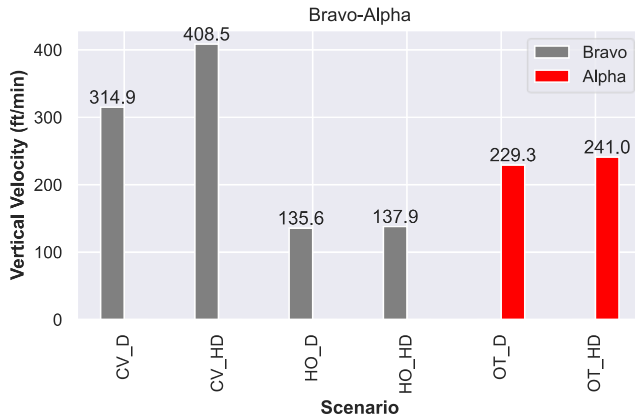


Figure 99. Round-2, sUAS-sUAS, RAC.

The bar chart in Figure 99. Round-2, sUAS-sUAS, RAC illustrates the vertical speed performance of two ScanEagle sUAS named Alpha and Bravo. Each bar represents the average vertical speed of repeated flight tests of a specified flight scenario. Note that the ‘Horizontal Only' criterion does not involve a descent maneuver, and thus, no data is presented for this condition.

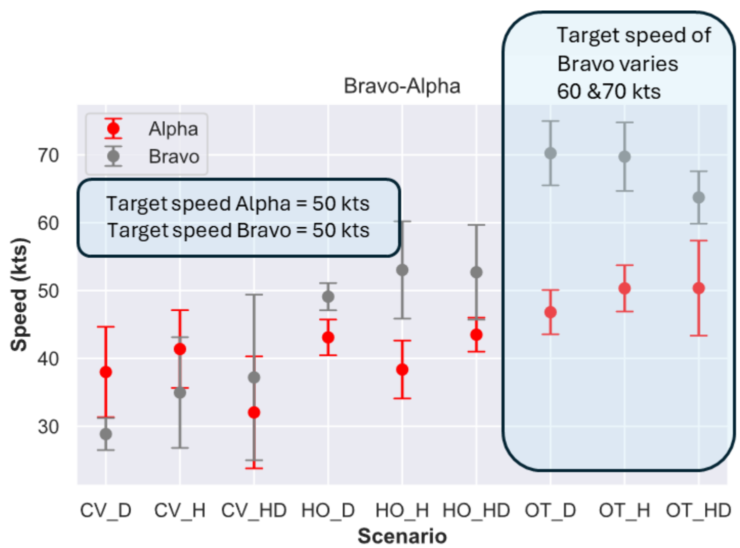


Figure 100. Ground Speed, Round-2 sUAS-sUAS.

The plot in Figure 100 shows the ground speed maintained during the flight testing by two ScanEagle sUASS, named Alpha and Bravo. Each line represents the mean ground speed achieved in a specific scenario, with vertical error bars indicating the standard deviation derived from repeated flight tests within that scenario. The target ground speed for the Alpha varies as 50, 60 and 70 knots , while the target for the Bravo is 50 knots.

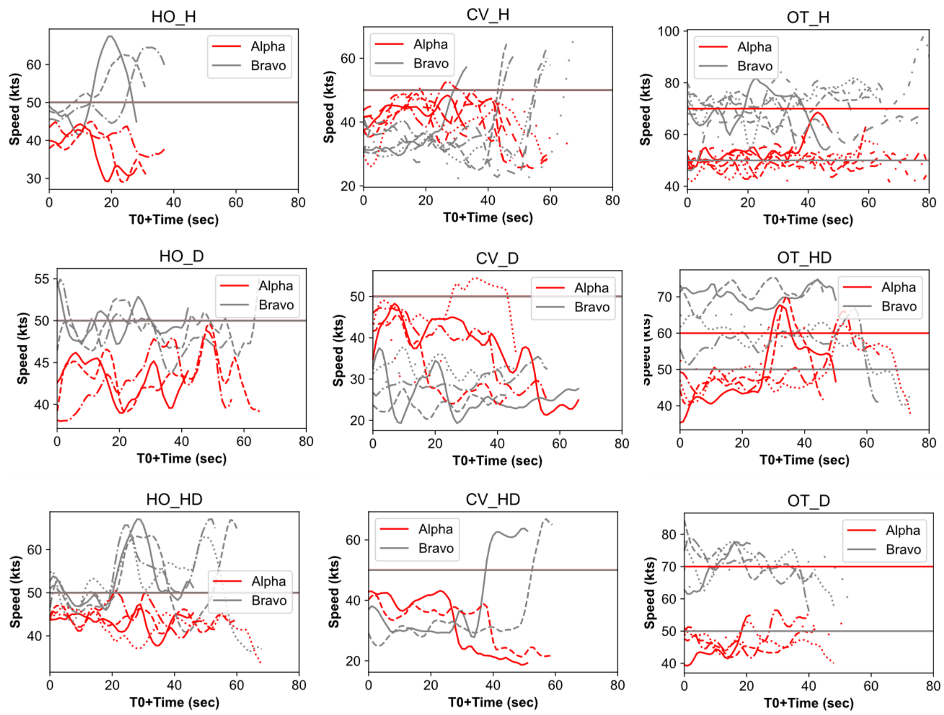


Figure 101. Round-2, sUAS-sUAS, RAC, Ground speed data.

In Figure 101 each subplot depicts the flight profile variations in ground speeds of Alpha (red) and Bravo (grey) across repeated flight tests for each scenario, commencing at the on-track time and concluding at the completion maneuver time. The target ground speed for the Alpha varies 50, 60 and 70 kts (indicated in a solid red horizontal line), while the target for the Bravo is 50 knots (indicated in a solid grey horizontal line).

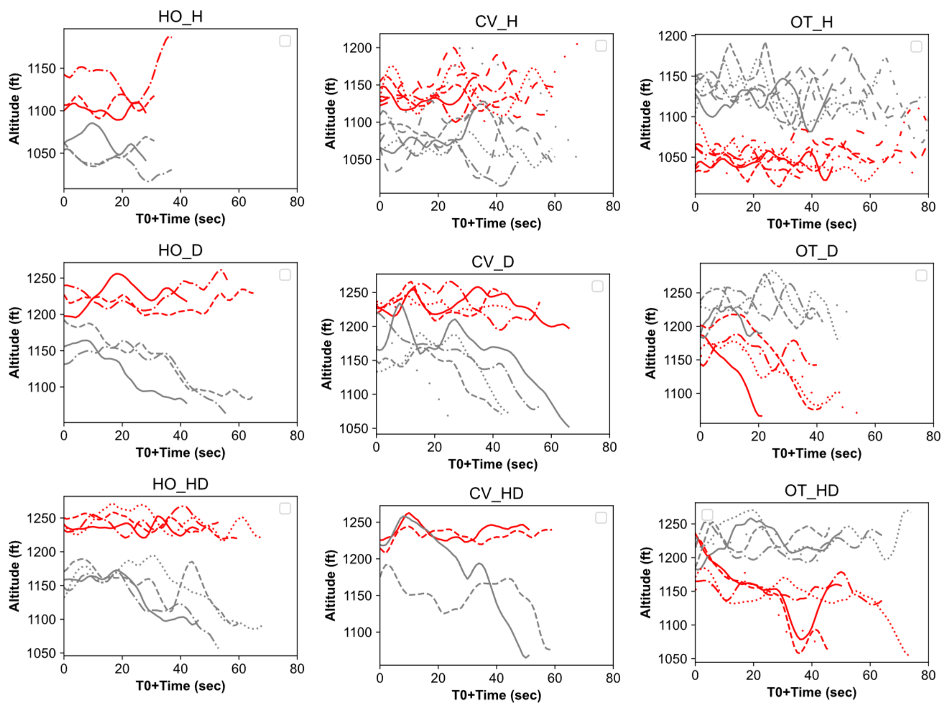


Figure 102. Round-2, sUAS-sUAS, RAC, Altitude data.

In the Figure 102 each subplot depicts the flight profile variations in altitude of Alpha (red) and Bravo (grey) across repeated flight tests for each scenario, commencing at the on-track time and concluding at the completion maneuver time.

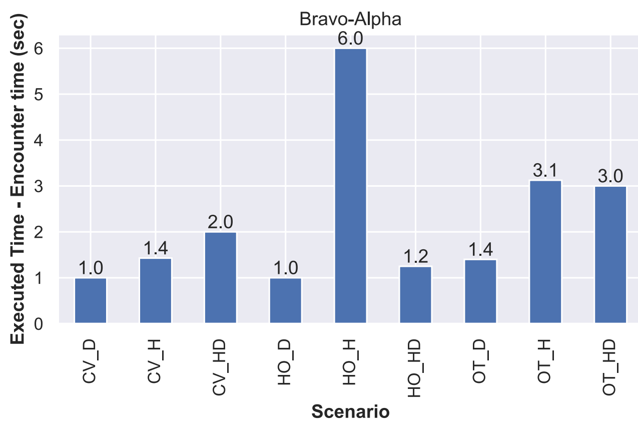


Figure 103. Round-2, sUAS-sUAS, RAC, Operator Reaction Times.

In the Figure 103 each bar represents the operator's reaction time (in seconds) upon a target sUAS entering the DAA radius. Reaction time is calculated as the difference between the moment the target sUAS enters the DAA radius and the moment the operator executes a maneuver command.

3.2.2 sUAS vs Crewed (KU)

3.2.2.1 Round 2.1 Flight Tests

Several Round 2.1 flight tests were flown on in June and July, with a mix of successful and unsuccessful avoidance maneuvers in a head-on encounter. Many changes to the navigation and guidance algorithms were instituted, including a completely new algorithm, based on simulation, flight data analysis, and hardware-in-the-loop testing. Recall that the Round 2.1 flight tests provide the same information as the Round 1 flight tests.

3.2.2.1.1 Head-On Encounters

On 17 July, however, flying vs a ***virtual*** Cessna 172, the sUAS successfully avoided in both head-on and converging scenarios without a RoWV. Figure 104. Head-on Encounter with Virtual Cessna 172 (17 July 2024)shows the ground tracks for the virtual Cessna 172 and the sUAS. Note that the deviation of the sUAS from its intended track was approximately 3000 ft. As noted earlier, this shows that the width of a corridor must be more than 2000 ft, and for the navigation and guidance logic used in this case, would need to be at least 3000 ft.

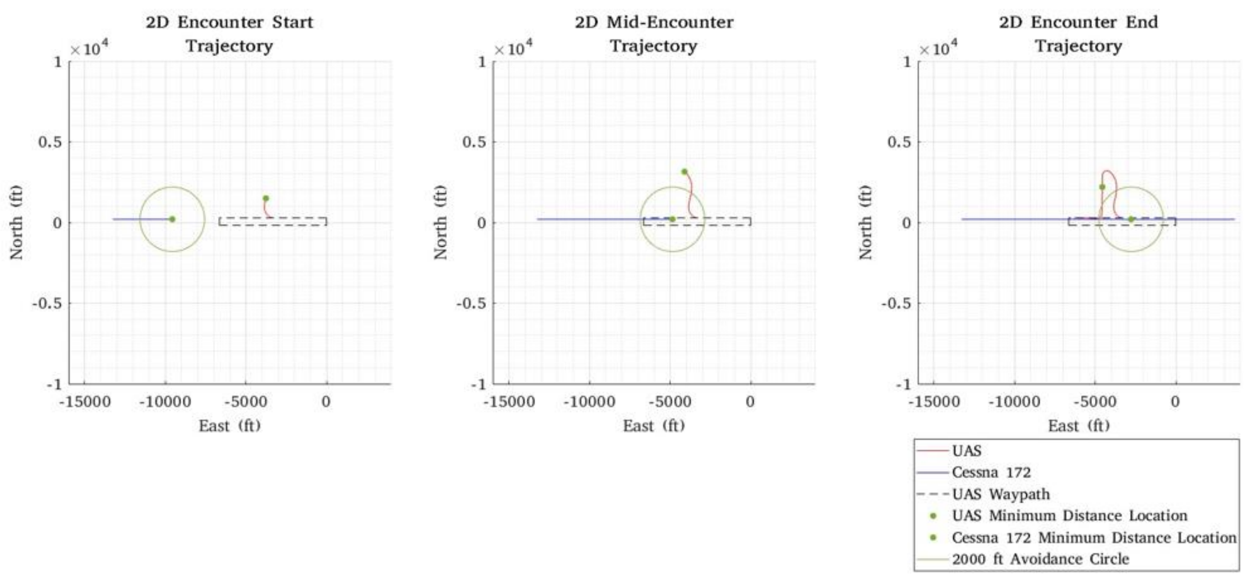


Figure 104. Head-on Encounter with Virtual Cessna 172 (17 July 2024).

On 18 July, flying vs a Cessna 172, multiple successful head-on avoidance maneuvers were conducted. Figure 105. Head-on Encounter with Cessna 172 (18 July 2024)5 shows the ground tracks for the Cessna and the sUAS. Note that the avoidance resulted in the sUAS deviating approximately 4500 ft from its intended track. This shows that this avoidance indicates that an even wider corridor would be needed in some cases using the navigation and guidance algorithm installed on the sUAS computer for these tests.

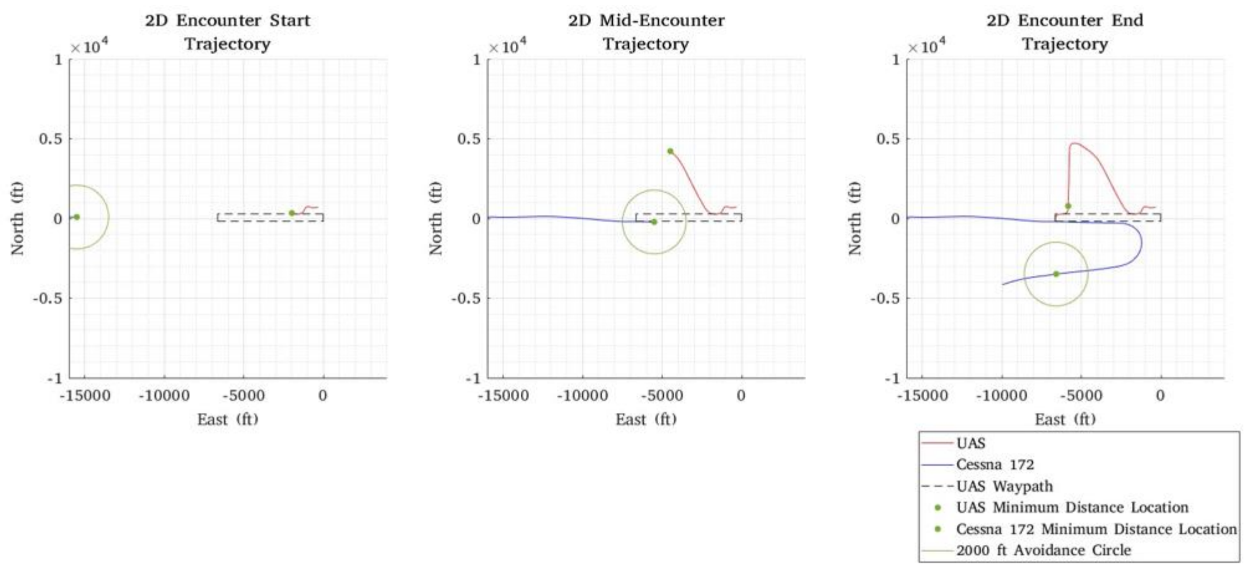


Figure 105. Head-on Encounter with Cessna 172 (18 July 2024).

3.2.3 Helicopter vs sUAS (ERAU)

This section reports on Round 2 RAC. Embry-Riddle Aeronautical University-Worldwide Campus, Department of Flight, conducted the Round 2 A54 flight tests at F75, Harrison Field of Knox City Texas on 20-23 May 2024,. For context, please refer to Figure 106.

<u>ERAU Flight Test Encounter General Information</u>

- There are three rounds of testing
  - Round 1 is sUAS vs. Crewed Aircraft in General Encounters (Head-on, Converging, and Overtaking). Section 4.1.4.
  - Round 2 is sUAS vs. Crewed Aircraft where the sUAS is confined to avoid within a notionally reserved block of airspace. This section.
  - Round 3 is sUAS vs. sUAS in Head-on and Converging encounters. Section 4.3.4.
- All Round 1 and 2 tests were run using Robinson R-44 Helicopter and an Applied Aeronautics Albatross FW UAS.
- All Round 3 tests were run using the Applied Aeronautics Albatross FW UAS and the DJI Matrice M300RTK.
- Test runs were designed using initial simulation recommendations.
- Each test intended to include three types of encounters; Head-on, Converging, and Overtaking. Head-on and Overtaking were combined as the reactions would be the same.
- Each type of encounter will include the UA avoiding a helicopter upon contact confirmation / by specified distances with three runs avoiding horizontally (banking right) and three runs avoiding with a descent.
- UA is considered WC if the volume at 2000’ horizontally and 250’ vertically is maintained.
- Flight altitudes placed both UA and Helicopter by at least a 540’ distance if passing each other with no maneuver (which is not currently planned).
- Albatross flights were semi-autonomous. This is to say that the aircraft was on an autonomous “mission” profile within a RAC, and RPIC decisions to conduct an

avoidance maneuver were an in-flight alteration to the mission. Upon completion, the RPIC returned to the autonomous mission.

Test team personnel;

Dr. Scott Burgess, Flight Director, LRS (runway) RPIC, recovery pilot, lead researcher.
Dr. David Thirtyacre, GCS RPIC, data collector, team researcher.
Dr. Joseph Cerreta, Ground Safety, VO, data collector, team researcher.
Mr. Ryan Johnston, Applied Aeronautics CEO, Lead Pilot, data collector and processor, team researcher.
Mr. Kevin Curry, Cedar Ridge Aviation, Helicopter PIC.

Test aircraft

Crewed aircraft consisted of a 1997 Robinson R-44
Uncrewed aircraft consisted of a 2023 Applied Aeronautics Albatross

Aviation Surveillance Equipment

Crewed Aircraft: UASionix Ping 2020i ADS-B In/Out
Uncrewed Aircraft: UASionix pingRX Pro ADS-B In

Ground Control Station (sUAS)

20' enclosed trailer as hardened Ground Control Station.
3 x monitors for ADS-B traffic feed, Airspace map or Weather map, RID traffic feed (run by Dell 5430 Latitude Rugged).
1 x monitor for the Applied Aeronautics Ground Station (AAGS) software (uses QGC as backbone).
AAGS (run by MacBook Pro).
1 x iCom IC-A120 VHF Base station.
1 x Davis Instruments Vantage Pro2 Weather Statement.
4 x Wireless VOX headsets

Test Location. Harrison Field of Knox City, Texas. Airport Identifier F75.

Test Area Run Configurations. The team designed three test area configurations based upon typical commercial sUAS mission sets. Our goal was to design configurations that could support as many encounter geometries as possible. The team designed two large areas for the Round 2 RAC, one for head-on encounters and one for converging.

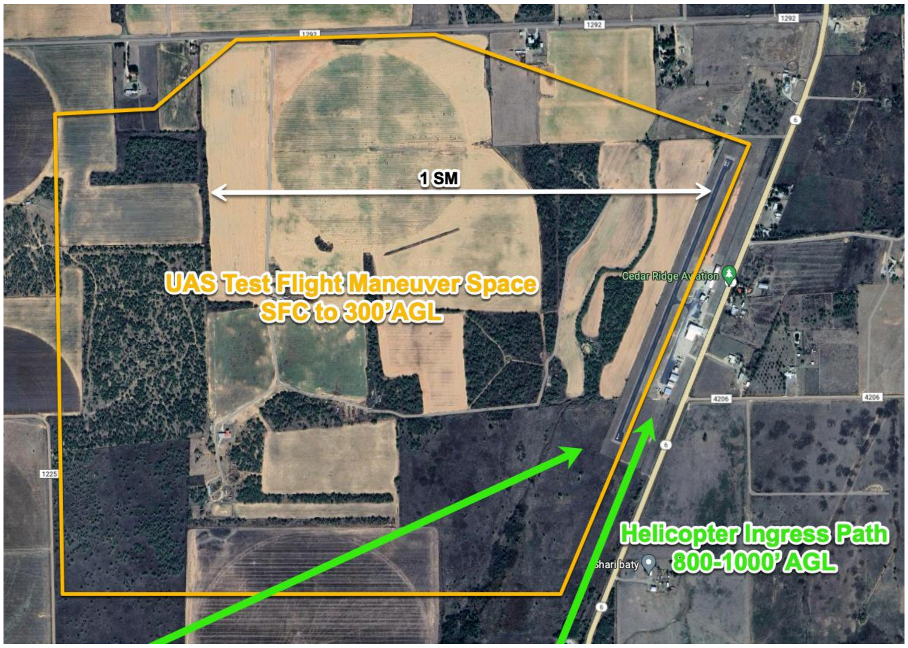


Figure 106. Flight Test Area.

Figure 106 shows the flight test area To maintain organizational aviation safety standards, FAR Part 107.39 (flight over people), and noise abatement considerations (helicopter), and emergency recovery tasks, this test area configuration provided the best total performance.

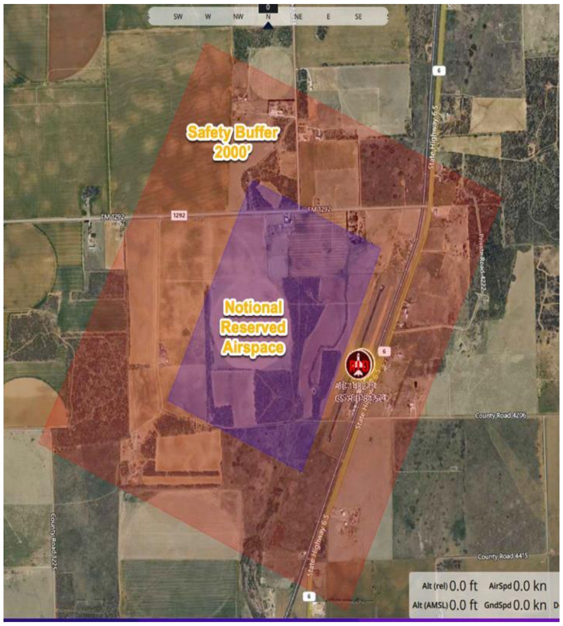


Figure 107. Applied Aeronautics Ground Station RAC and Buffer Zone GUI.

In this Round of flight testing, two visible and connected airspace graphics representing the notional RAC and buffer zone were developed for each test scenario as shown Figure 107 . The initial intent was to enhance visualization in the post-test analysis. The resultant effect triggered RPIC decision making to initiate an avoidance maneuver (with the goal of remaining within the RAC and maintaining safe separation). The team assesses these Human Factors benefits increased situational awareness and risk mitigation.

Round 2 RAC	Run #	Turn Initiated Separation Distance	Closest Point of Approach (CPA)	Delta of Turn and CPA
Head-On Aspect	2-1	3117	1755	1362
	2-2	3493	1630	1863
	2-3	2363	1039	1324
	2-4	4651	1934	2717
	2-5	4308	2158	2150
	2-6	5447	1993	3454
	2-7	3216	1816	1400
	2-8	2213	1720	493
	2-9	2353	1214	1139
	AVG	3462.3	1695.4	1766.9
Converging Aspect	2-10	4057	3558	499
	2-11	2382	2359	23
	2-12	6451	3127	3324
	2-13	3412	3159	253
	2-14	3093	3093	0
	AVG	3879	3059.2	819.8

Figure 108. Encounter Disance Results between Ownship and Intruder.

Figure 108. Encounter Disance Results between Ownship and IntruderInformation was acquired with ADS-B Out and In data. For WC, the horizontal volume standard was 2000ft. Red shading indicates outside standard, yellow indicates within 100ft of violation and green is greater than standard. Refer to data analysis within the objectives analysis below. As explained herein, moderate to heavy winds and aircraft heading were instrumental in affecting the ability to remain WC. The table shows some turns initiated well prior to others and penetrating the WC volume, whereas others initiating closer remained WC or close to that.

Aspect Angle – Head-on vs. Overtaking. The team opted to equate an overtaking maneuver as no significant difference to a Head-on encounter. The reaction would be nearly the same in every case. Environmental conditions, intruder detection, and available maneuver space are all factors in this assessment.

Environmental Conditions. In discussion of this round of testing, the term ‘environmental conditions’ will consider primarily the wind effects on maneuvering and groundspeed. In a broader sense, this must also consider vertical maneuver space (400ft AGL restriction vs. natural and manmade obstacles) as well as visual (electronically or human-detectable) obscuration.

Shielded Operations. This test did not consider the application of shielded operations concepts.

Data Analysis. The team was able to compile the data on each run and portray relevant data at a given time. This enables an assessment of how various factors (like winds) affected an avoidance maneuver, showing aircraft aspects, and closest points of approach. The following chart plots are samples of the results. Top left panel shows all relevant speeds. Bottom left panel shows aircraft locations and (to a degree) the aspect angle. Top right panel identifies horizontal distance and helps determine the closest point of approach. Bottom right panel is intended to show when flight modes changed indicating an avoidance maneuver initiated.To see the complete results, please refer to the bottom of this section.

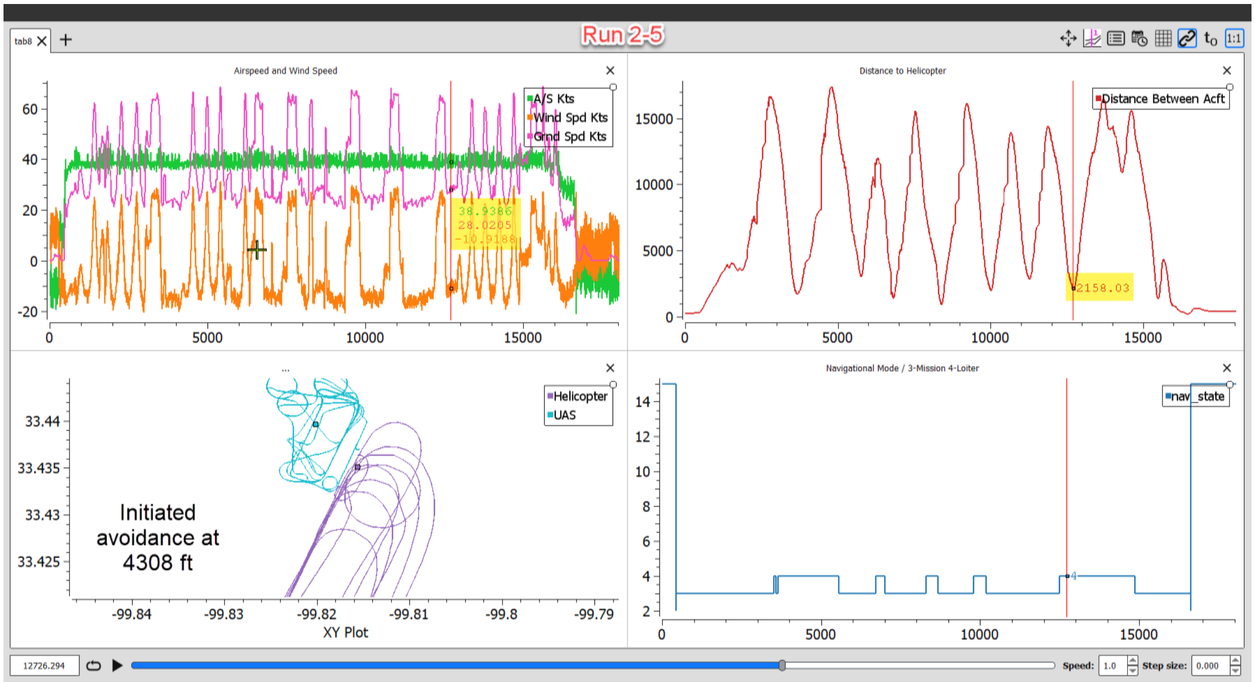


Figure 109. Run 2-5 Head On Encounter with Successful Avoidance.

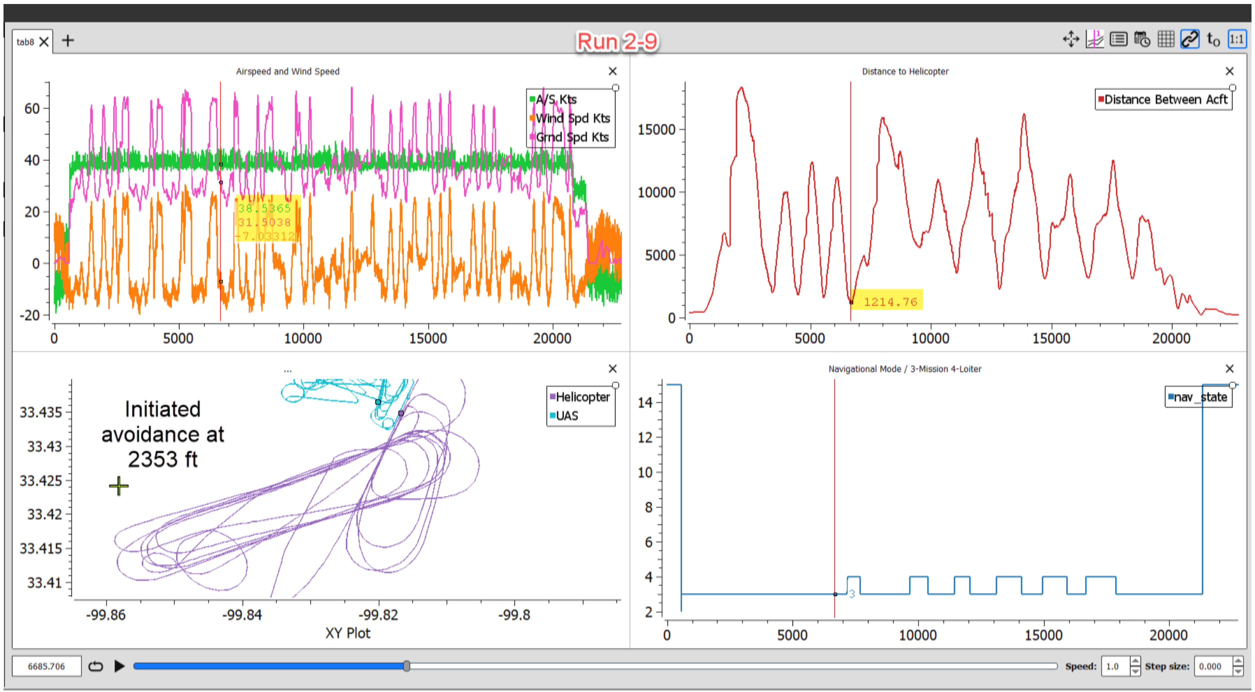


Figure 110. Run 2-9 Head On Encounter with Unsuccessful Avoidance.

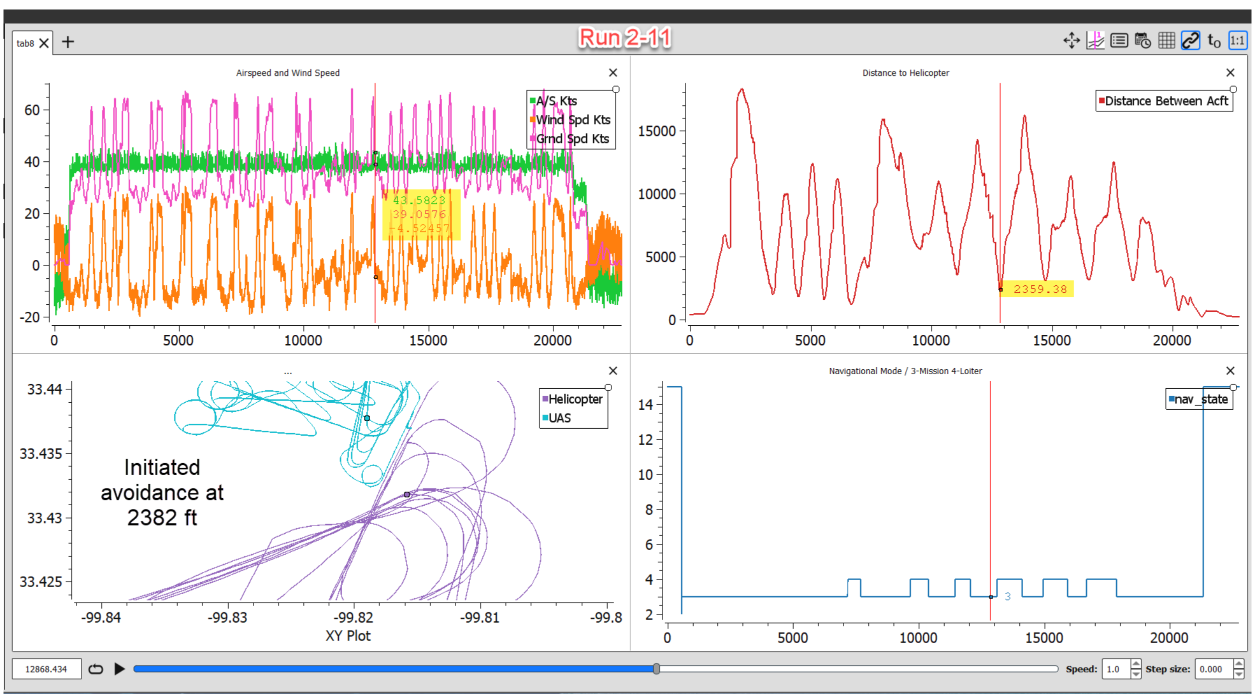


Figure 111. Run 2-11 Converging Encounter with Successful Avoidance.

Round 2 Objectives. Round 2 mimics Round 1 flight test patterns with the added inclusion of a notional 3D RAC to measure affects to maintenance of ROW rules. While conducting rehearsals, the impending wind shifts prompted some modifications to the planned encounters. Crosswinds were forecasted to present some challenges. High tailwinds were experienced in the head-on aspect of the Round 2 flight tests. The team agreed that it would have an effect on results, but it also presented a worst-case scenario that would mimic itself in commercial drone operations. Additionally, vertical maneuvering was not attempted due to perceived safety risks. As discussed in this report, vertical avoidance maneuvering for sUAS restricted to 400' AGL makes any such action a high and calculable risk. Results of simulation coincide with the results of the flight tests in that increased risk exists in maintaining RoW within a RAC boundary, even with enhanced UI for RPIC situational awareness. The round 2 objectives and Interaction scenarios are given in section 3.1.3.

Assessment of Objectives

Usefulness of the RAC on sUAS(s) and Crewed aircraft operating in the RAC. In this test, the notional RAC was presented to the RPIC as shown in Figure 111. While the RAC (notionally presented on GUI to RPIC) aided in identifying available maneuver space, it will likely only benefit a possible violation based upon the quality of the DAA equipment alerting the RPIC of Intruder, and RPIC assessment and handling of environmental conditions. The RAC was found to be very useful for the RPIC to identify intruders and initiate avoidance maneuvers. This was an observation found attributed to the application of both the RAC and associated 2000ft buffer graphics applied to the GCS GUI Figure 112. Accurate DAA equipment and accompanying GUI symbology enhanced RPIC decision making.

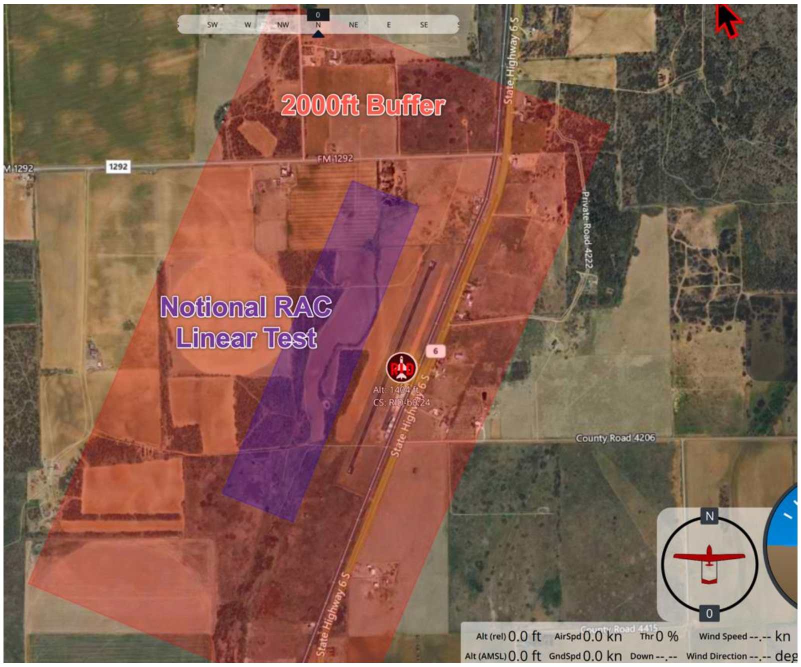


Figure 112. Applied Aeronautics Ground Station GUI.

The image shown in Figure 112. Applied Aeronautics Ground Station GUI. depicts this tests notional linear RAC (such as could be found on a transmission line inspection or package delivery) with a 2000’ buffer. This was the test flight GUI embedded into the AAGS GCS which could be turned on for graphics of the scenario to be flown.

Factors that increase or inhibit usefulness of the RAC

- Environmental conditions (primarily wind and visibility) for the crew and sUAS. The aspect angles and wind conditions chosen were assessed as the most challenging to negotiate and therefore thought the best to test.
    - Wind. Winds aloft were a factor in these tests and for round 2 specifically. Winds were 20-30 mph throughout the Round 2 test. The increased tailwinds on the sUAS were the contributing factor in encroachment of the WC horizontal volume (of 2000ft) as shown in the table above.
        - In Head-On runs (2-1 through 2-9), the sUAS flew with tailwinds and ground speeds reached 65 kts. This factor challenged the avoidance maneuvers (turns), elongating and slowing the turn, which then allowed the intruder to easily encroach into the 2000’ horizontal WC volume.
        - In Converging runs (2-10 through 2-13), the same wind speeds and general directions were encountered. In this encounter aspect, there was a left crosswind and the intruder encountered a left-front crosswind. The sUAS avoidance maneuvers were both with and without the benefit of wind conditions (that could push the aircraft faster through the avoidance maneuver) as part of the turn elongates the turn arc (with the wind affecting the left and top of the aircraft in the bank), and part of the turn (whit the wind now on the opposite side) then catches the underside and pushes a tighter turn.

- Visibility. Dust, haze, fog, instrument flight rules, and low light can negatively affect vision-based systems. This was not formally tested, though a system was used to maintain safe separation. The system was found to work approximately 50% of the time (in Round 1 so it was not used in Round 2).
- Maneuver Space. The space available to maneuver safely away from an intruder and remain within the RAC can assist aviation safety if that space is large enough to support safe evasion and continued maneuvering. With a 2000’ buffer outside the RAC, this adds the element of time to add the possibility of a safe avoidance maneuver to occur. It is likely that in some cases, maneuver space is not possible to remain within the RAC and maintain WC, even with adequate DAA capability present.
- UAS flight control software flexibility added to the RPIC’s ability to decide when to begin an avoidance maneuver. This contributed to the ease of changing course immediately during an autonomous flight. Even though violations of the RAC occurred, turns were initiated as an evaluation by the RPIC based upon the AAGS display.
- Airspace Intelligence. UAS GUI SA of intruder through DAA equipment interface. The collision avoidance symbology greatly enhanced RPIC ability to maneuver in the best direction to avoid.
  - Applied Aeronautics Ground Station (AAGS). The ground user interface (GUI) for these tests included scenario-based graphics to assist the RPIC in maintaining flight inside the RAC boundaries. Additionally, a 2000ft buffer was also present to assist the RPIC in decision making for maneuvering to avoid conflict. See Figure 112**.**
- Latency in any DAA equipment GUI lengthens pilot reaction time.

Identify ability for the UAS pilot to initiate an avoidance maneuver with a crewed aircraft with ADS-B Out while remaining within the RAC.
The ability to successfully accomplish this scenario rested upon airspace intelligence provided to RPIC (Intruder position relevant to RAC dimensions). Our intent was to allow the RPIC to decide the best turn direction based upon the situation presented for each encounter. It was found in fact, that the RPIC was best in determining the direction of maneuvering (left or right turn) for avoidance of the (intruder) helicopter. The scenario prompted the ability to determine the amount of space available in which to maneuver. Considerations of the wind direction and speed, combined with the available space to which a maneuver would place the SUAS in a perpendicular aspect to the oncoming aircraft was found to be the most effective. The 2000ft buffer around the RAC was very effective in helping the RPIC attempt to avoid a conflict. In the event where an intruder would suddenly change directions when entering the RAC, an sUAS crew would experience extreme challenges in maintaining safe separation (especially in smaller sized RAC airspace (linear inspections, etc.). The RAC concept would define an intrusion by non-cooperative aircraft as an airspace violation by the crewed aircraft.

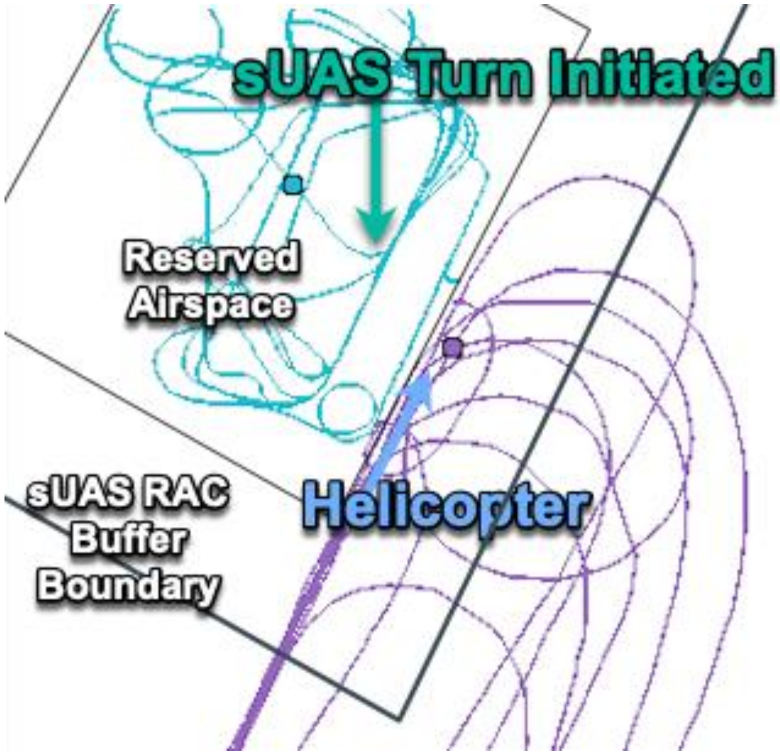


Figure 113. Intruder Avoidance Concept.

Figure 113 shows that The blue and purple dots in this image represent aircraft locations at the CPA. The sUAS had made the right turn prior to the CPA. The black box images depict the notional reserved airspace with a 2000’ Buffer).

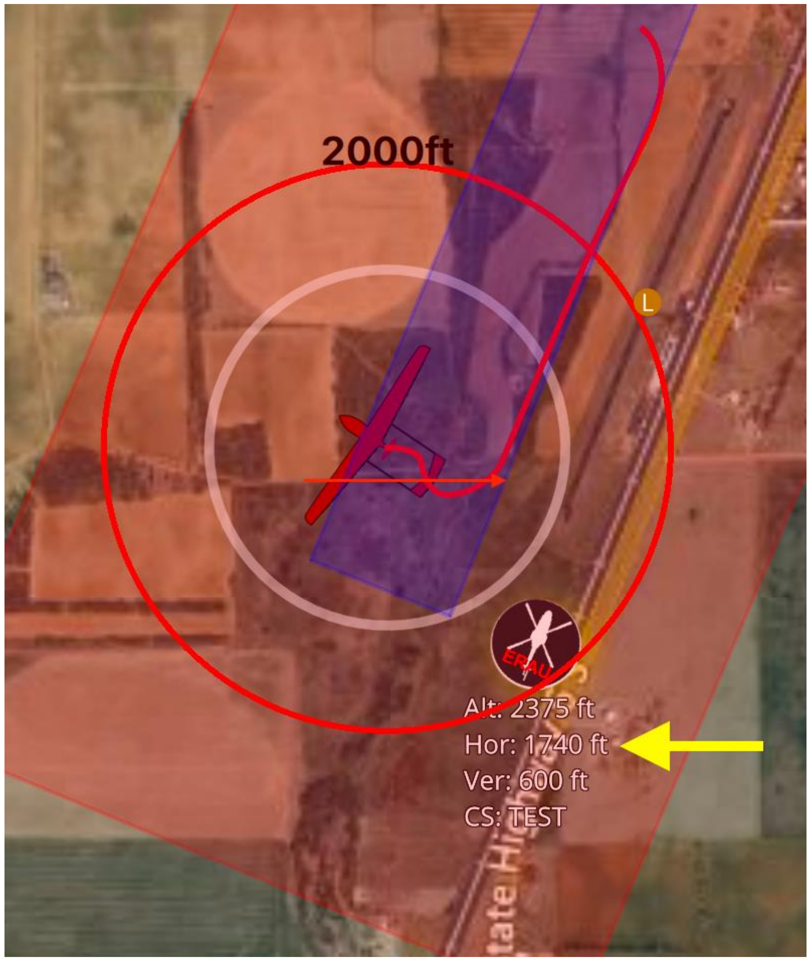


Figure 114. Actual sUAS Linear RAC Avoidance Maneuver Linear RAC avoidance maneuver.

Figure 114 shows the <2000ft horizontal separation with the sUAS almost penetrating the RAC box. Linear RACs are clearly of more concern for sUAS inability to remain WC.

Figure 115. Actual sUAS Area RAC Avoidance Maneuver.

In Figure 115. Actual sUAS Area RAC Avoidance Maneuver Area RAC avoidance maneuver showing < 2000ft horizontal separation. The yellow arrow identifies the horizontal approach distance. These graphics were very helpful in identifying the CPAs, the aspect angles of aircraft during maneuvers, and how the winds effected the sUAS throughout an avoidance maneuver. Linear RACs are clearly of more concern for sUAS inability to remain WC.

In each case, the collision avoidance detection (buffer) displayed on the GCS GUI, aided the RPC in determining when to initiate avoidance maneuvers and where to orient for safest possible separation while remaining inside the RAC. There was variability of location to avoid intruders for each iteration as would be expected for conditions, however, this well represents expected conditions in the field. Immediate RPIC reaction to a perceived impending violation in nearly all cases, enabled the RPIC begin to avoid a WC (horizontal) violation. Maintaining WC in every avoidance maneuver was not always possible. In the Figure above, the horizontal separation shows over 100ft less than the intended minimum separation distance of 2000ft.

Factors that delay or inhibit maintaining flight within the RAC in an encounter

- Environmental conditions (constituting of primarily wind and visibility, and though computer visibility was intended for safe separation, the Casia system did not provide reliable data) for the crew and sUAS. The aspect angles and wind conditions chosen were assessed as the most challenging a commercial operator would possibly negotiate, and therefore thought the best to test. These aspect angles would add difficulty to any avoidance scenario with the goal to maintain flight integrity within the RAC in an encounter.
  - Wind. Winds aloft were a factor in these tests and for round 2 specifically. Winds were 20-30 mph throughout the Round 2 test.
    - In Head-On runs (2-1 through 2-9), the sUAS flew with tailwinds and ground speeds reached 65 kts. This factor challenged the avoidance maneuvers (turns), elongating the arc and thus delaying completion of the turn, which then allowed the intruder to easily encroach into the 2000’ horizontal WC volume.
    - In Converging runs (2-10 through 2-13), the same wind speeds were encountered, though from different angle to the direction of flight. In this encounter aspect, there was a left crosswind while the intruder encountered a left-front crosswind. The sUAS avoidance maneuvers were both with and without the benefit of wind conditions to push the aircraft faster through the avoidance maneuver.
    - Visibility. Dust, haze, fog, instrument flight rules, and low light can negatively affect vision-based systems (A18_A11L.UAS.22). This was not formally tested, though a system was used to maintain safe separation. The system was found to work approximately 50% of the time (in Round 1 so it was not used in Round 2).
- Maneuver Space. An avoidance maneuver could be a challenge for flights in an RAC as wind conditions, intruder vector and time of detection, size of RAC, mission profiles will all affect rapid RPIC decision making. Success in this test was assessed as a result of training, experience, and preplanning and preparing for a need to maneuver to avoid. It was found that an RPIC must turn to avoid in a direction that keeps the sUAS within the RAC and the turn (for head on) to be a 90 to 135 degree turn to both slow the intercept AND increase separation distance to the intruder flight vector. The "correct" avoidance maneuver and timing must be continually assessed by the RPIC based on the situation. This could have a negative effect on the aircrew in their mission profile, depending on the size of the RAC and the environmental conditions. Avoidance maneuvers should also include an altitude change when sufficient altitude exists. Geographically speaking, this will not always be possible due to natural or manmade obstacles. Co-altitude encounters present the greatest challenge. Altitude changes to avoid the helicopter (typically a descent) would best accompany a simultaneous horizontal maneuver to ensure the best chance for separation, however, remaining within the RAC and maintaining WC could present airspace safety challenges. Of note, is the AAGS procedure to descend in semi-autonomous flight is a step-by-step procedure (first to descend, then to turn) and adds 10-15 seconds of additional time. This is even more important should the helicopter change course.
- Airspace Intelligence. UAS GUI SA of intruder through DAA equipment interface. The collision avoidance symbology greatly enhances RPIC ability to maneuver in the best direction to avoid. As some RPIC actions may require immediate actions for avoidance, the ease of operation of the software controlling the aircraft is a contributing factor for evasion in close encounters. Latency in any DAA equipment GUI lengthens pilot reaction time.
- While a penetration of the RAC by an non-cooperative crewed aircraft could constitute an airspace violation, the penetration by a cooperative crewed aircraft presents the exact same challenge but without a violation. In either situation, an avoidance maneuver is necessary.

Determine the best avoidance maneuver for given interactions in the RAC with crewed intruders to inform RoW rules. As previously indicated, it was found that the best avoidance maneuver depended upon several factors: Environmental conditions, Maneuver Space, Airspace Intelligence, and Immediate follow-on task of the operational mission.

Figure 116. Avoidance Maneuver Initiated.

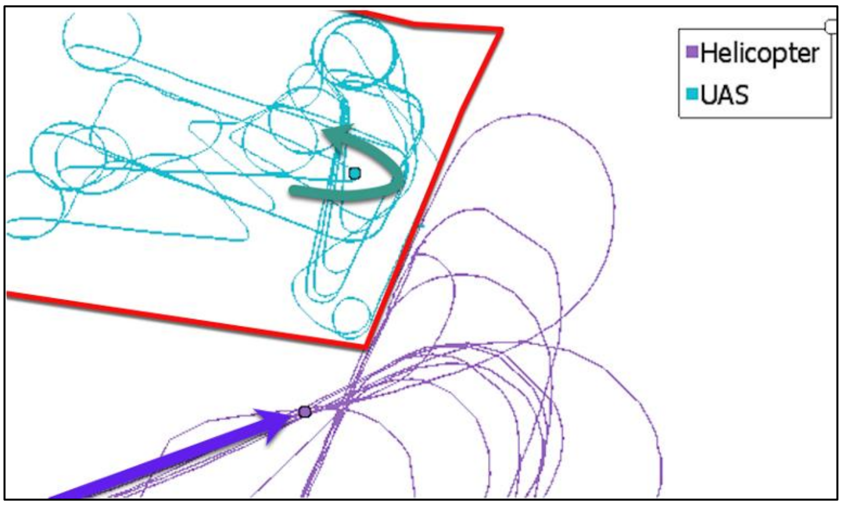


Figure 117. Best Avoidance under Given Interactions.

These two images Figure 116 and Figure 117 depict a planned maneuver (top) for the test iteration with the helicopter on a converging aspect to the sUAS. In this case, the RPIC assessed a left hand turn away from the intruder (bottom) provided the best separation and opportunity to remain WC and not penetrate outside the RAC.

Factors that enable or inhibit the best avoidance maneuver for given interactions in the RAC

- Environmental conditions. Primarily, winds will dictate avoidance maneuver directions. As discussed above, the RPIC best makes the decision based upon perceived wind direction and effects to planned maneuver, and the aspect angle of the intruder.

- Maneuver Space. The space available within the RAC to maintain WC at the point of RPIC decision making is key to determining the best avoidance maneuver. It was found that an RPIC must turn to avoid in a direction that keeps the sUAS within the RAC and the turn (for head on) to be a 90 to 135 degree turn to both slow the intercept AND increase separation distance. to the intruder flight vector. The "correct" avoidance maneuver and timing must be continually assessed by the RPIC based on the situation. Collision avoidance maneuver directions for all sUAS cannot be preassigned. Every situation is different and it requires RPIC decision making just as is in crewed aviation.
- Airspace Intelligence. The Reserved Airspace Concept would require an ability to detect cooperative and non-cooperative crewed aircraft. This airspace intelligence capability was found in Round 2 to present the RPIC with the best opportunity to safely avoid a conflict (though this test was conducted only using cooperative aircraft DAA equipment; ADS-B). As shown, Round 2 sUAS GUI SA of an intruder through DAA equipment interface. The collision avoidance symbology greatly enhanced RPIC ability to maneuver in the best direction to avoid.
- Immediate follow-on task of operational mission. In each encounter, an RPIC will have an immediate task upon initiating an avoidance maneuver, to place their aircraft in a safe flight condition and WC from an intruder. In Round 2 tests, winds were clearly a factor in enabling an ability of the RPIC to continue a mission. The linear RAC conditions presented the greatest challenge in not only choosing the best avoidance maneuver, but also placing the ownship in a position to continue a mission. The figure below shows how this situation played itself out in a given encounter.

Identify impact of RAC boundaries that may delay or inhibit reaction time and distance needed to avoid a RoWV.

RAC boundaries are, by design, essential to provide a safe area for an sUAS to maneuver within a given operation. Allowances to their size will need to consider not just intended sUAS operations, but other (crewed and uncrewed) airspace users as well. This could affect influence RAC size calculations. What was found in Round 2 testing, was that sizing of any RAC would need to consider the maneuverability of the sUAS vehicle (speed, rates of turn, altitude, obstacles, etc). A linear inspection RAC may be too narrow to safely support an avoidance maneuver intended to remain WC. Round 2 test results support this assessment. An intruder could change flight path at any time thus nullifying the avoidance maneuver made by the RPIC.

Test runs show that the buffer zone worked to help RPIC decision making. Factors of RAC boundaries on the reaction time and distance to avoid RoWV.

- Environmental Conditions. As found in one iteration of this test, a notional linear RAC was used that paralleled the strong wind conditions present. This led to an inability to remain WC (horizontally) when in a tailwind condition as it elongated a turn and shortened the avoidance maneuver time (due to an increased rate of closure with the intruder). In a headwind condition, ownship turns will be faster, sharper and depending on conditions, would generally present the possibility of maneuverability in a smaller area such as the linear RAC. Tests showed that aspect angle to winds on a medium sized sUAS were a large influence to maneuvering in such a way as to remain within RAC boundaries or not.

- Reserved Airspace Volume. Notional RAC boundaries in our tests were based upon industry operations and with that, variations in RAC sizes and shapes could never be realistically tested as yet, as there is no set standard. The FAA UTM CONOP v2.0 (2020) identifies UAS Volume Reservations without defining standards. The teams' approach was to test worst possible situations that would be the most challenging for maneuvering to stay within the designed RAC space.
- Location. Maneuvering an sUAS where there may be natural (trees exceeding 100' AGL) or manmade obstacles (towers with wires) would add more complex decision making into RPIC flight tasks.
- Airspace Intelligence. As in the objectives discussions above, RAC boundaries that are displayed in real time with sUAS and intruder information and vectors, enhance the RPIC ability to remain within the RAC in an encounter. Our testing indicates that RAC boundaries do influence maneuverability and thus imply that a much larger boundary would always provide a best opportunity to avoid an encounter.
- Spatial Visualization. As an adjunct to aeronautical decision making, spatial visualization, or three-dimensional thinking, was found necessary to maintain integrity of the RAC boundaries. This is an ability of the sUAS crew to observe situations from all sides. It requires the disassembly of the situation to find the core issue, in this case, of the impact of RAC boundaries (the situations being obstacles, winds, maneuver space) and then find a creative solution outside the current domain to resolve, in this case, an encounter.

Flight Test Run Profiles

The following figures provide visual reference to the intended flight parameters of test vehicles for each run.

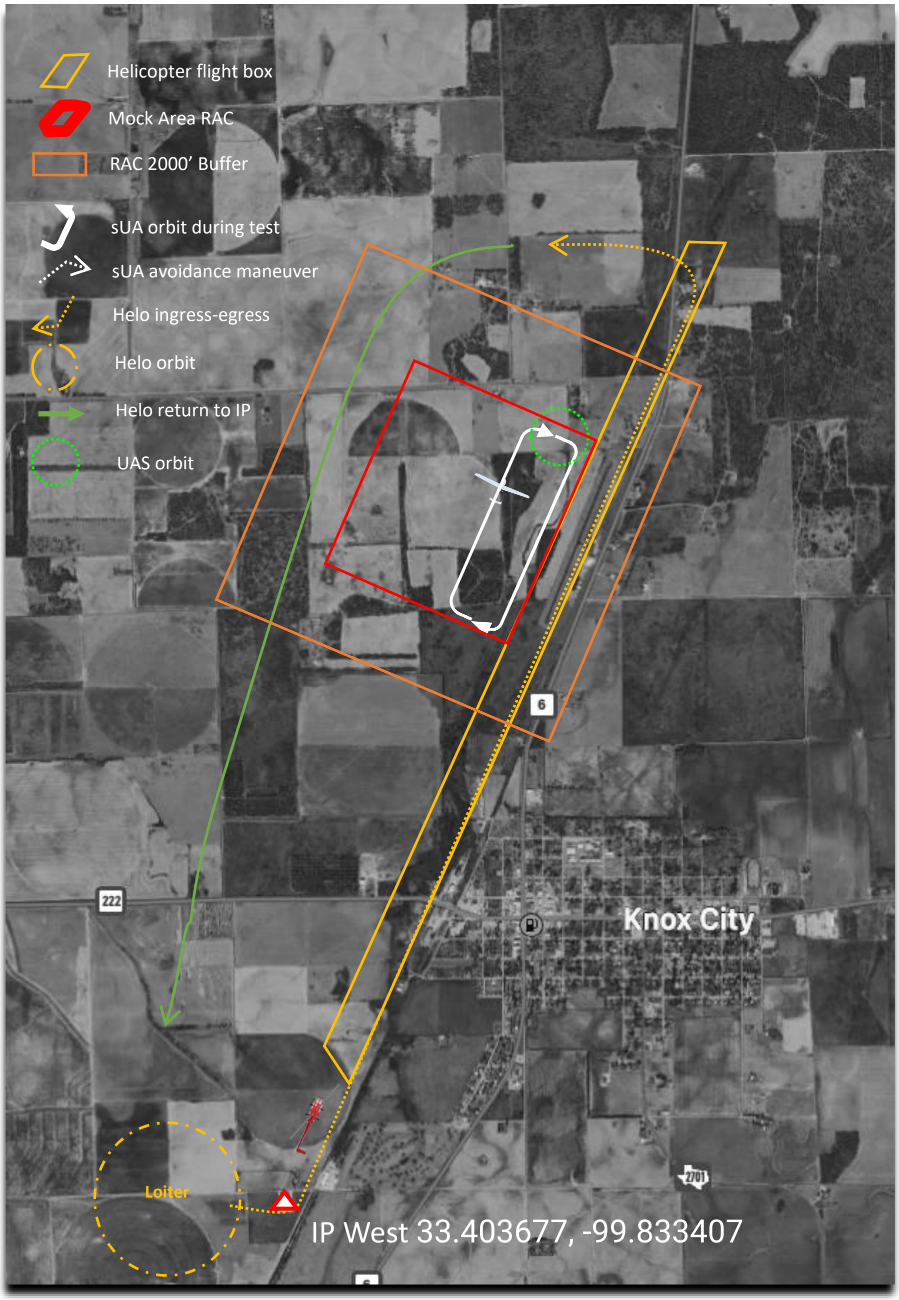


Figure 118. Round 2 Area RAC, Head-On Encounter.

Figure 118 identifies test card instructions for test runs. The Area RAC emulates a large UAS flight area such as would be seen in agriculture missions, mining, orthogrammetry, etc.

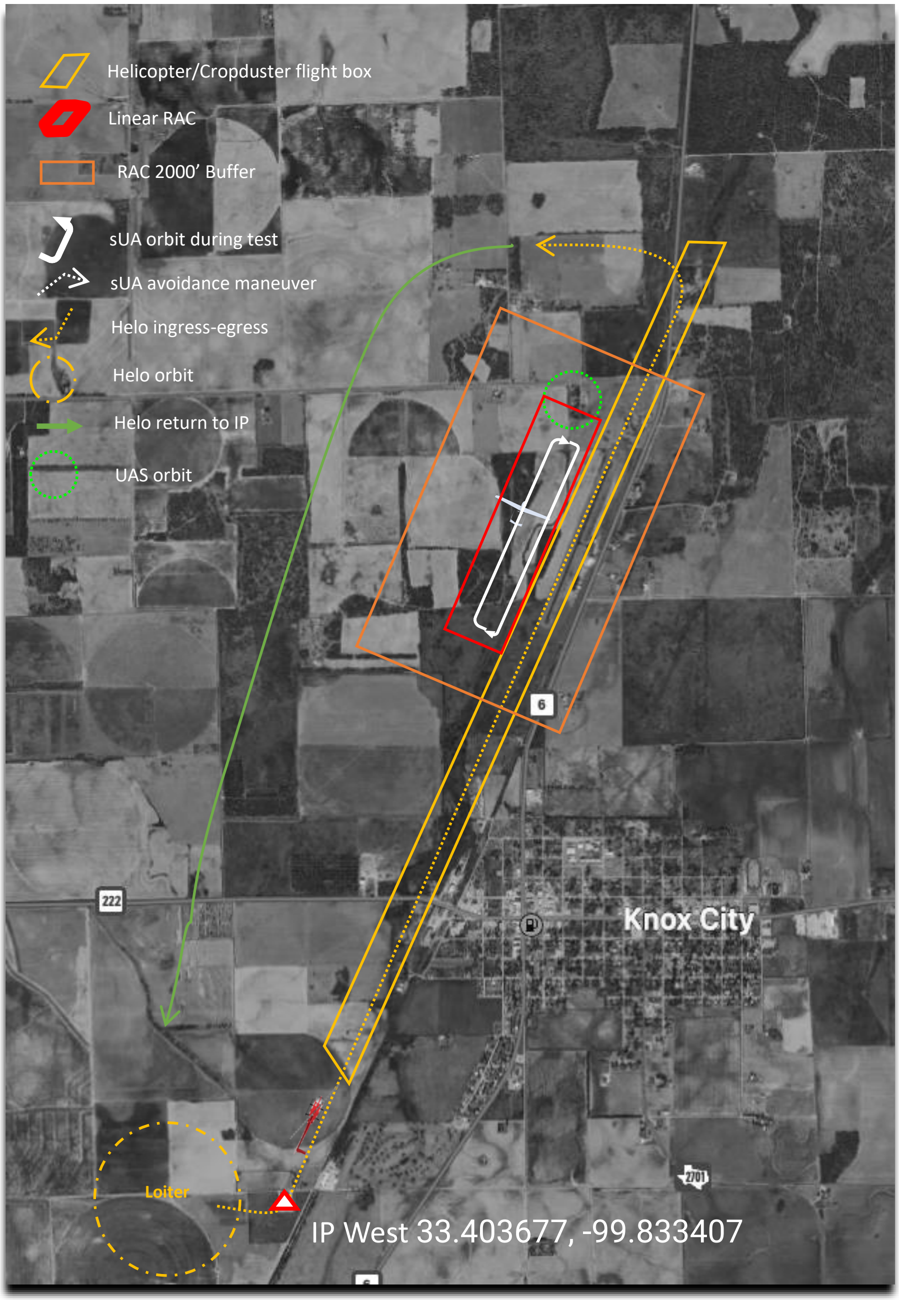


Figure 119. Round 2 Linear RAC, Head-On Encounter.

Figure 119 identifies test card instructions for test runs. The Linear RAC emulates a UAS flight area such as would be seen in infrastructure inspection, package delivery corridor, etc.

Figure 120. Round 2 Area RAC

Figure 120 illustrates that Head-On Converging Encounter. This identifies test card instructions for test runs. The Area RAC emulates a UAS flight area such as would be seen in agriculture missions, mining, orthogrammetry, etc.

Test Run Result Analysis

Head On Encounters. There were six runs planned for head on encounters. The team flew eight as there were some runs where test parameters were not met upon the encounter due to timing.

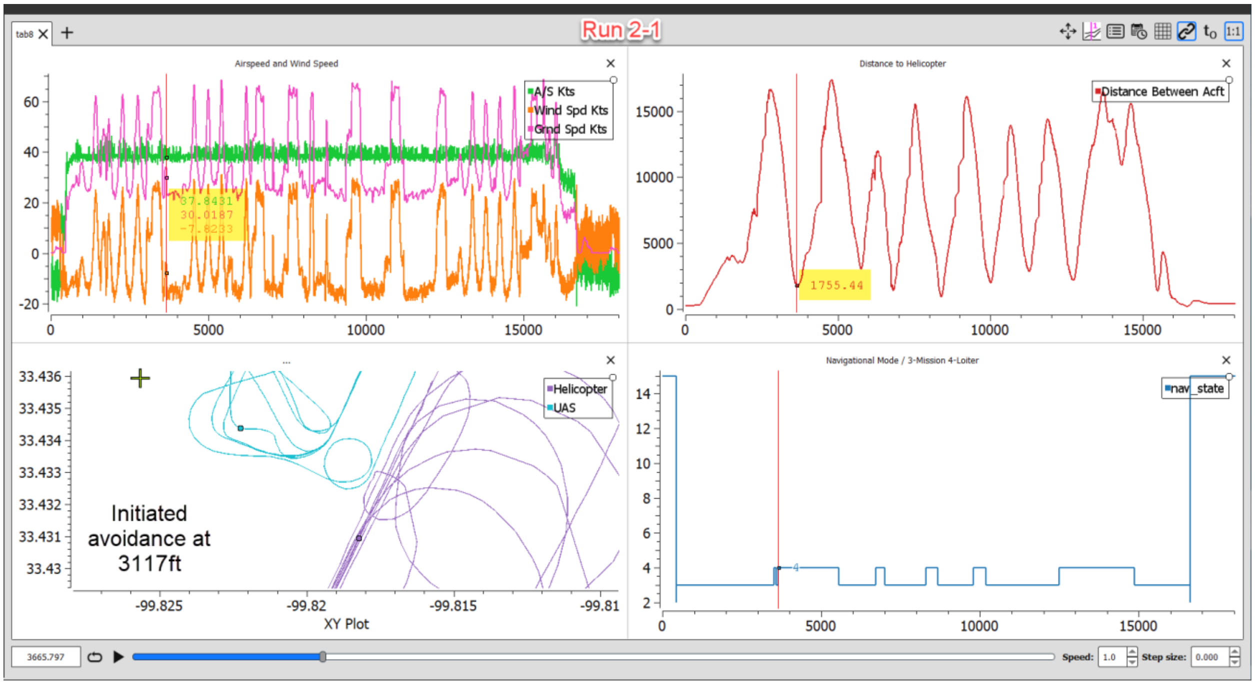


Figure 121. Round 2, Run 2-1, Area RAC, Head On Encounter.

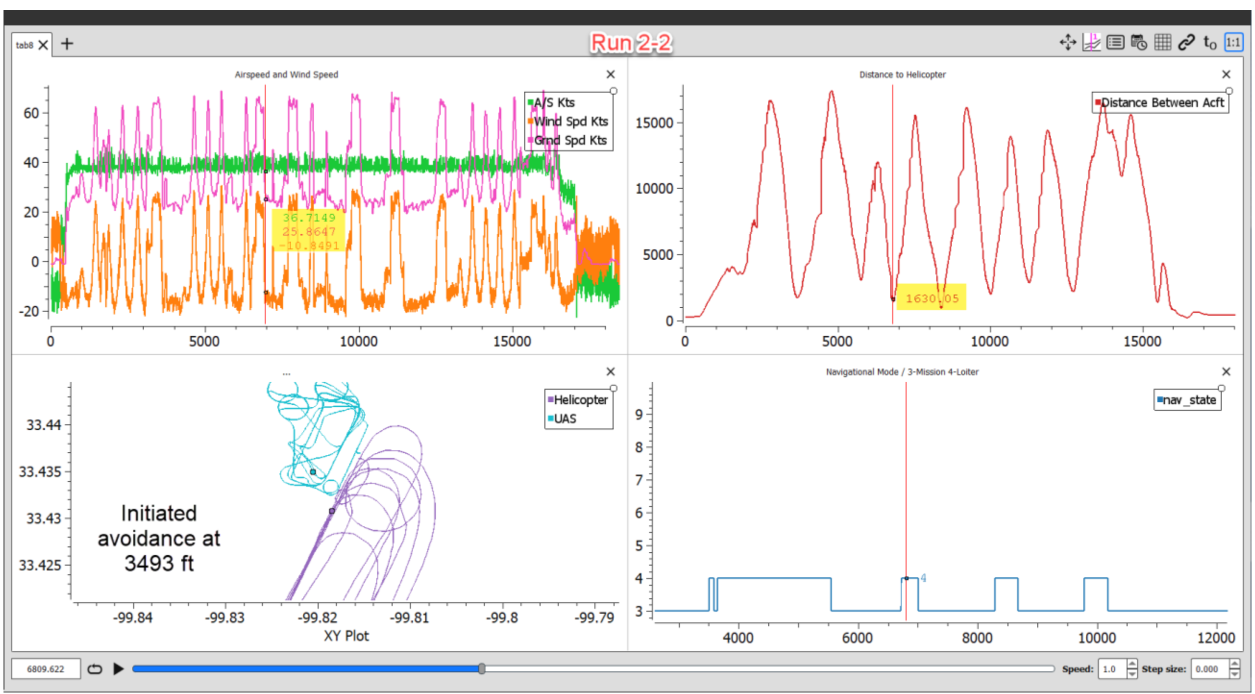


Figure 122. Round 2, Run 2-2, Area RAC, Head On Encounter.

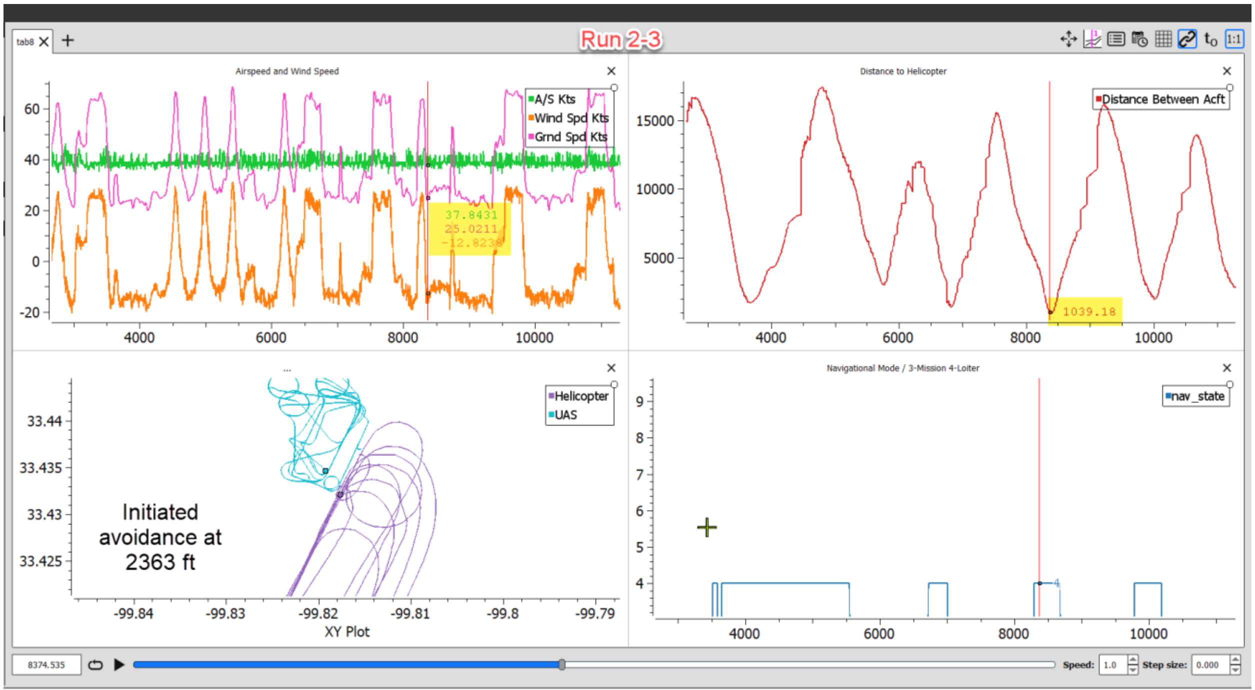


Figure 123. Round 2, Run 2-3, Area RAC, Head On Encounter.

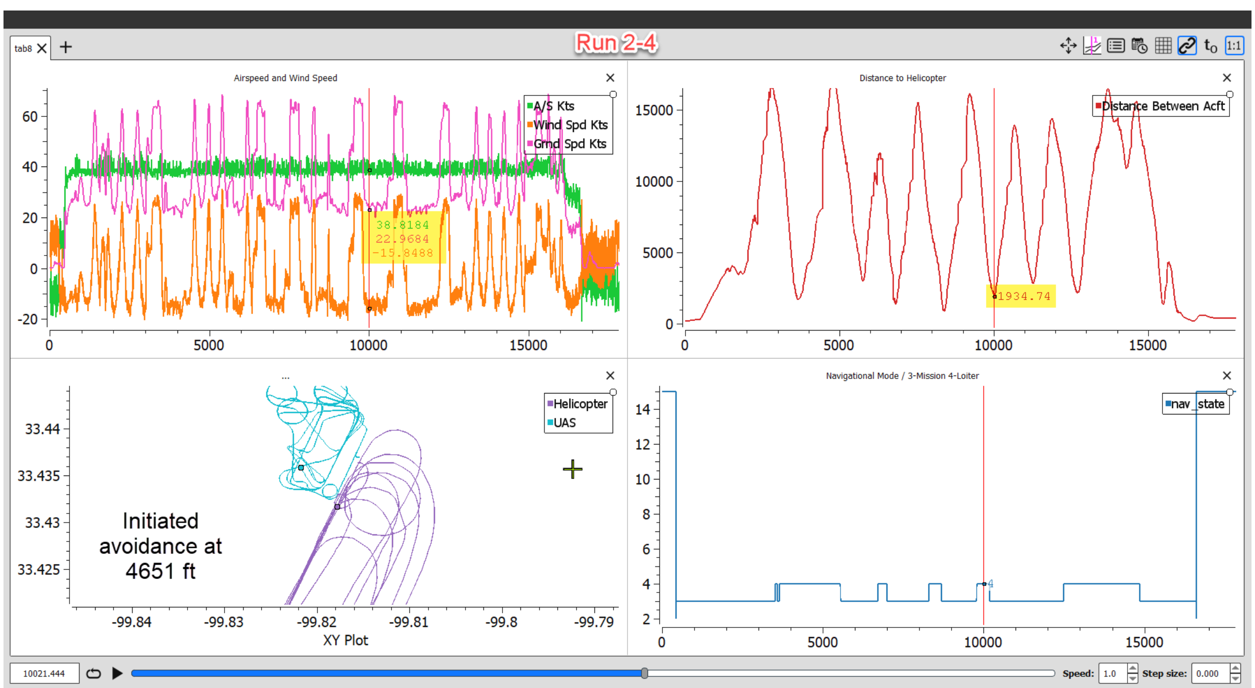


Figure 124. Round 2, Run 2-4, Linear RAC, Head On Encounter.

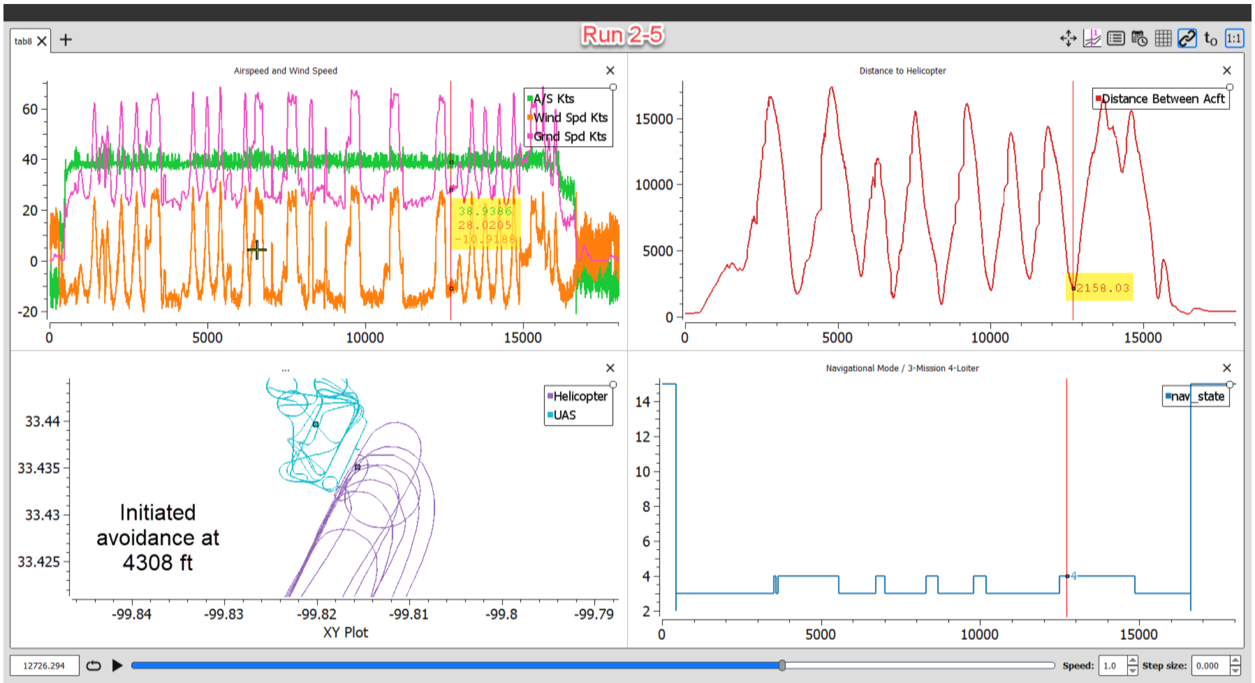


Figure 125. Round 2, Run 2-5, Linear RAC, Head On Encounter.

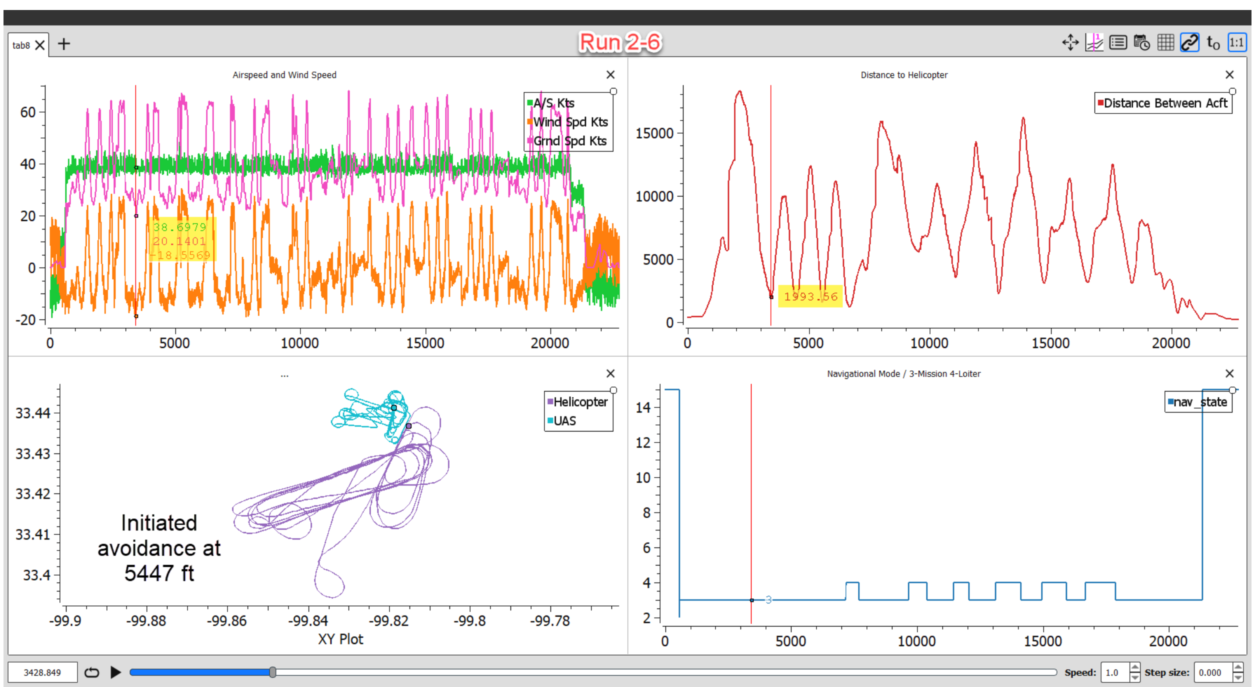


Figure 126. Round 2, Run 2-6, Linear RAC, Head On Encounter.

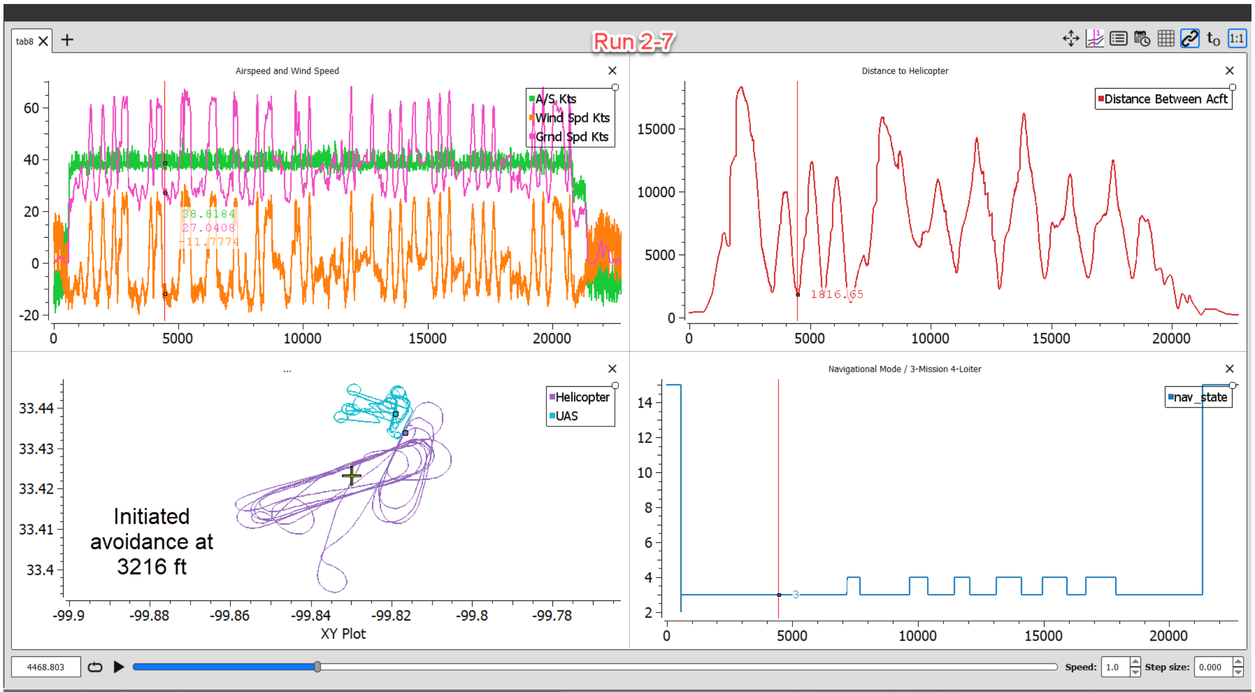


Figure 127. Round 2, Run 2-7, Linear RAC, Head On Encounter.

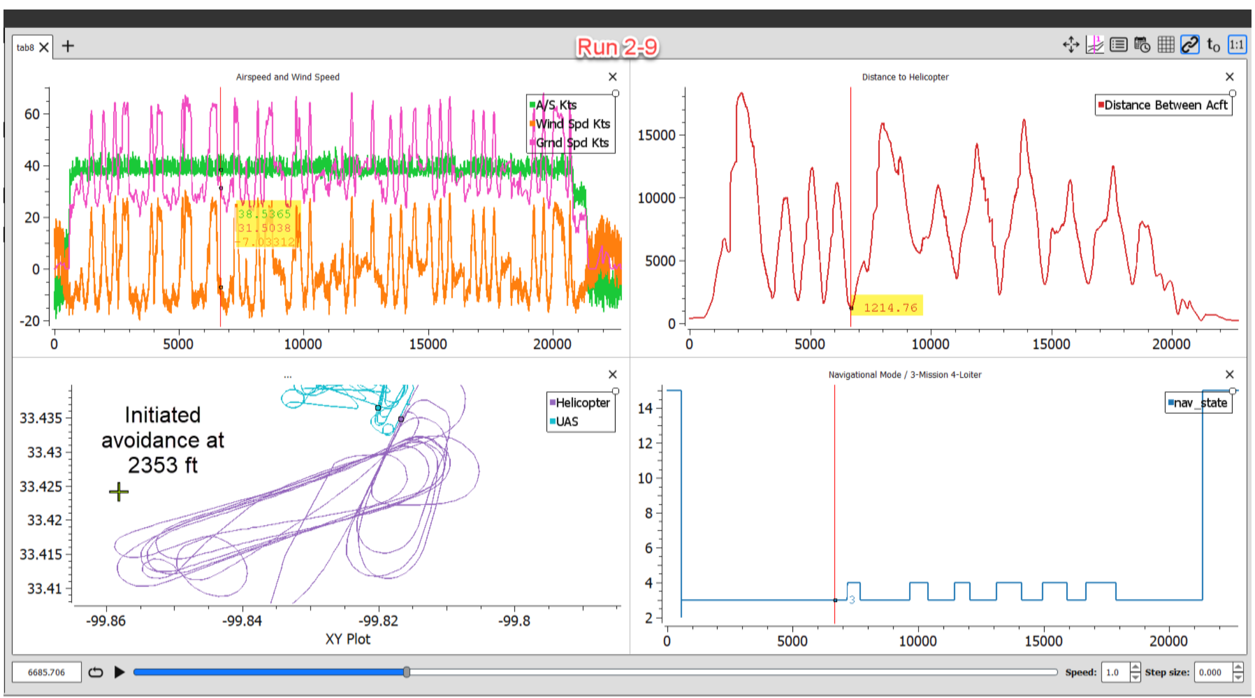


Figure 128. Round 2, Run 2-9, Linear RAC, Head On Encounter.

Converging Encounters. The team had planned three runs and accomplished four.

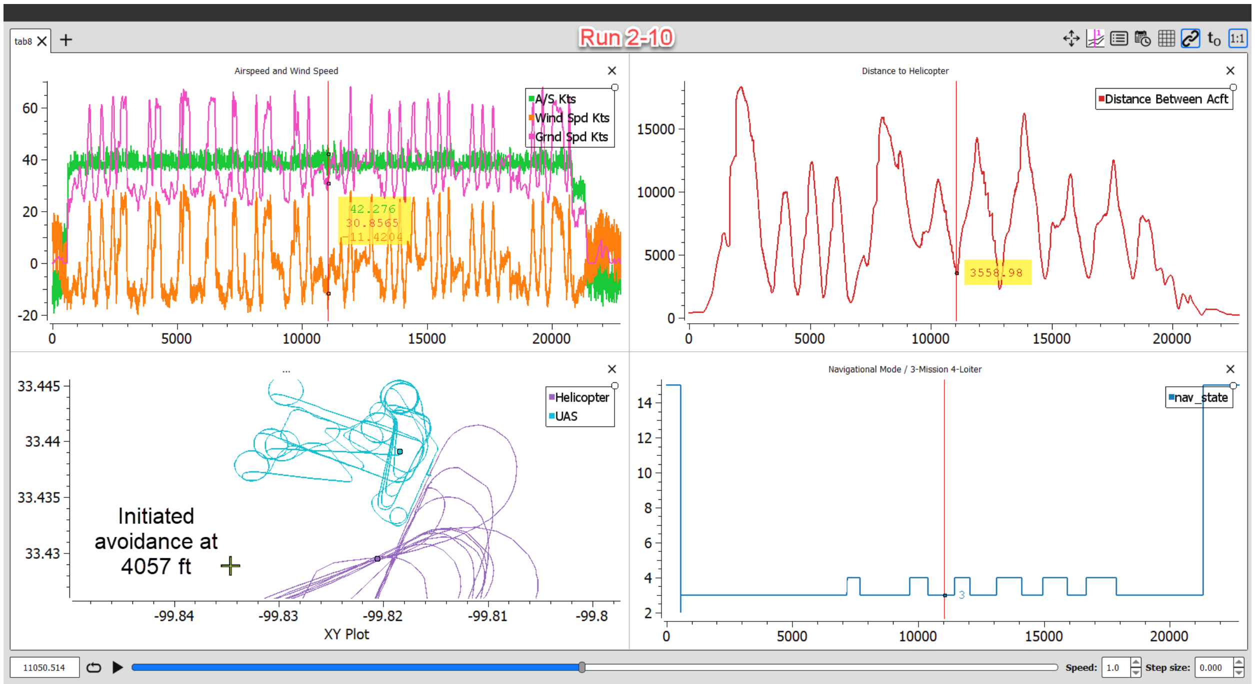


Figure 129. Round 2, Run 2-10, Area RAC, Converging Encounter.

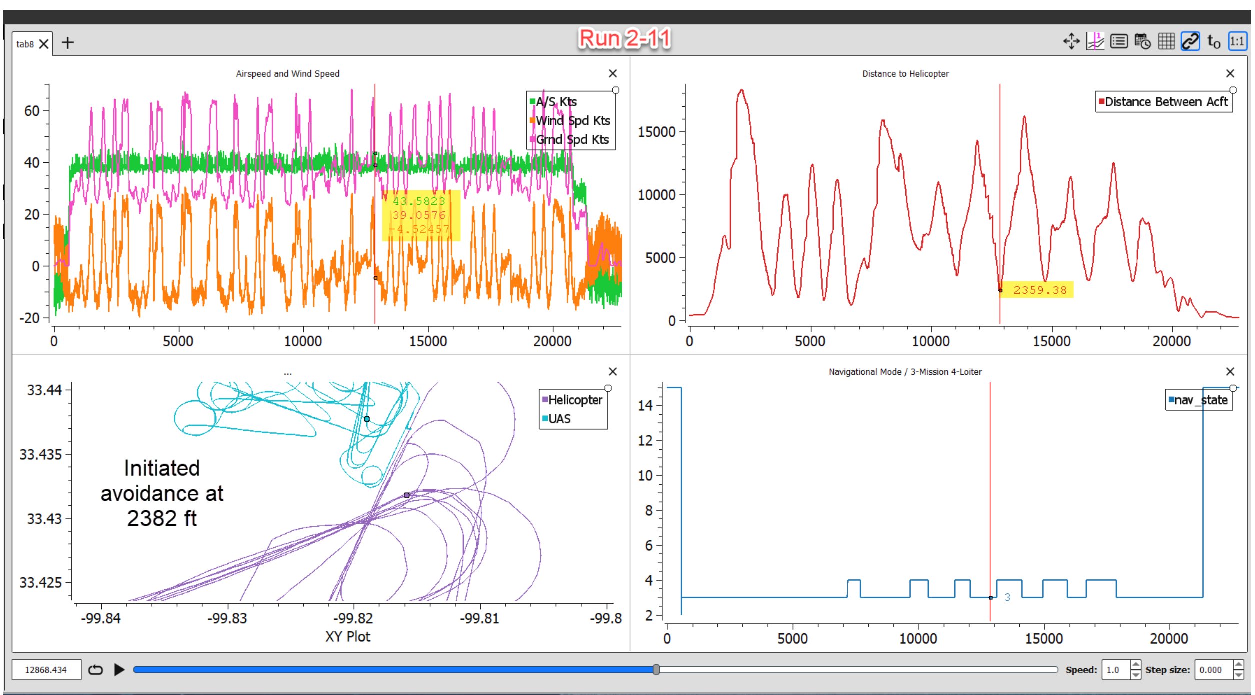


Figure 130. Round 2, Run 2-11, Area RAC, Converging Encounter.

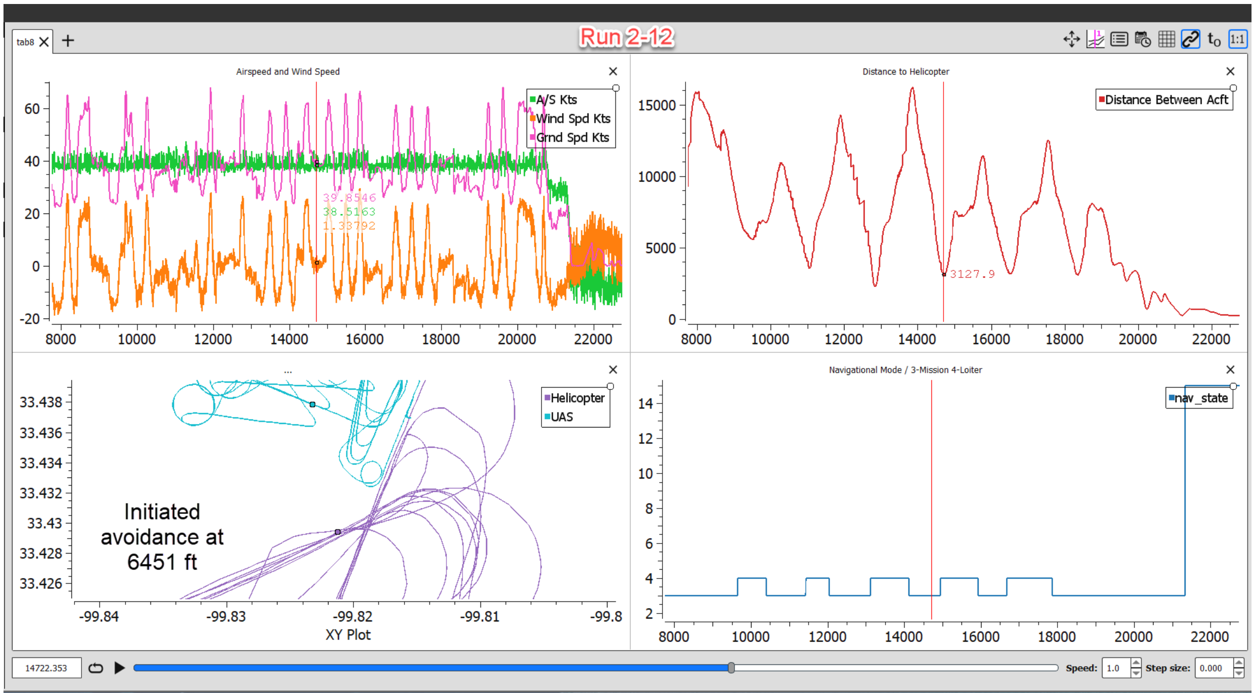


Figure 131. Round 2, Run 2-12, Area RAC, Converging Encounter.

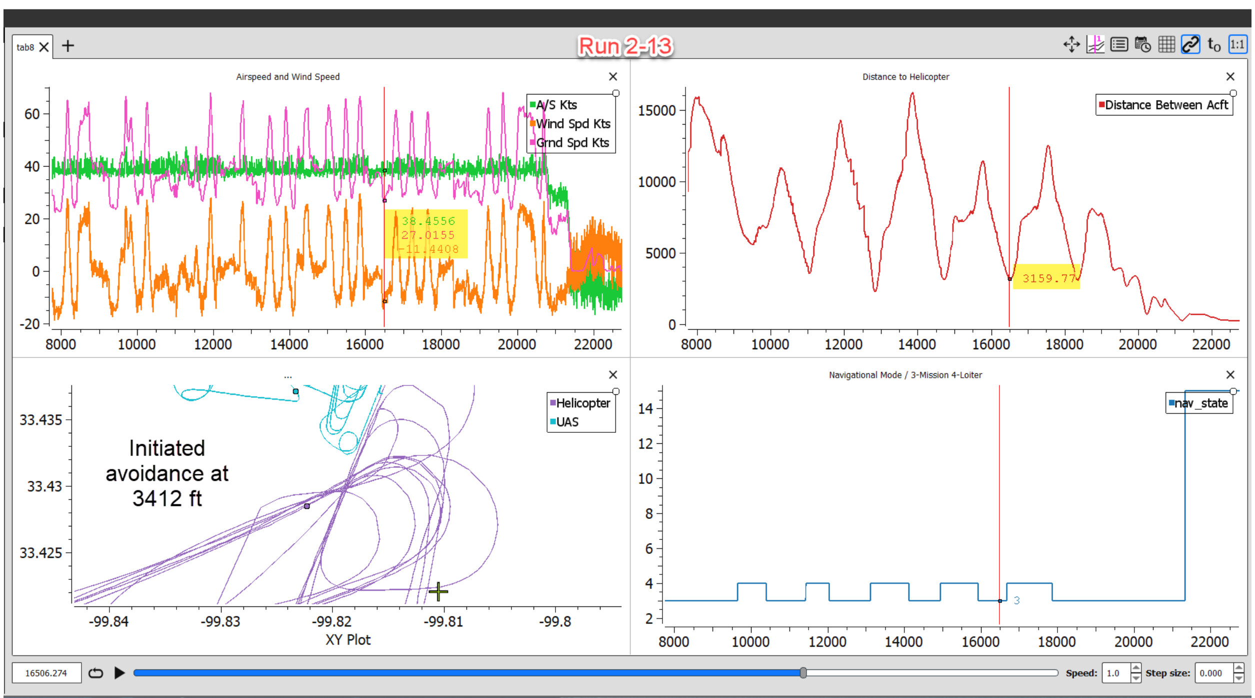


Figure 132. Round 2, Run 2-13, Area RAC, Converging Encounter.

3.3 Remote ID – Round 3

3.3.1 sUAS vs sUAS (UND)

3.3.1.1 Round-3, sUAS_sUAS

Table 86. Round 3 (RID) Encounter Criteria and Objectives.

Encounters	Objective
Symmetric	Aircraft will parallel each other while increasing and then decreasing in horizontal separation distances in order to collect UAS to UAS received RID data for analysis.
Head-On Horizontal	Aircraft will approach on a head-on course with a horizontal separation of 300ft, with the same altitude.
Head-On Vertical	Aircraft will approach on a head-on course with a vertical separation of 75 ft.

An iPod Touch is used as a receiver, mounted on the ScanEagle. An iPod Touch with a Bluetooth 4.0-enabled receiver was used as the receiver. The effectiveness of the RID system depends not only on the receiver but also on the sender's configuration. This includes the type of RID wireless technology (e.g., WiFi, Bluetooth), transmission power, broadcast rate, etc. The packet reception rate depends on the number of packets sent by the sender versus the number of packets successfully received by the receiver. This rate can vary based on factors such as the distance between the receiver and sender, antenna orientation, and the mobility of the sender, receiver, or both. The iPod Touch devices are installed with the Drone Scanner app and configured to capture Bluetooth RID packets. Each Scan Eagle is equipped with a receiver module, set up to collect RID data from other aircraft. Two aircraft, both equipped with RID modules, were flown in parallel with varying horizontal distances, starting with a minimum of 300 feet. These symmetric flights increased the distance by 300 feet each time. The results indicate that the receiver module could capture only a few data packets when the distance was 300 feet. The data captured by the RID module is insufficient for an operator to determine the trajectory of an incoming aircraft and make immediate decisions.

The head-on horizontal approach aims to evaluate the efficiency of the RID receiver in capturing packets when unmanned aircraft are on a head-on course with a smaller horizontal separation. The aircraft speeds are set at 50 knots and 70 knots on a head-on course. The data received from the receiver module shows that it could capture very few packets. The average receiving rate is slightly higher compared to the vertical head-on approach, where a vertical distance of 75 feet separates aircraft. As shown in Figure 138, the receiver rate, which is the packet count per second at the receiver, is calculated. The receiver rate is calculated as follows: First, measure the flight duration for each event with a given separation. Next, count the total number of data packets within that duration. Finally, divide the total number of packets by the flight duration for the given segment.

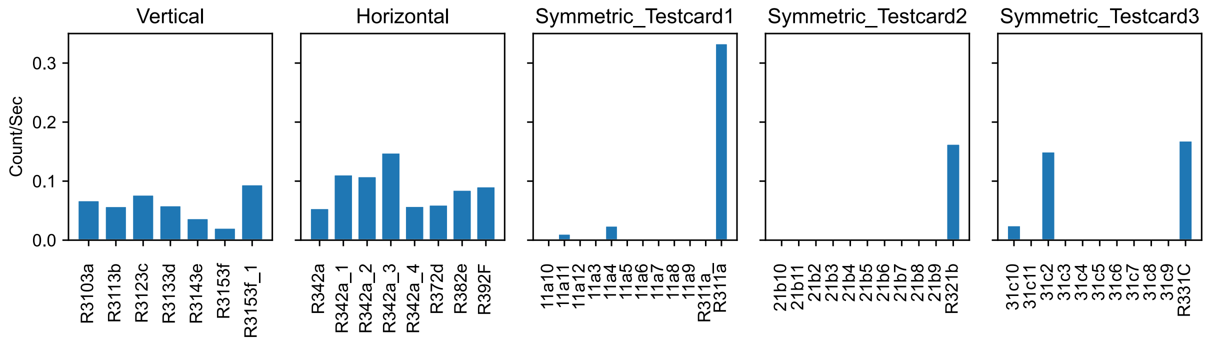


Figure 133. Round-3, RID:1 Data receiving rate (counts/sec) for different encounter criteria.

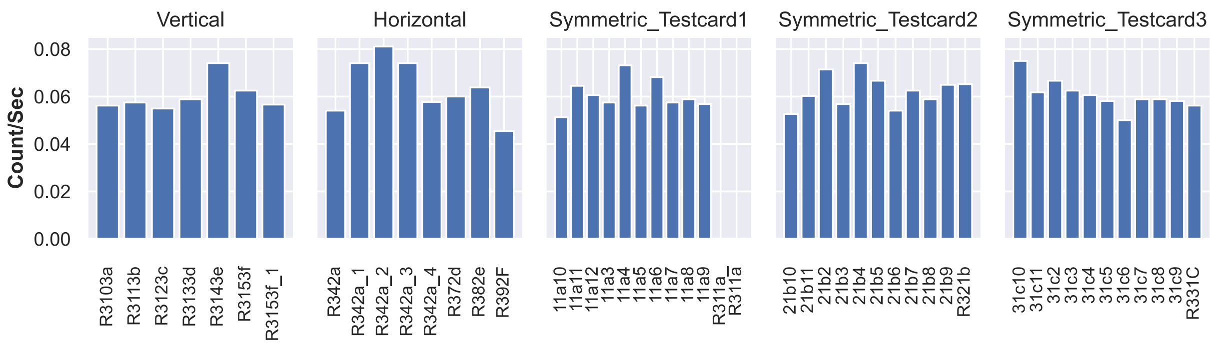


Figure 134. Round-3, RID:2 Data receiving rate (counts/sec) for different encounter criteria.

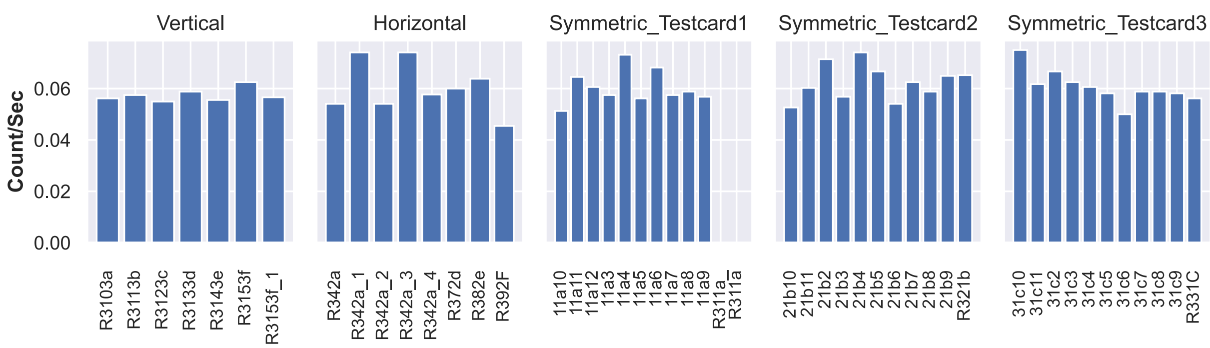


Figure 135. Round-3, RID:3 Data receiving rate (counts/sec) for different encounter criteria.

3.3.1.2 Flight Test-Observation

On average, a detection rate of approximately 0.06 packets per second was observed. RID messages were frequently absent. Rate of detection and the probability of detection is very low. During flight testing, Remote ID information received at RPIC (sUAS) did not provide enough data to be used to avoid another aircraft or assist in RoW decisions.

The broadcast rate was set at 1 Hz. Increasing the sender rate to 10 packets per second would enhance the probability of message receipt. However, in scenarios involving multiple UAVs or a swarm of UAVs, an increase in data broadcasts can lead to higher packet collisions, potentially resulting in a lower reception rate. As the number of senders grows, the likelihood of interference also increases. Therefore, further research is necessary to determine the optimal broadcast rate for situations where multiple UAVs are operating (high-density operation) in the same area.

3.3.2 Flight test Observation (ERAU)

This section reports on Round 3 RID. Embry-Riddle Aeronautical University-Worldwide Campus, Department of Flight, conducted the Round 3 A54 flight tests at F75, Harrison Field of Knox City Texas on 20-23 May 2024,. For context, please refer to Figure 1 below.

ERAU Flight Test Encounter General Information

- There are three rounds of testing
  - Round 1 is sUAS vs. Crewed Aircraft in General Encounters (Head-on, Converging, and Overtaking). Section 4.1.4.
  - Round 2 is sUAS vs. Crewed Aircraft where the sUAS is confined to avoid within a notionally reserved block of airspace. Section 4.2.4.
  - Round 3 is sUAS vs. sUAS in Head-on and Perpendicular encounters. This section.
- All Round 1 and 2 tests were run using Robinson R-44 Helicopter and an Applied Aeronautics Albatross FW UAS.
- All Round 3 tests were run using the Applied Aeronautics Albatross FW UAS and the DJI Matrice M300RTK.
- Test runs for this round were designed using initial simulation recommendations from the UND Team.
- Each type of encounter in this round will include the Albatross FW sUAS avoiding a Matrice RW sUAS and collection of signal strength for detectability.
- UA sNMAC volume used for the test runs was 100’ horizontally and 25’ vertically.
- The aircraft were co-altitude.

Test team personnel;

Dr. Scott Burgess, Flight Director, LRS (runway) RPIC, recovery pilot, lead researcher.
Dr. David Thirtyacre, GCS autonomous RPIC, data collector, team researcher.
Dr. Joseph Cerreta, Ground Safety, VO, data collector, team researcher.
Mr. Ryan Johnston, Applied Aeronautics CEO, Lead Pilot, data collector and processor, team researcher.

Test aircraft

Rotary-Wing sUAS aircraft consisted of a 2022 DJI Matrice M300RTK
Fixed-Wing sUAS aircraft consisted of a 2023 Applied Aeronautics Albatross

Aviation Surveillance Equipment

Rotary-Wing sUAS Aircraft:	DJI proprietary Remote Identification
	DroneTag Mini RID Module
	iPod Touch (Drone Scanner Application)
Fixed-Wing sUAS Aircraft:	UASionix pingRX Pro ADS-B In
	DroneTag Mini RID Module
	iPod Touch (Drone Scanner Application)

Ground Control Station (sUAS)

20' enclosed trailer as hardened Ground Control Station.

3 x monitors for ADS-B traffic feed, Airspace map or Weather map, RID traffic feed (run by Dell 5430 Latitude Rugged).

1 x monitor for the Applied Aeronautics Ground Station (AAGS) software (uses QGC as backbone).

AAGS (run by MacBook Pro).

1 x iCom IC-A120 VHF Base station.

1 x Davis Instruments Vantage Pro2 Weather Statement.

4 x Wireless VOX headsets

Test Location. Harrison Field of Knox City, Texas. Airport Identifier F75.

Test Area Run Configurations. The team designed two test area configurations based upon typical commercial sUAS mission sets. The goal was to design configurations that could support as many encounter geometries as possible. The team designed two large areas for the Round 2 RAC, one for head-on encounters and one for converging. There was a linear

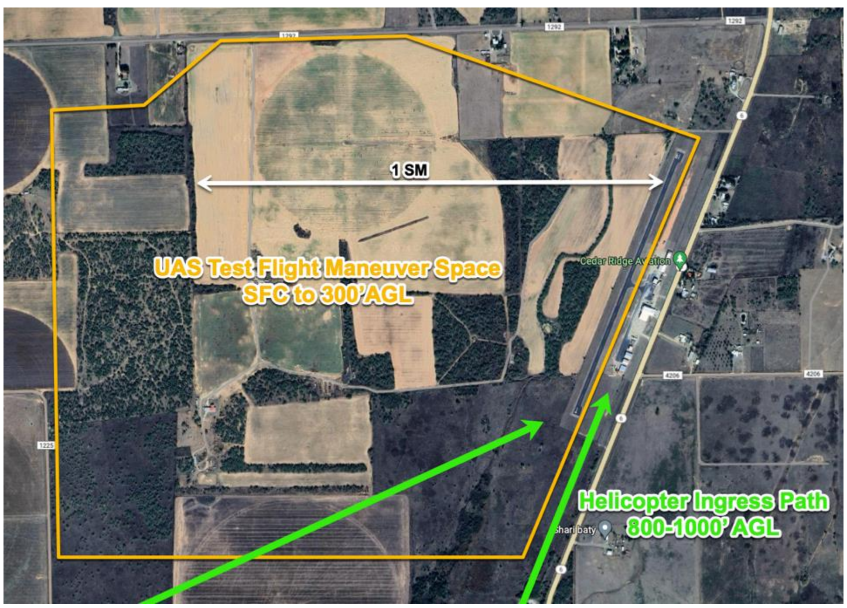


Figure 136. Flight Test Area.

The above figure illustrates that to maintain organizational aviation safety parameters, FAR Part 107.39 (flight over people), and noise abatement considerations (helicopter), emergency recovery tasks, this test area configuration provided the best total performance.

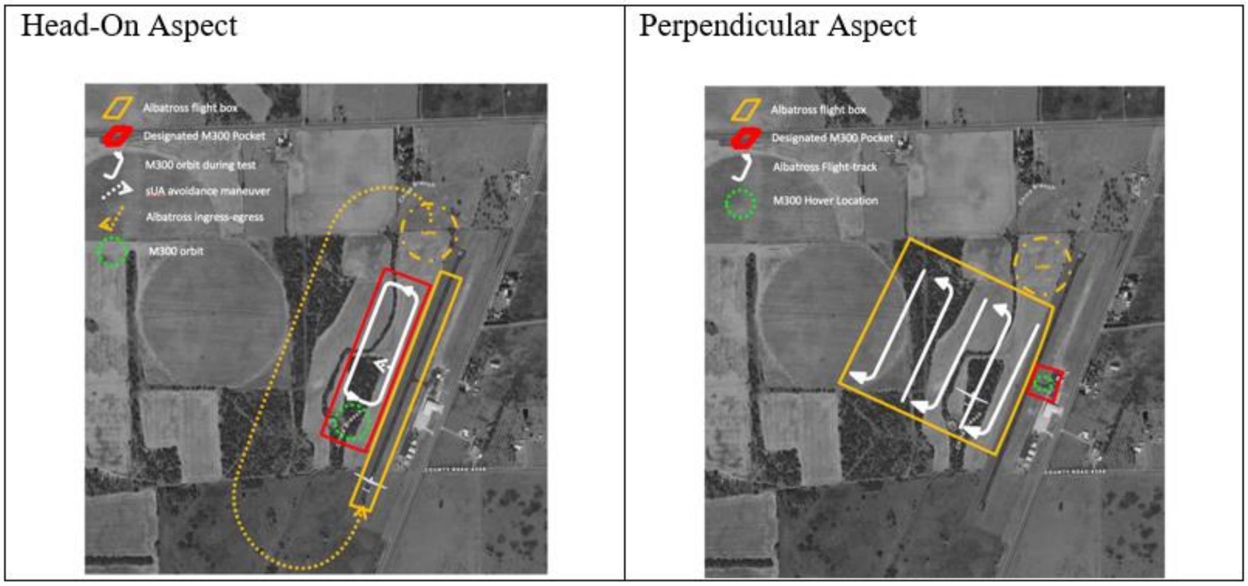


Figure 137. Test Run Configurations In this round of flight, the head-on and perpendicular aspects are tested.

The above figure shows that the intent was to collect RID packet data at varying distances. ERAU used a similar flight pattern concept to UND for consistency.

Round 3 Objectives.

- While conducting a variety of encounters, (head-on and converging geometries) identify the usefulness of RID devices on sUAS(s) to inform ROW rules.
  - Collect RID data and analyze its usefulness for sUAS to identify position (i.e. head-on & converging) in relation to another sUAS.
  - Analyze if the RID data provides the sUAS operator(s) the necessary information to determine what path to comply with when following proposed RoW rules.
- Evaluate the data received, including update rate, from RID equipment installed on sUAS and determine its impact on sUAS operator actions to identify a possible sUAS encounter or decide what RoW rule will be performed.
  - Evaluate the change of the update rate as you get closer to the sUAS intruder to determine its usefulness on RoW decision making for UAS interactions between two unmanned aircraft.

This test was planned in conjunction with UND parameters in parallel for data commonality. The ERAU test was to support data collection on two sUAS, one fixed wing and one multi-copter.

Test cards were followed. Preflight procedures and test setup went according to plan. Flights were conducted and when completed, the data was downloaded. Upon review of the data, however, it was found that the iPod Touch collected data was corrupted. Lat/Long data did not mimic flight route information from the flight thought to be incapable due to compatibility with RID reception capabilities.

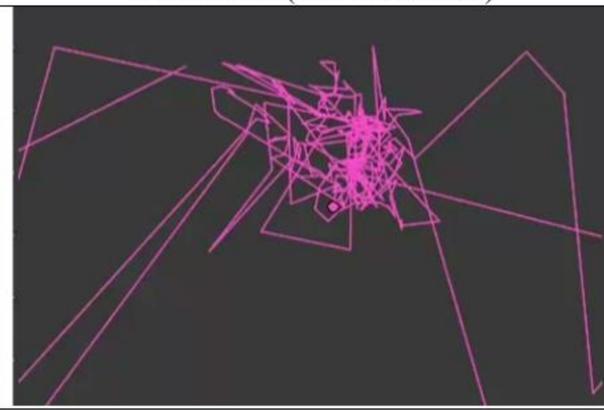
Albatross Flight Log	iPod Touch (Drone Scanner)
	

Figure 138. Flight test stations iPod Touch.

The following imagery above shows Albatross flight paths from two sources. Flight log data from the Albatross GPS (left side) and the RID signal in Drone Scanner App (iPod Touch) data (right side). We have reached out to the Drone Scanner authors (Czech Republic) for assistance on these anomalies and they feel that the iOS power saving features may have disrupted accurate scanning of signals. Replay of the static tests somewhat confirm this as intermittent signal receptions at points near where the aircraft was located (on a table) show some gaps in time and different locations (all within 0-15 meters). Time anchors in the data are inadequately aligned.

The DroneTag RID devices were functioning properly as shown in the flight test GCS recordings below indicate the live RID data matches GPS location of the Albatross in flight.

Figure 139. GCS monitor layout shows simultaneous aircraft locations in two different programs.

Both the Albatross telemetry and the DroneTag telemetry as you can see in this side-by-side image below, show identical flight paths.

Albatross Flight Log	DroneTag Mini Log
	

Figure 140. AAGS Albatross Telemetry (left) and DroneTag Mini Telemetry of test flight run 3-1.

4 CONCLUSION/INTERPRETATION OF SIMULATION AND FLIGHT TESTING DATA

4.1 Key Interpretations identified to inform RoW Recommendations

Throughout the document, there have been prominent themes. These themes will lay the groundwork for the final report which will provide the final RoW Recommendations.

- Distances for sUAS to safely maneuver to avoid other sUAS is significantly less distance than between a sUAS and crewed aircraft.
- In situations where there is ample altitude, vertical and combined vertical and horizontal (unrestricted) maneuvers require the least distance and time to safety avoid another aircraft. When sUAS descended, speed increased, also causing closure rate to increase as well.
- In situations where altitude flexibility and terrain details are limited, especially below 400 ft AGL, horizonal maneuvers are more advantageous unless a crewed aircraft who does not have RoW, is overtaking a sUAS and does not alter course.
- Assuming a sUAS or crewed aircraft may not properly follow given right of way rules, participating sUAS may need to establish additional spacing (i.e. buffer) to ensure separation.
- Handling characteristics of sUAS must be standardized to enable predictability when avoidance maneuvers are initiated.
- Based on distance required for separation, various maneuvers may be recommended for a given scenario to remain well clear. These findings will also inform RoW recommendations.
- Reserved airspace concept shows to provide greater protection by reducing risk of non-cooperative traffic or traffic that does not execute RoW avoidance maneuvers. Additional research is needed to identify boundaries needed to prevent NMAC or WC violations.
- Short-term - there are significant human factors and situational awareness benefits of using ADS-B In as a viable solution for separation of sUAS and crewed aircraft. Consideration should be given to required ADS-B out for crewed and possibly unmanned aircraft.
- Crewed aircraft are unable to effectively visually identify sUAS; therefore, the burden must be left to the sUAS aircraft to detect and avoid.
- SUAS standards are not consistent for GPS accuracy, maintaining a given altitude, or having the current terrain data to safety prevent controlled flight into terrain.
- Standards are needed to identify “Well Clear” between two or more sUAS.
- If sUAS are equipped with appropriate GPS systems, aviation grade altimeters and DAA systems need new standards identified to create a new “Well Clear” between sUAS and Crewed Aircraft. For example, different GPS sensors on the Albatross recorded varying altitudes. This discrepancy shows an average difference of 19 feet between the two sensors. This highlights the importance of considering potential variations when using multiple GPS devices.
- RPIC DAA situational awareness is enhanced when distance graphics (criteria based) were available

- Criteria-based distance graphics should be displayed on GUI to enhance situation awareness to RPICs.
- Response times to execute a RoW maneuver vary based on the complexity of the system, the amount of steps RPIC must perform to complete maneuver, situational awareness, and time provided to make decision.
- Reserved airspace concept provides a short-term solution to enable sUAS to conduct commercial operations BVLOS while new DAA standards and related infrastructure are developed.
- Reserved airspace concept research identifies viability of concept to enable RoW rules for shielded operations while protecting non-cooperative crewed aircraft for mid-air collisions.
- Non-cooperative traffic provides a unique challenge, reserved airspace concept research results provide a unique opportunity to enable non-cooperative crewed aircraft and sUAS to conduct commercial operations without fear of a mid-air collision.
- The burden of maintaining RoW cannot be placed on a crewed aircraft who cannot reasonably be expected to see and avoid a sUAS.
- Developing the reserved airspace concept provides a way to separate non-cooperative crewed aircraft and sUAS with DAA systems that do not have 360-degree capability to detect and avoid but are equipped with ADSB In to identify all cooperative crewed aircraft.
- Required ADS-B In and Out for all crewed aircraft would improve safety between sUAS and crewed aircraft.
- Based on the research, certified and larger UAS or AAM aircraft who operate above 400 ft will be more effective at maintaining well clear if vertical and combined vertical and horizontal maneuvers are executed.
- If an identification and priority system could be developed (with associated standards) and approved for sWC and sNMAC distances (for sUAS), small sUAS could use vertical separation for situations where the aircraft are in a confined area such as shielded flight operations.
- Reserved airspace concept approvals could be predicated on sUAS saturations levels for requested areas, complexity of airspace, type of equipment, weather conditions, and DAA capabilities.

4.2 Conclusion

In conclusion, there are several themes which stand out and will help researchers to address RoW rules in the final recommendations. As the previous tasks reported and guided the team, the efforts planned for flight testing were prompted by a need to address the following areas in support of the original research questions derived out of the request for proposal;

- General interactions
  - between (cooperative and non-cooperative) crewed and uncrewed aircraft,
  - between uncrewed versus uncrewed aircraft,
- Concepts for reserved airspace interactions
  - between (cooperative and non-cooperative) crewed and uncrewed aircraft,

    - between uncrewed versus uncrewed aircraft,
- Remote Identification viability in supporting any RoW recommendation.

The themes which will influence final recommendations are the following;

- Maneuverability factors related to both currently available aircraft and aircrew capabilities.
- Human Factors regarding decision making and crew reaction times.
- Capabilities of industry-wide available sUAS DAA, and flight systems, supporting accuracy and airspace intelligence
- Clear separation standards

With the interpretations above, guided by simulation and flight testing, the A54 team has a path to providing viable RoW recommendations to the FAA.

BIBLIOGRAPHY

UND

[1] RTCA. (2017). Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems. RTCA DO-365.

[2] Weinert, A., Campbell, S., Vela, A., Schuldt, D., & Kurucar, J. (2018). Well-clear recommendation for small unmanned aircraft systems based on unmitigated collision risk. *Journal of air transportation*, *26*(3), 113-122.

[3] SC, R. (2020). Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment. RTCA DO-229F.

[4] Grayson, B., Penna, N. T., Mills, J. P., & Grant, D. S. (2018). GPS precise point positioning for UAS photogrammetry. *The photogrammetric record*, *33*(164), 427-447.

[5] United States. Federal Aviation Administration. (2022). Wide Area Augmentation System Performance Analysis Report #81. U.S. Dept. of Transportation, Federal Aviation Administration.

[6] United States. Federal Aviation Administration. (2021). Global Positioning System Standard Positioning Service Performance Analysis Report #115. U.S. Dept. of Transportation, Federal Aviation Administration.

[7] ASTM. (2019). Standard Specification for Remote ID and Tracking. ASTM F3411 – 19.

KU

[1] Khatib, O., 1985, "Real-Time Obstacle Avoidance for Manipulators and Mobile Robots," SIGGRAPH '87 Proceedings of 1985 IEEE International Conference on Robotics and Automation, St. Louis, MO, March 25–28, pp. 500–505.

[2] Reynolds, C. W., 1987, "Flocks, Herds and Schools: A Distributed Behavioral Model," Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques, ACM, New York, pp. 25–34.

[3] Leonard, N. E., and Fiorelli, E., 2001, "Virtual Leaders, Artificial Potentials and Coordinated Control of Groups," Proceedings of the 40th IEEE Conference on Decision and Control, Orlando, FL, Vol. 3, pp. 2968–2973.

[4] Stastny, T.J., Garcia, G., Keshmiri, S., "Collision and Obstacle Avoidance in Unmanned Aerial Systems Using Morphing Potential Field Navigation and Nonlinear Model Predictive Control," ASME Journal of Dynamic Systems, Measurement and Control, ASME, 2014, https://doi.org/10.1115/1.4028034.

A. APPENDIX A – GENERAL INTERACTIONS – ROUND 1

A.1. sUAS vs sUAS (UND)

A.1.1 Following Right-of-Way Rules

These results are for a 35 knot sUAS ownship vs a 50 knot sUAS intruder in the scenario where both aircraft follow right-of-way rules. There are four GPS uncertainties, four climb/descent rates, two pilot response times, and three maneuver restrictions for each of the geometry categories. The four GPS uncertainties are RTK, WAAS, SPS GPS, and GPS MAX. Climb rates are 250fpm, 500fpm, 750fpm, and 1000fpm. Pilot response times of one second and five seconds. Maneuver restrictions of horizontal-only, vertical-only, and unrestricted.

A.1.1.1. Head-on

Table 87. General Interactions sUAS vs sUAS Following Rules, Head-on, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1313	657	1313	657	1313	673	1329
vertical-only	771	1444	837	1493	952	1625	1592	2248
unrestricted	657	1313	657	1313	657	1313	673	1329
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1313	657	1313	657	1313	673	1329
vertical-only	607	1280	640	1296	657	1313	968	1641
unrestricted	607	1280	640	1296	640	1313	673	1329
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1313	657	1313	657	1313	673	1329
vertical-only	509	1165	607	1264	607	1280	771	1444
unrestricted	509	1165	607	1264	607	1280	673	1329
1000fpm desc	**RTK (0.03m 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1313	657	1313	657	1313	673	1329
vertical-only	493	1149	509	1165	591	1264	657	1313
unrestricted	493	1165	509	1165	591	1264	657	1313

A.1.1.2. Converging from Right

Table 88. General Interactions sUAS vs sUAS Following Rules, Converging from Right, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	771	1428	771	1428	771	1428	804	1444
vertical-only	1132	1772	1411	2051	1460	2100	2560	3216
unrestricted	755	1395	788	1428	788	1428	804	1444
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	771	1428	771	1428	771	1428	804	1444
vertical-only	771	1411	919	1559	952	1608	1575	2231
unrestricted	624	1280	739	1395	755	1411	870	1477
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	771	1428	771	1428	771	1428	804	1444
vertical-only	624	1280	739	1395	771	1411	1247	1887
unrestricted	607	1264	624	1280	640	1296	903	1542
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	771	1428	771	1428	771	1428	804	1444
vertical-only	607	1247	624	1280	640	1296	968	1608
unrestricted	591	1247	607	1264	624	1264	804	1444

A.1.1.3. Overtaking

Table 89. General Interactions sUAS vs sUAS Following Rules, Overtaking, Required Detection Range in Feet.

Pilot Response Time	1	5	1	5	1	5	1	5
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	378	575
vertical-only	460	673	525	722	575	771	968	1165
unrestricted	345	542	361	558	361	558	378	575
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	378	575
vertical-only	312	509	361	558	378	575	591	788
unrestricted	329	525	345	542	345	542	361	558
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	378	575
vertical-only	279	460	312	509	312	509	460	673
unrestricted	312	509	329	525	329	525	361	558
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	378	575
vertical-only	263	460	279	460	279	476	394	591
unrestricted	296	493	312	509	312	509	361	558

A.1.2. Not Following Right-of-Way Rules

These results are for a 35 knot sUAS ownship vs a 50 knot sUAS intruder in the scenario where the intruder aircraft does not follow the right-of-way rules. There are four GPS uncertainties, four climb/descent rates, two pilot response times, and three maneuver restrictions for each of the geometry categories. The four GPS uncertainties are RTK, WAAS, SPS GPS, and GPS MAX. Climb rates are 250fpm, 500fpm, 750fpm, and 1000fpm. Pilot response times of one second and five seconds. Maneuver restrictions of horizontal-only, vertical-only, and unrestricted.

A.1.2.1. Head-on

Table 90. General Interactions sUAS vs sUAS Not Following Rules, Head-on, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	788	1444	788	1460	788	1460	804	1477
vertical-only	1165	1821	1444	2100	1493	2166	2625	3298
unrestricted	755	1428	788	1460	804	1460	821	1477
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	788	1444	788	1460	788	1460	804	1477
vertical-only	788	1444	936	1592	985	1641	1625	2281
unrestricted	640	1313	755	1428	771	1428	821	1493
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	788	1444	788	1460	788	1460	804	1477
vertical-only	640	1313	755	1428	788	1444	1280	1936
unrestricted	624	1280	640	1313	657	1329	837	1493
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	788	1444	788	1460	788	1460	804	1477
vertical-only	607	1280	640	1296	657	1313	985	1657
unrestricted	607	1264	624	1296	640	1296	821	1477

A.1.2.2. Converging from Left

Table 91. General Interactions sUAS vs sUAS Not Following Rules, Converging from Left, Required Detection Range in Feet

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	

horizontal-only	739	1395	739	1395	755	1395	771	1411
vertical-only	1132	1772	1411	2051	1460	2100	2560	3199
unrestricted	739	1395	755	1395	755	1411	771	1428
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	739	1395	739	1395	755	1395	771	1411
vertical-only	771	1411	919	1559	952	1608	1575	2231
unrestricted	624	1280	722	1346	755	1395	788	1428
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	739	1395	739	1395	755	1395	771	1411
vertical-only	624	1280	739	1395	771	1411	1247	1887
unrestricted	607	1247	624	1280	640	1296	788	1428
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	739	1395	739	1395	755	1395	771	1411
vertical-only	607	1247	624	1280	640	1296	968	1608
unrestricted	591	1231	607	1264	624	1264	788	1428

A.1.2.3. Overtaking

Table 92. General Interactions sUAS vs sUAS Not Following Rules, Overtaking, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	411	624	558	771	575	771	968	1165
unrestricted	837	968	903	1001	919	1034	1756	1838
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	

horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	312	509	361	558	361	558	624	821
unrestricted	312	509	329	525	361	558	903	1018
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	296	493	312	509	312	509	460	673
unrestricted	279	476	312	509	312	509	722	870
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	279	460	296	493	312	509	411	624
unrestricted	279	460	296	493	312	509	411	624

A.2. sUAS vs Crewed (UND)

A.2.1. Following Right-of-Way Rules

These results are for a 50 knot sUAS ownship vs a 120 knot Crewed intruder in the scenario where both aircraft follow the right-of-way rules. There are four GPS uncertainties, four climb/descent rates, two pilot response times, and three maneuver restrictions for each of the geometry categories. The four GPS uncertainties are RTK, WAAS, SPS GPS, and GPS MAX. Climb rates are 250fpm, 500fpm, 750fpm, and 1000fpm. Pilot response times of one second and five seconds. Maneuver restrictions of horizontal-only, vertical-only, and unrestricted.

A.2.1.1. Head-on

Table 93. General Interactions sUAS vs Crewed Following Rules, Head-on, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6792	7924	6792	7924	6792	7924	6792	7924
vertical-only	19292	NA	NA	NA	NA	NA	NA	NA
unrestricted	6792	7924	6792	7924	6792	7924	6989	8121
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6792	7924	6792	7924	6792	7924	6792	7924

vertical-only	10827	11959	11073	12205	11319	12451	12451	13583
unrestricted	6743	7875	6743	7875	6792	7924	7038	8121
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6792	7924	6792	7924	6792	7924	6792	7924
vertical-only	7973	9105	8219	9351	8268	9400	9056	10188
unrestricted	5709	6841	5906	7038	5906	7038	6201	7333
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6792	7924	6792	7924	6792	7924	6792	7924
vertical-only	6792	7924	6792	7973	6841	7973	7382	8514
unrestricted	5365	6497	5365	6497	5365	6497	5611	6743

A.2.1.2. Converging from Left

Table 94. General Interactions sUAS vs Crewed Following Rules, Converging from Left, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6644	7382
vertical-only	19095	NA	19636	NA	NA	NA	NA	NA
unrestricted	6497	7235	6497	7235	6644	7382	6644	7382
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6644	7382
vertical-only	10778	11861	10975	12107	11221	12304	12304	13436

unrestricted	6644	7382	6644	7382	6644	7382	6644	7382
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6644	7382
vertical-only	8071	9154	8121	9252	8219	9302	8957	10089
unrestricted	6497	7235	6497	7235	6644	7382	6644	7382
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6644	7382
vertical-only	6693	7825	6743	7875	6890	7973	7432	8563
unrestricted	5758	6546	5955	6644	5955	6693	6300	7038

A.2.1.3. Converging from Right

Table 95. General Interactions sUAS vs Crewed Following Rules, Converging from Right, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6644	7382	6644	7382	6644	7382	6644	7382
vertical-only	19144	NA	19636	NA	NA	NA	NA	NA
unrestricted	6644	7382	6644	7382	6644	7382	6644	7382
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6644	7382	6644	7382	6644	7382	6644	7382
vertical-only	10729	11861	10975	12107	11221	12353	12353	13485
unrestricted	6644	7382	6644	7382	6644	7382	6644	7382
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6644	7382	6644	7382	6644	7382	6644	7382
vertical-only	7973	9056	8170	9302	8170	9302	9006	10138
unrestricted	6644	7382	6644	7382	6644	7382	6841	7530

1000fpm desc	RTK (0.03m, 0.1m)		WAAS (1m, 2.2m)		SPS (1.72m, 3.42m)		MAX (8m, 13m)	
horizontal-only	6644	7382	6644	7382	6644	7382	6644	7382
vertical-only	6743	7875	6792	7875	6792	7924	7333	8465
unrestricted	5758	6497	5906	6693	5906	6693	6300	7038

A.2.1.4. Overtaking

Table 96. General Interactions sUAS vs Crewed Following Rules, Overtaking, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	12943	13632	13239	13977	13436	14125	14715	15453
unrestricted	12747	13436	13091	13780	13239	13977	14567	15256
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	7579	8268	7727	8465	7875	8613	8613	9302
unrestricted	7530	8268	7727	8416	7776	8416	8416	9105
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	5906	6644	5955	6693	5955	6693	6497	7186
unrestricted	5808	6497	5906	6644	5955	6644	6447	7136
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	5020	5709	5069	5758	5069	5808	5463	6152
unrestricted	4922	5611	5020	5709	5069	5808	5463	6152

A.3. General Interactions (KU)

A.3.1. Single vs Crewed (KU)

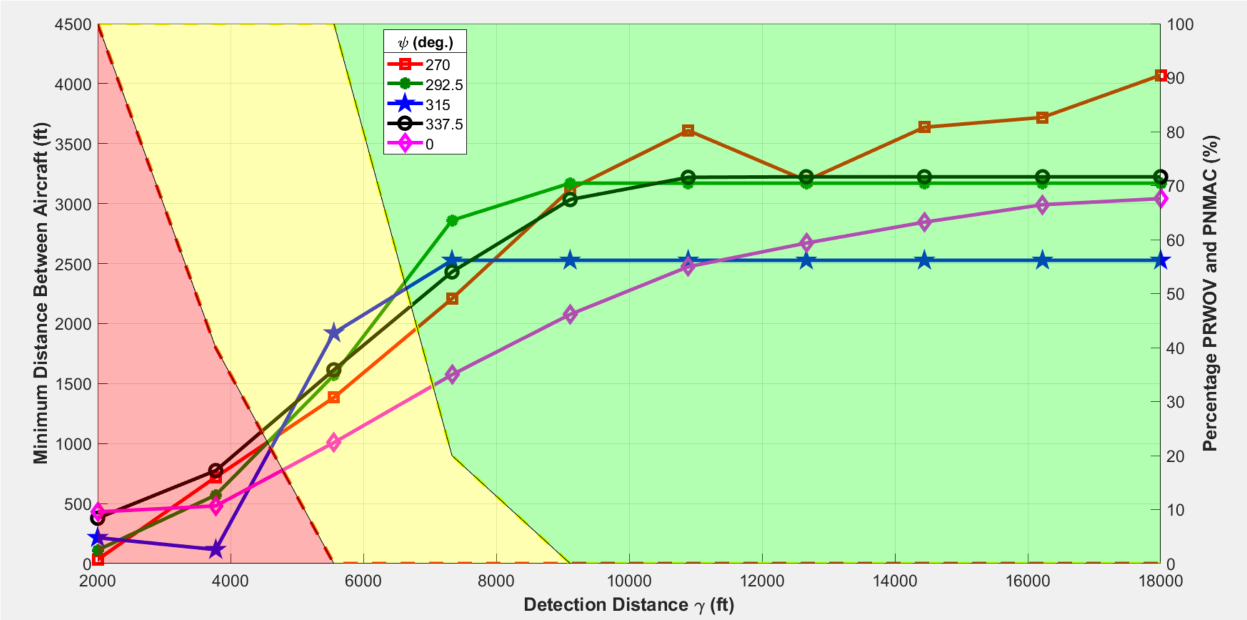


Figure 141. 145 ft/s Overtaking Single sUAS.

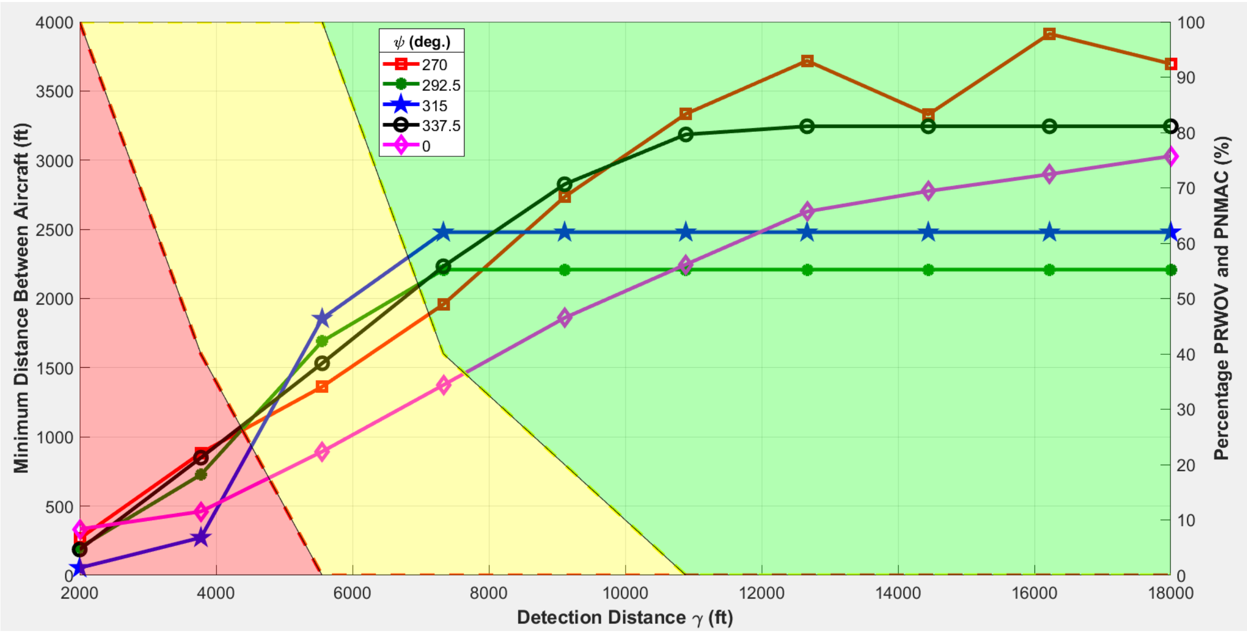


Figure 142. 170 ft/s Overtaking Single sUAS.

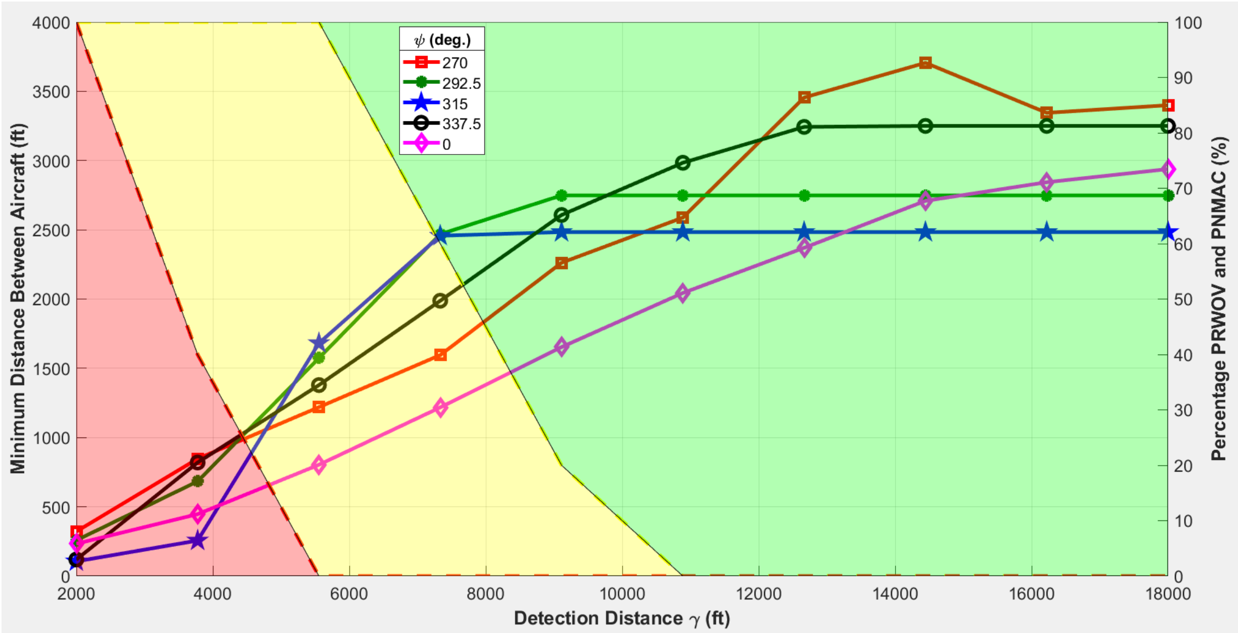


Figure 143. 195 ft/s Overtaking Single sUAS.

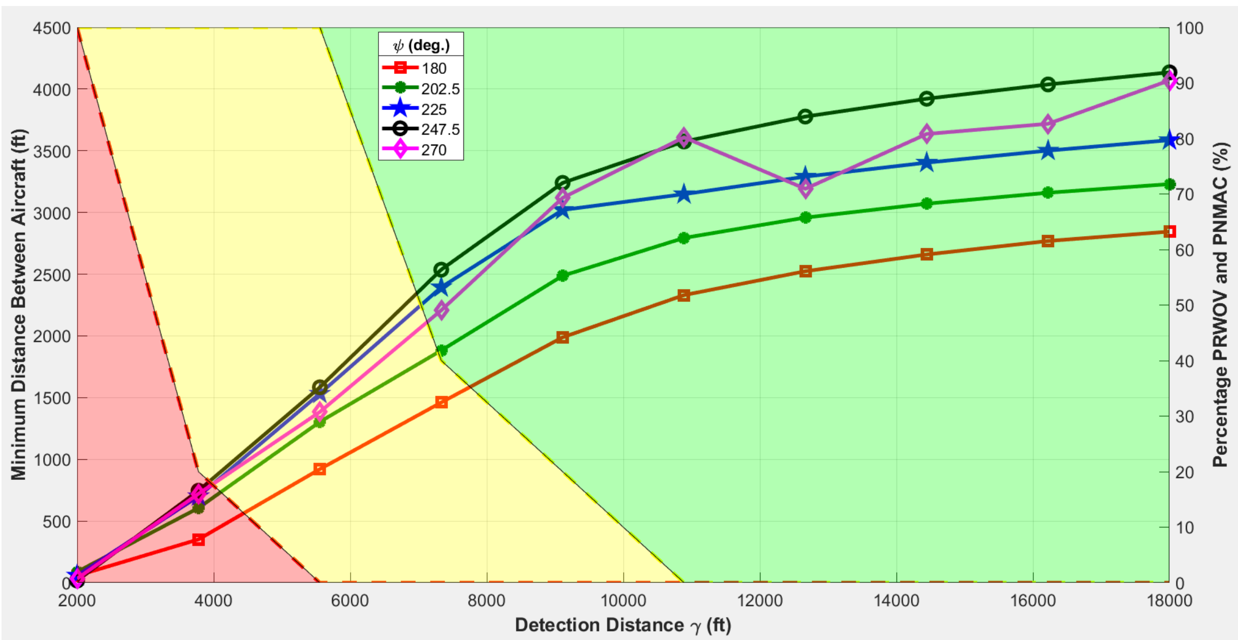


Figure 144. 145 ft/s Head-On Converging Single sUAS.

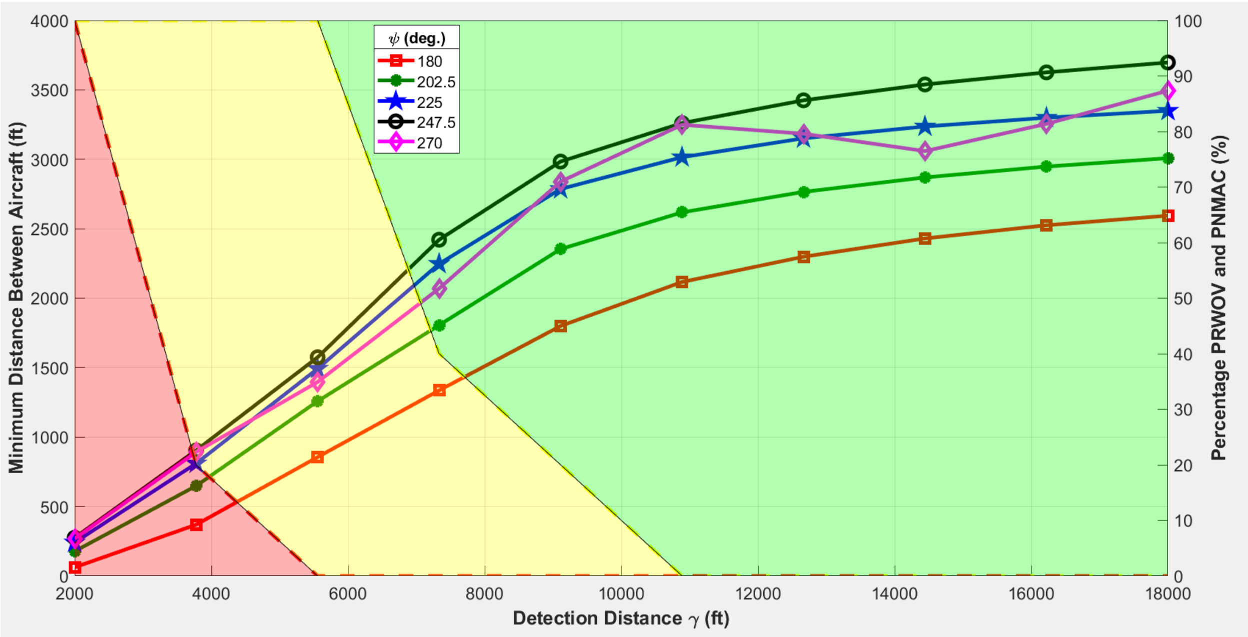


Figure 145. 170 ft/s Head-On Converging Single sUAS.

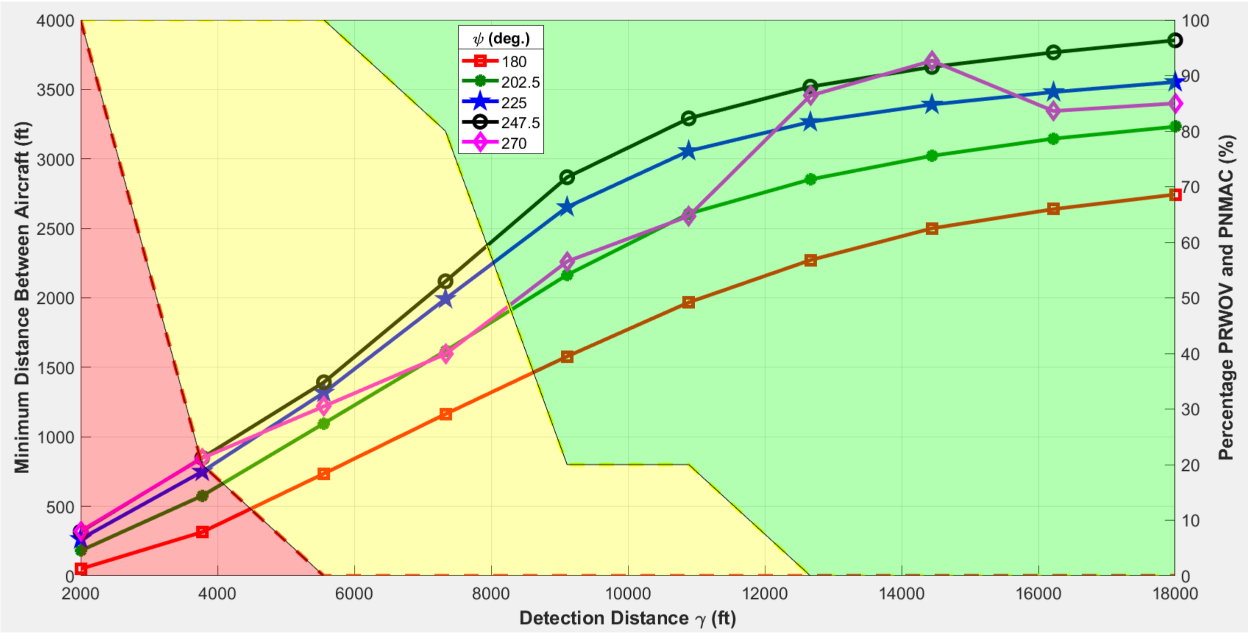


Figure 146. 195 ft/s Head-On Converging Single sUAS.

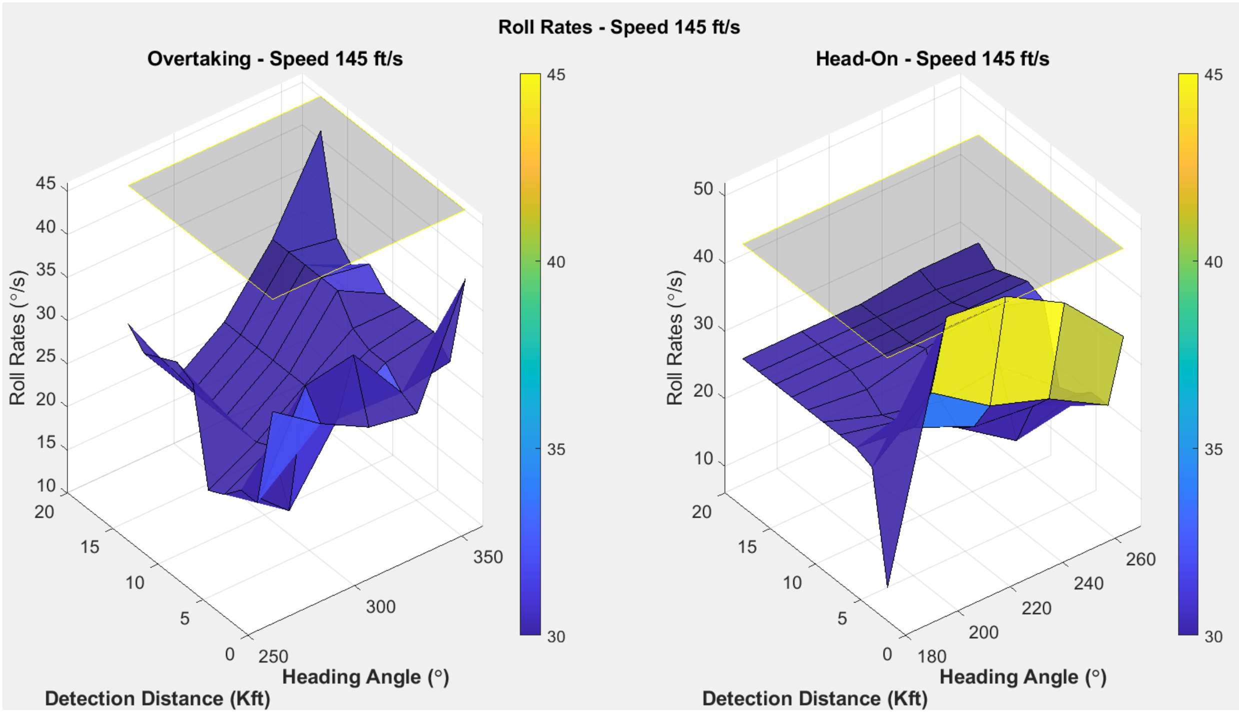


Figure 147. Roll Rates 145 ft/s.

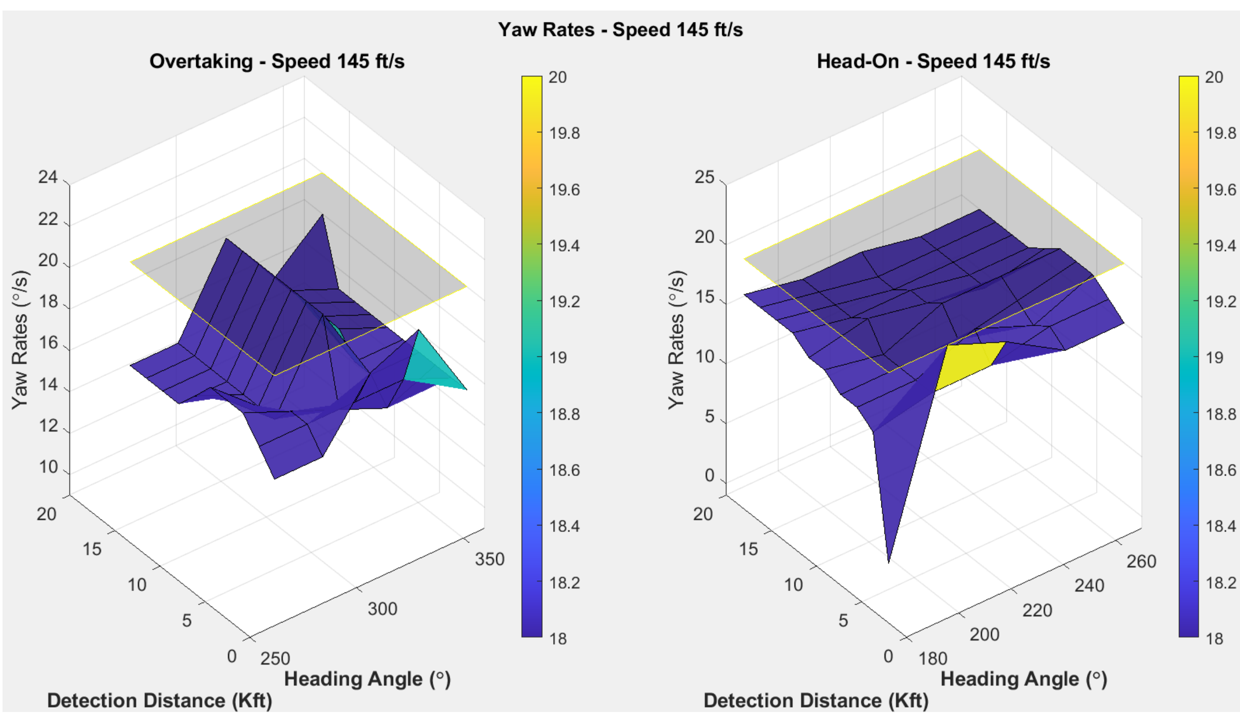


Figure 148. Yaw Rates 145 ft/s.

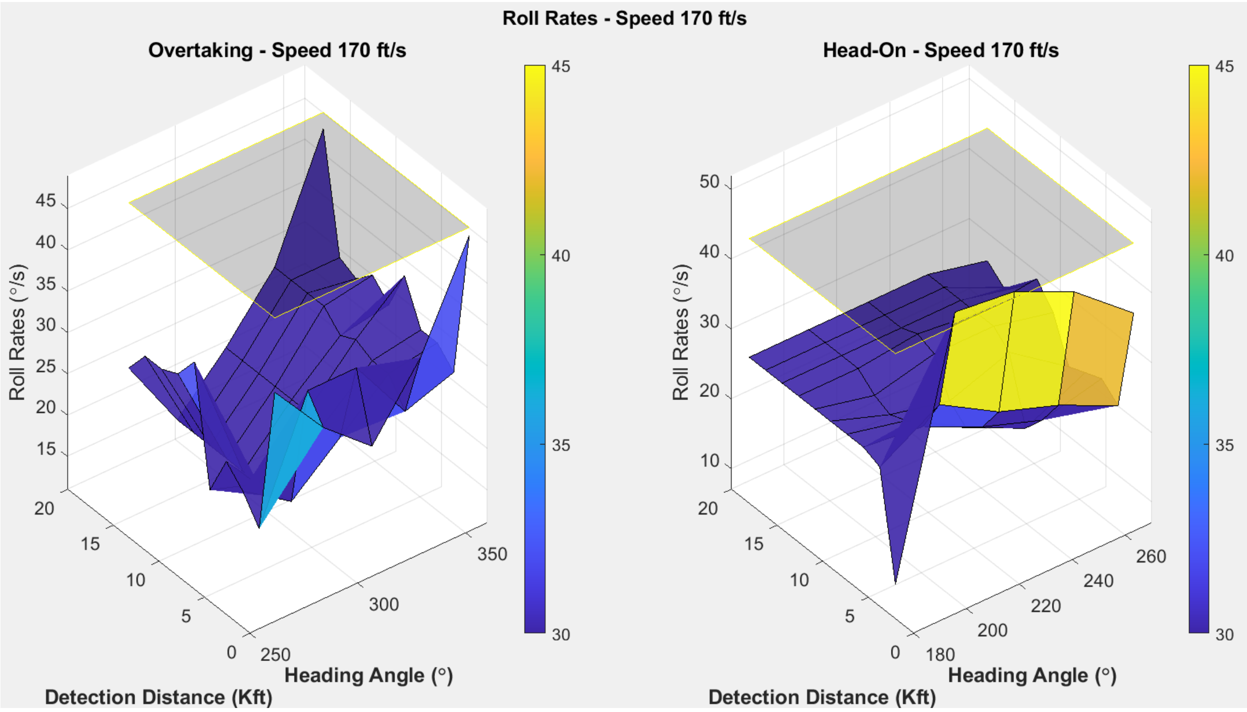


Figure 149. Roll Rates 170 ft/s.

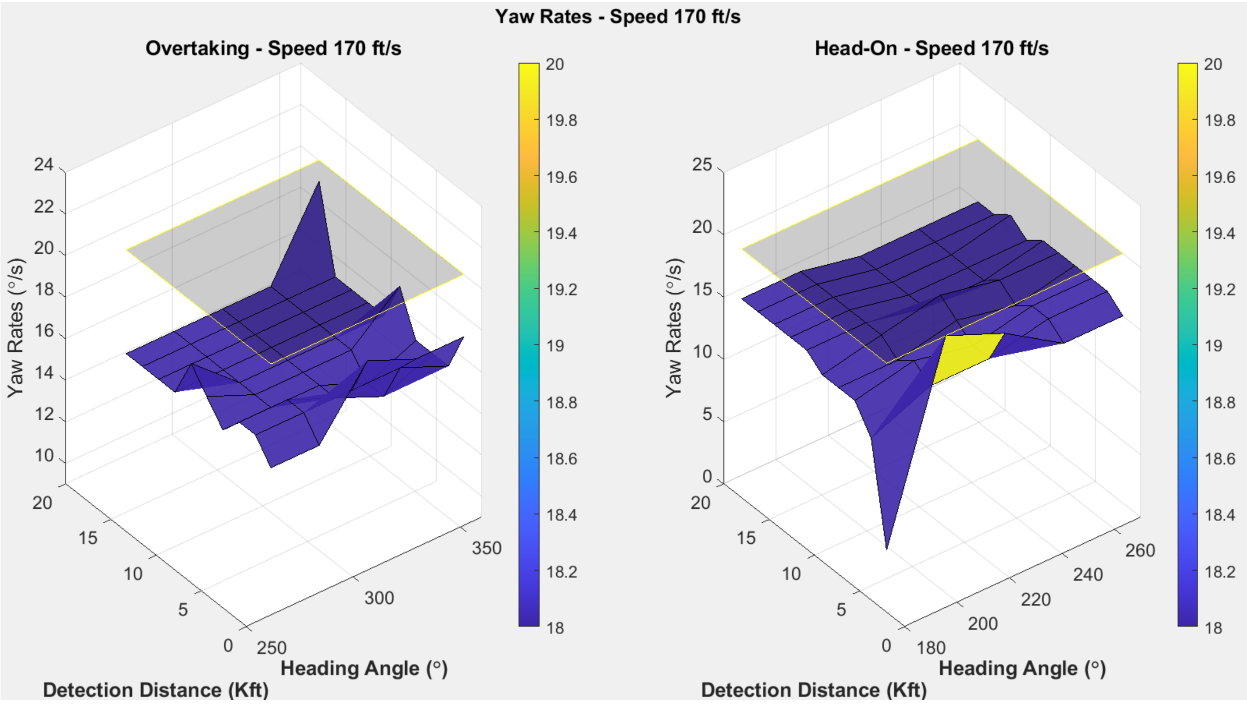


Figure 150. Yaw Rates 170 ft/s.

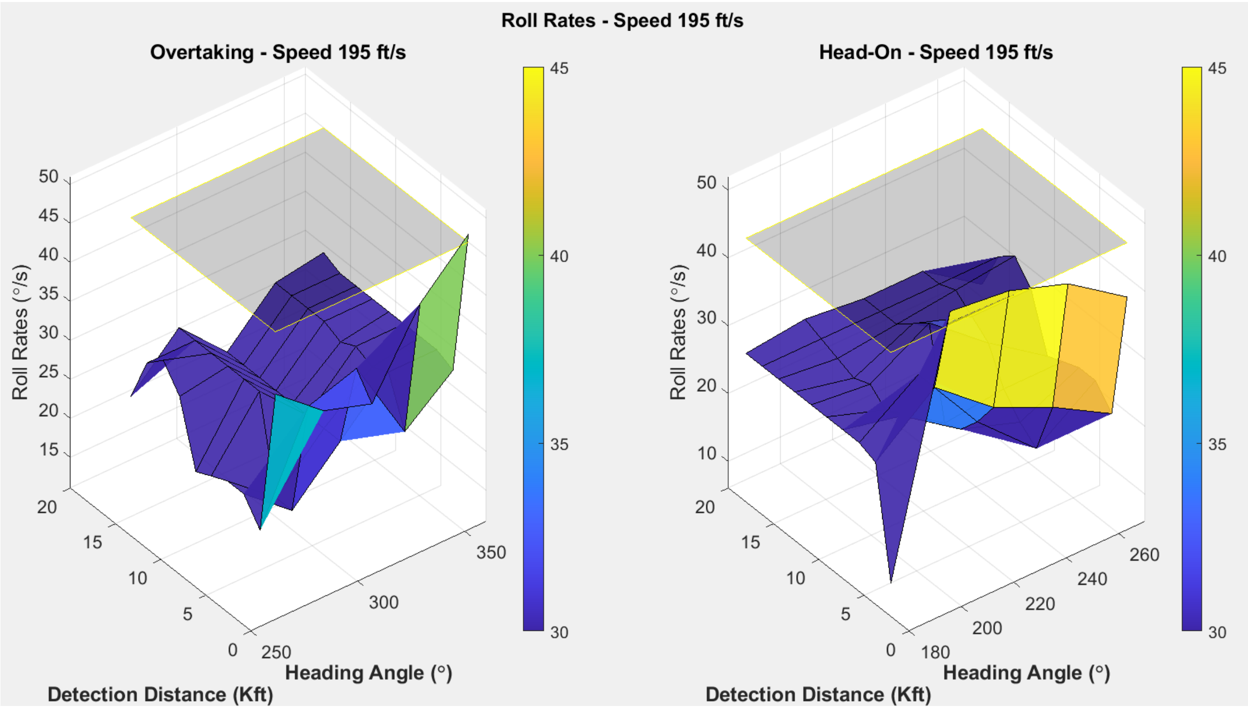


Figure 151. Roll Rates 195 ft/s.

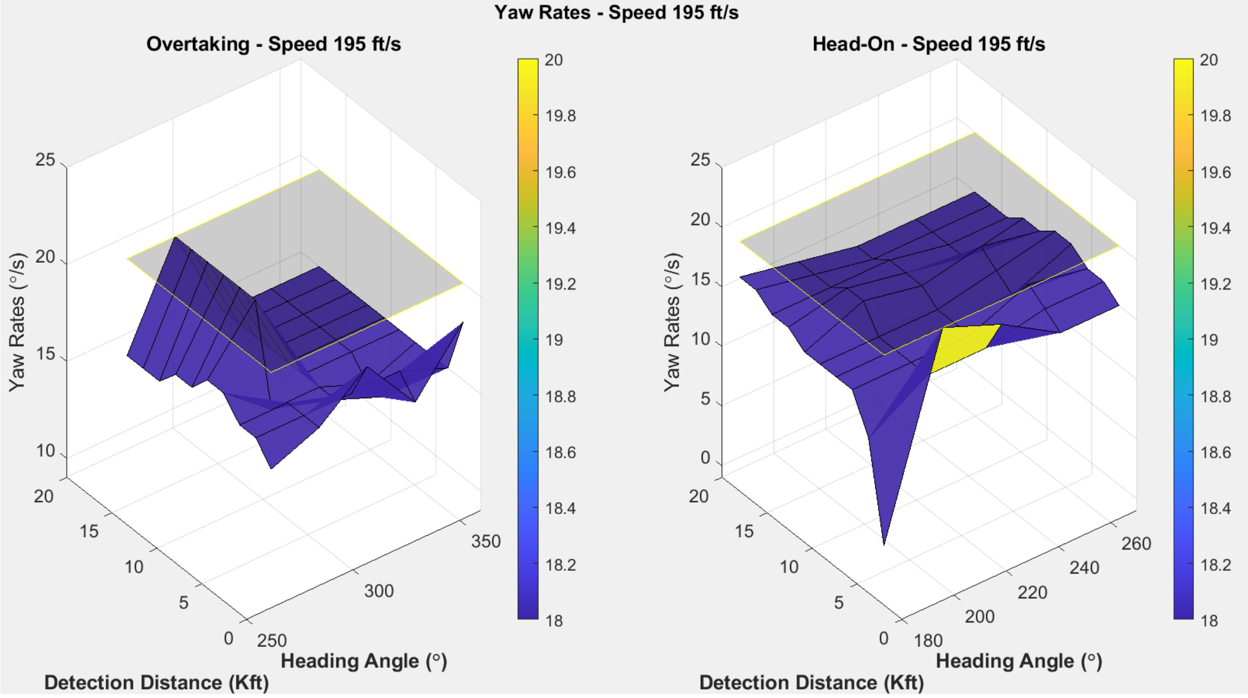


Figure 152. Yaw Rates 195 ft/s.

A.3.2. Mutiple sUAS vs Crewed (KU)

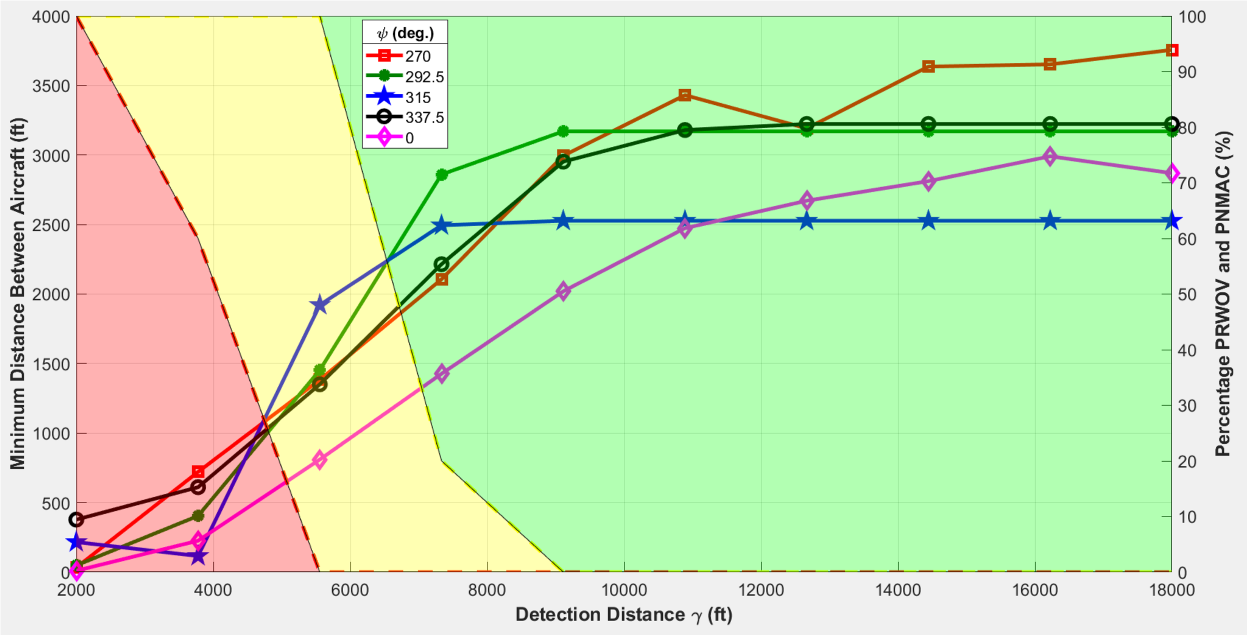


Figure 153. 145 ft/s Overtaking Multi sUAS.

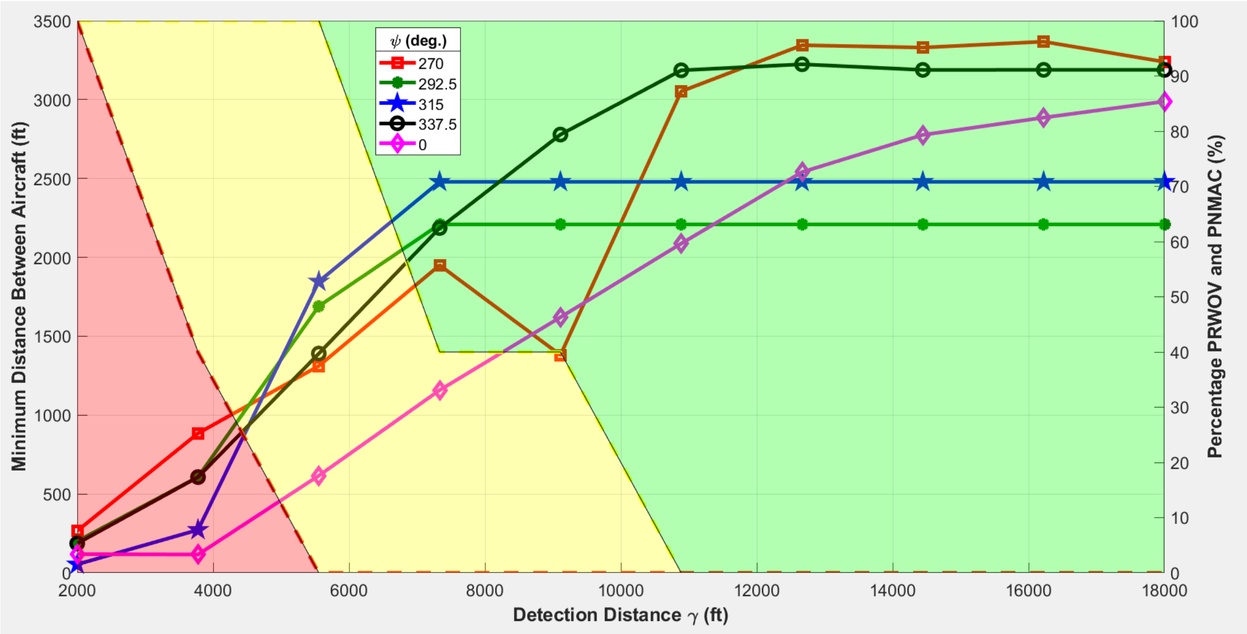


Figure 154. 170 ft/s Overtaking Multi sUAS.

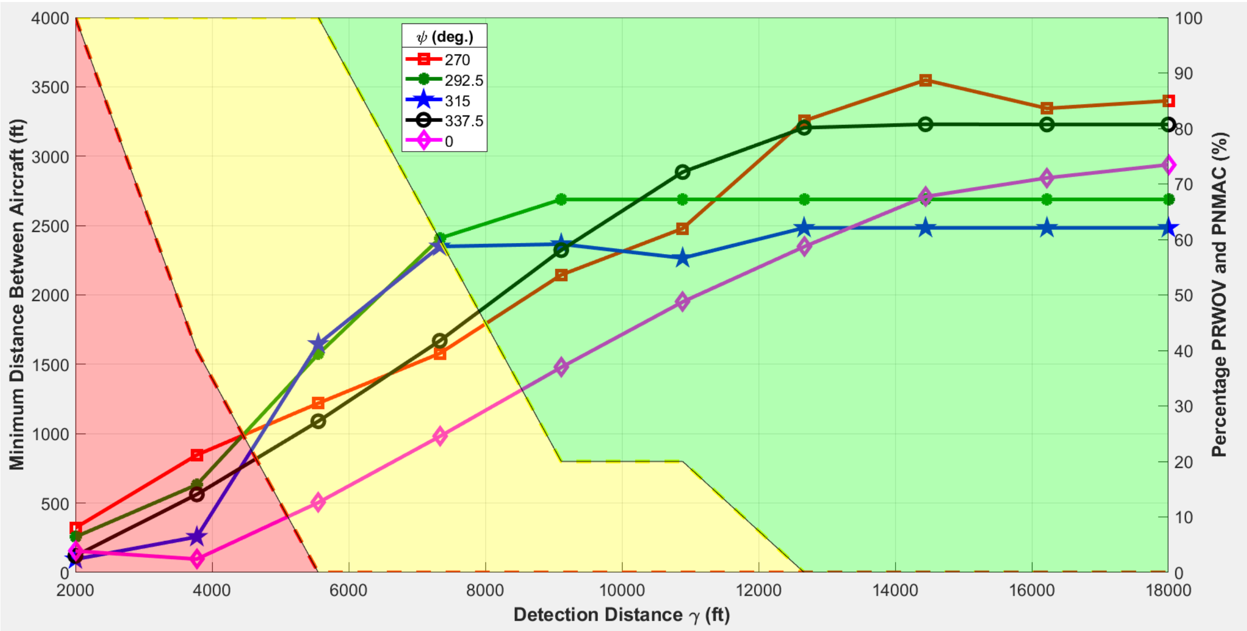


Figure 155. 195 ft/s Overtaking Multi sUAS.

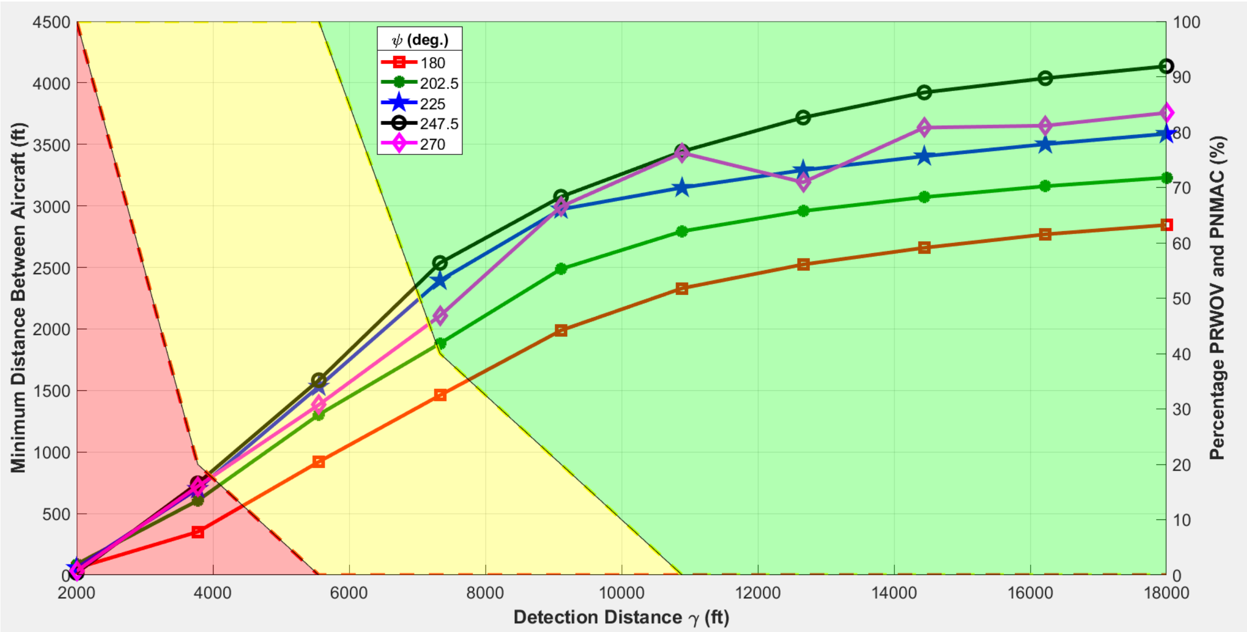


Figure 156. 145 ft/s Head On Converging Multi sUAS.

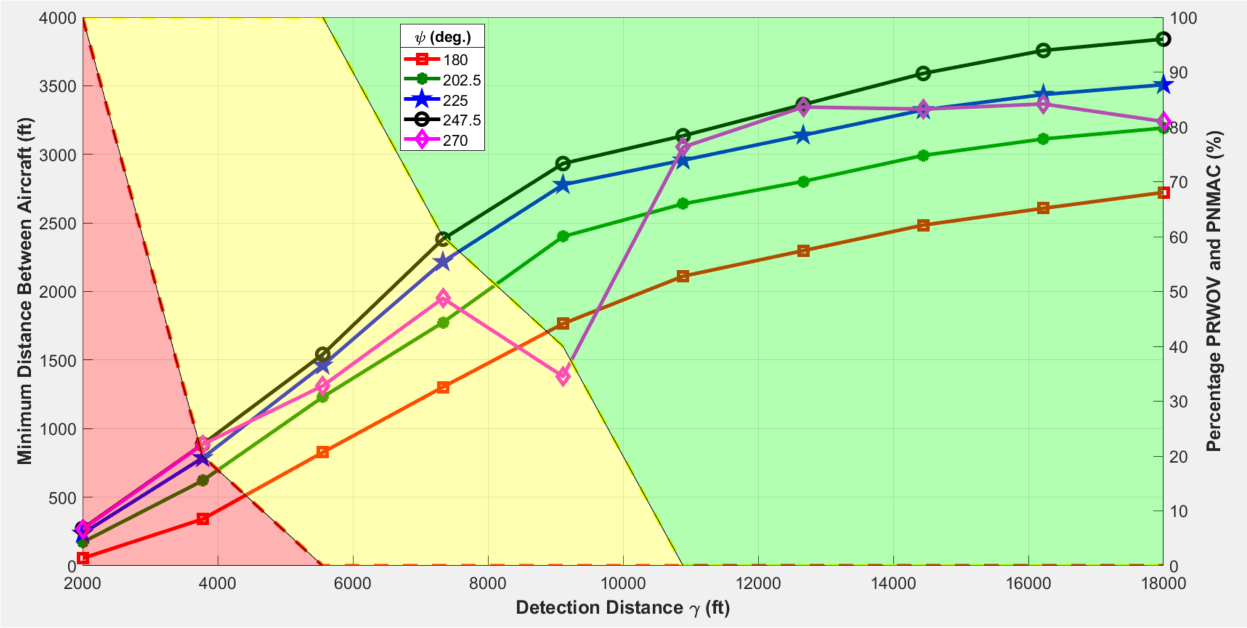


Figure 157. 170 ft/s Head On Converging Multi sUAS.

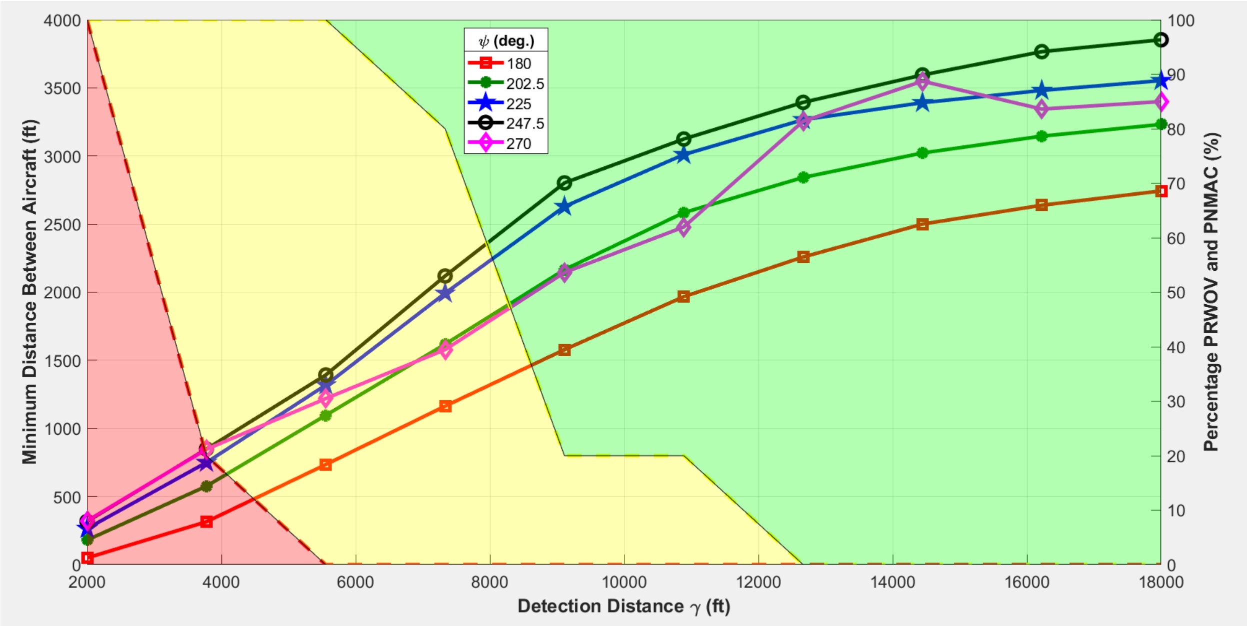


Figure 158. 195 ft/s Head On Converging Multi sUAS.

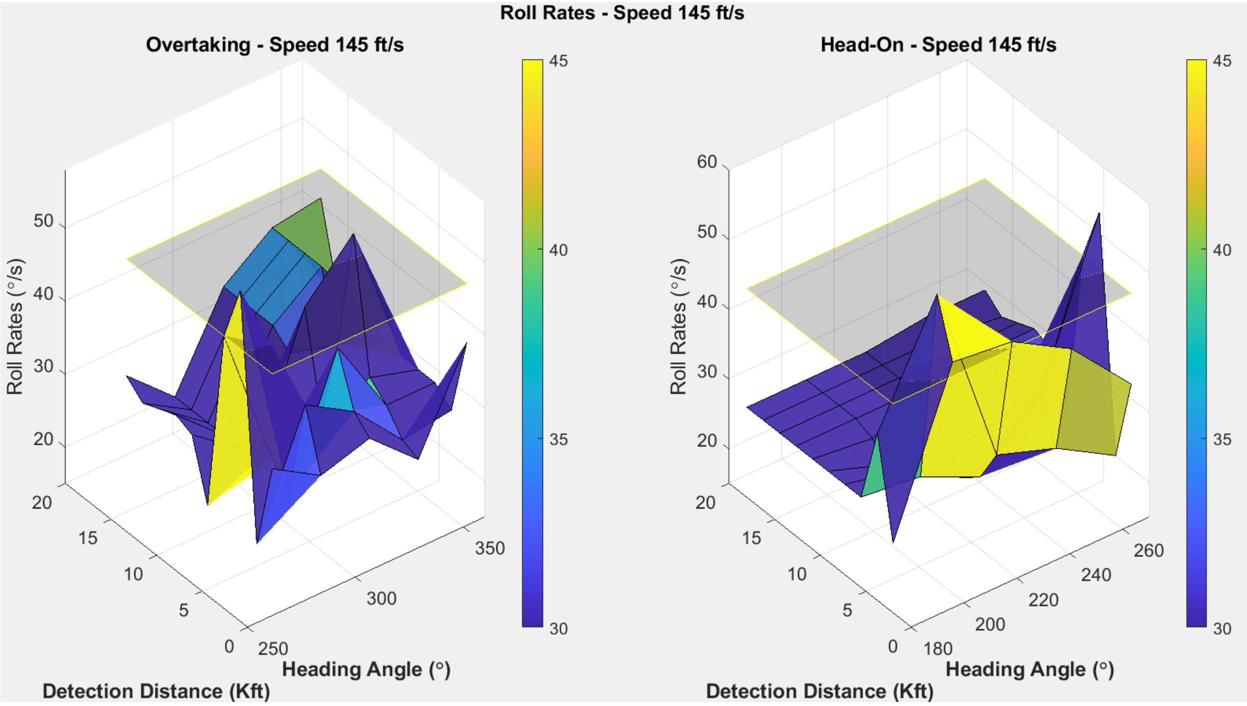


Figure 159. Roll Rates 145 ft/s.

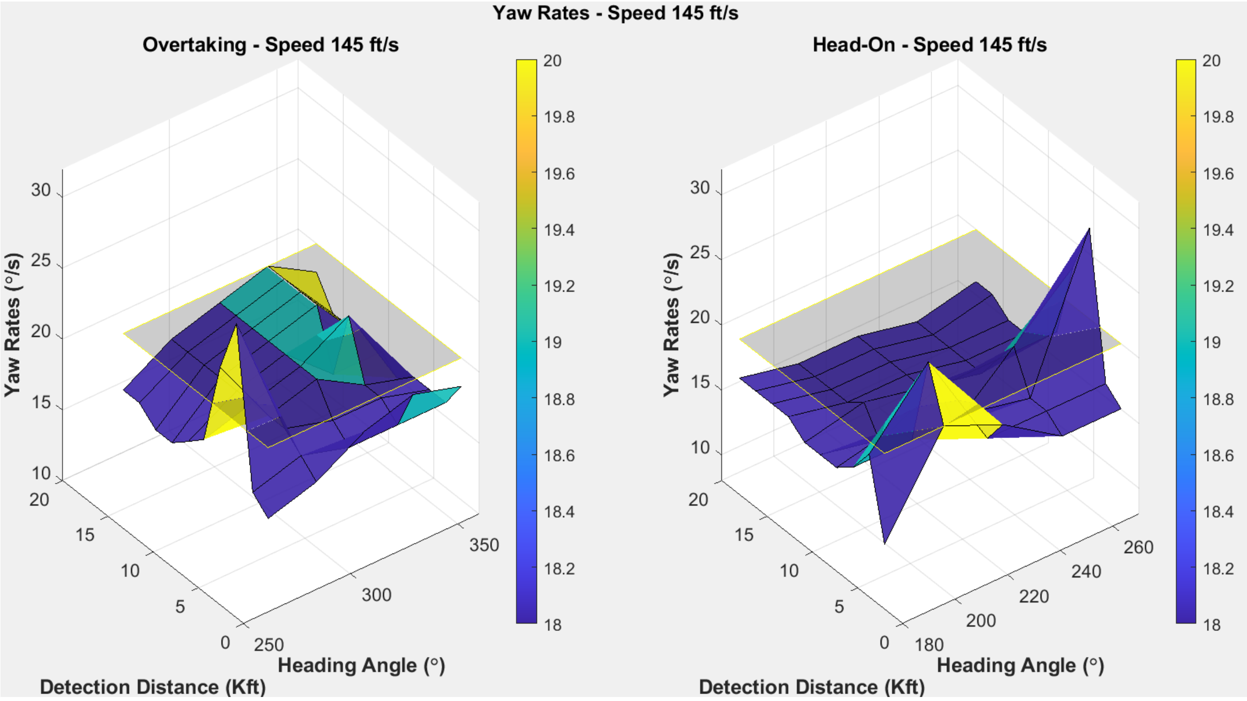


Figure 160. Yaw Rates 145 ft/s.

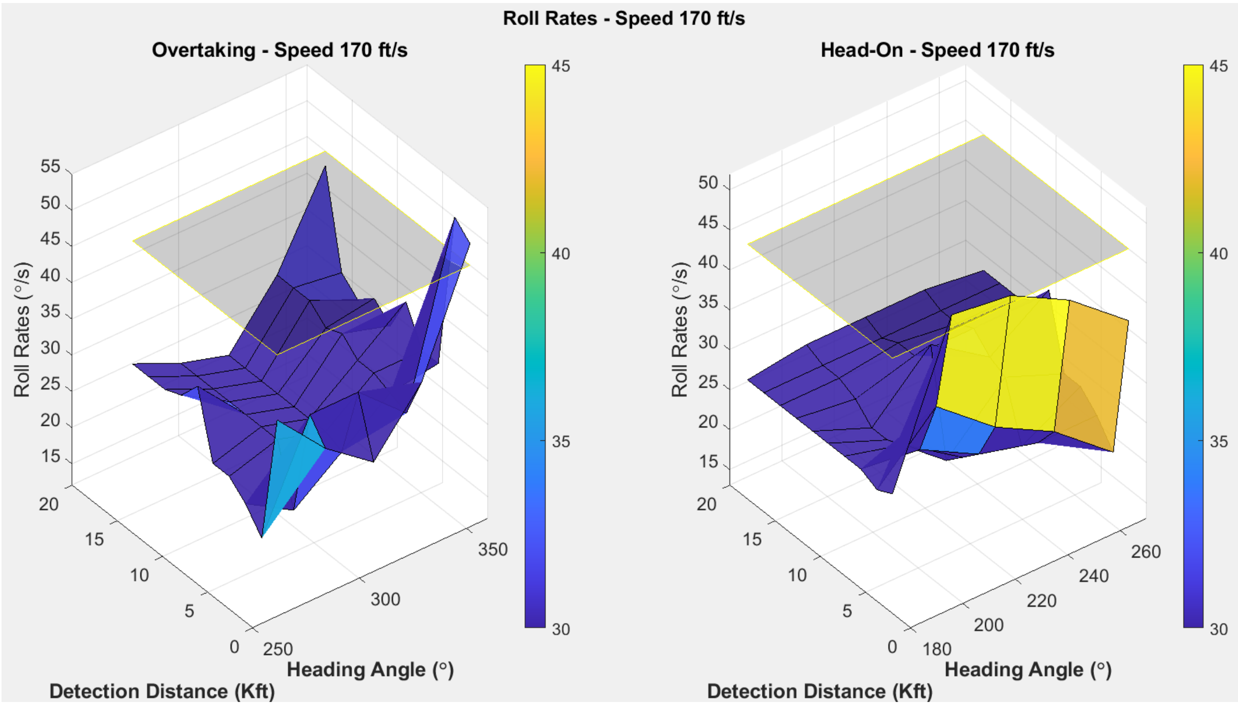


Figure 161. Roll Rates 170 ft/s.

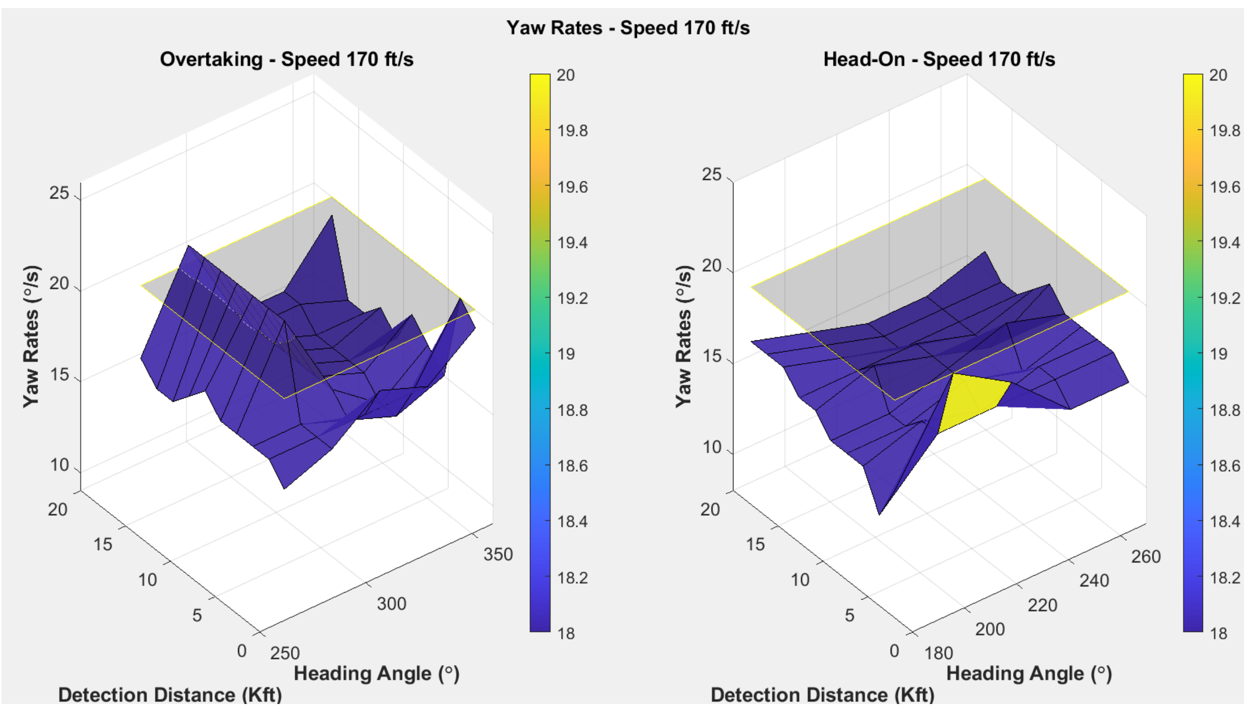


Figure 162. Yaw Rates 170 ft/s.

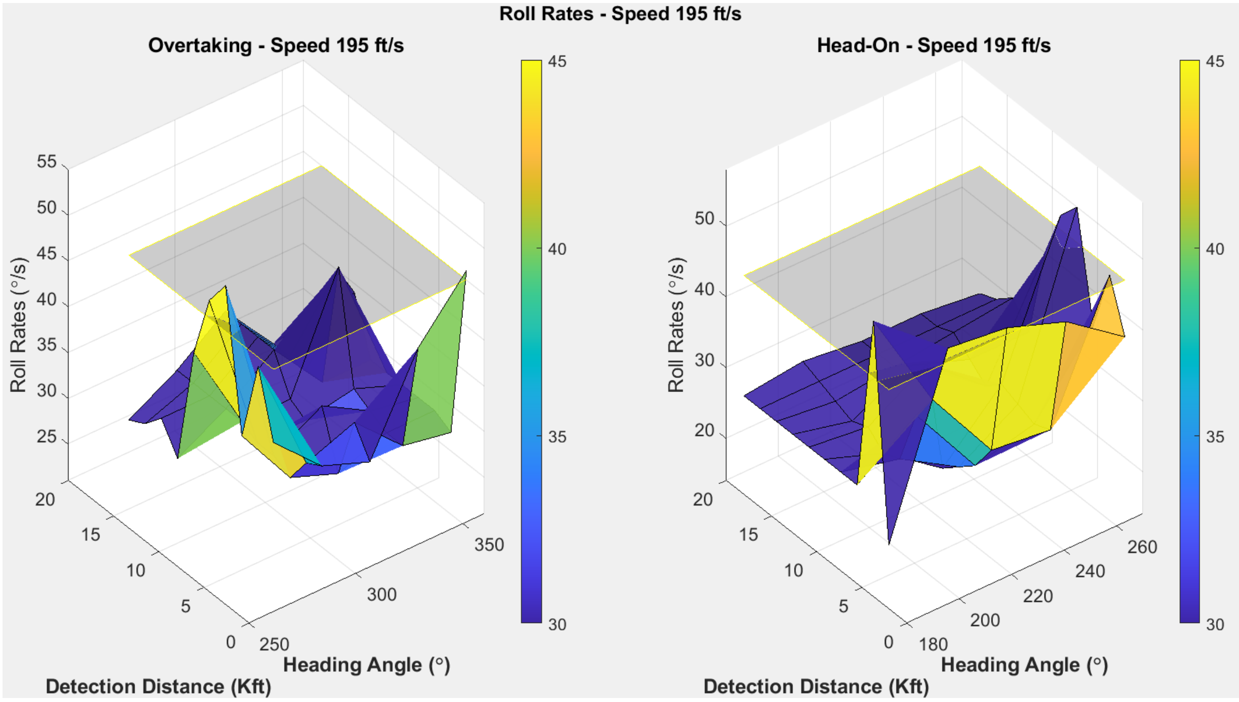


Figure 163. Roll Rates 195 ft/s.

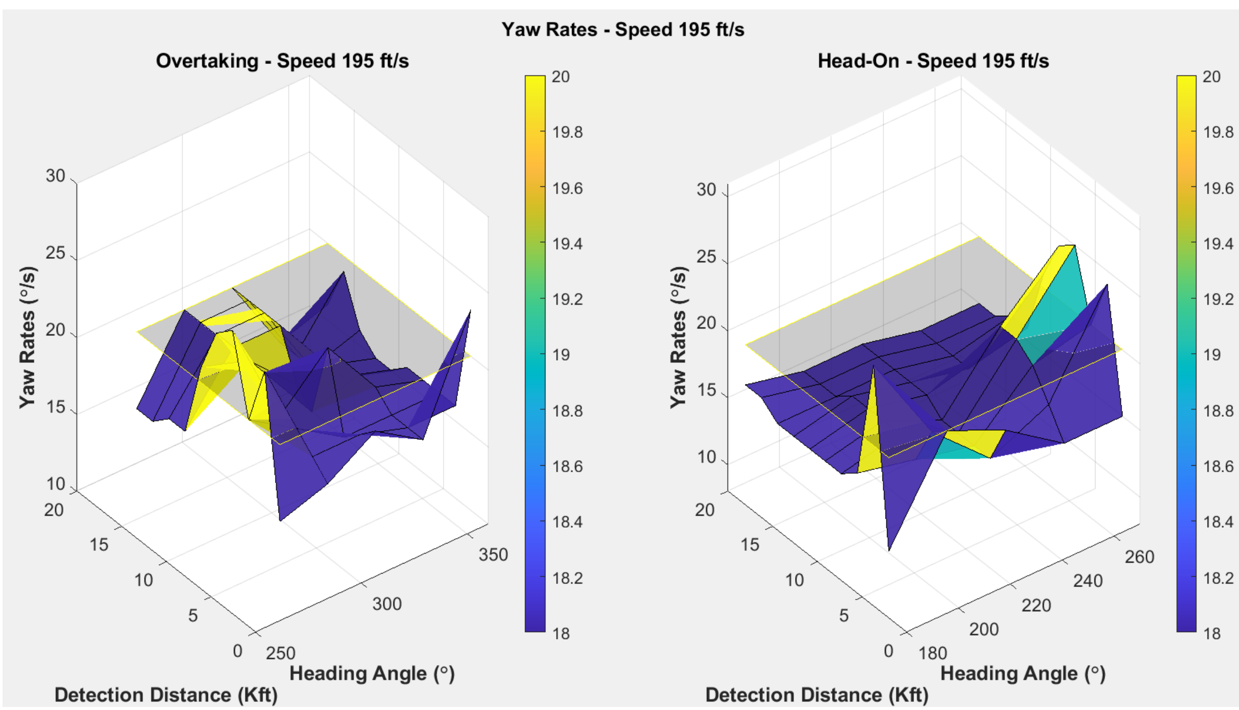


Figure 164. Yaw Rates 195 ft/s.

APPENDIX B – RESERVED AIRSPACE – ROUND 2

B.1 sUAS vs sUAS (UND)

B.1.1 Following Right-of-Way Rules

These results are for a 35 knot sUAS ownship vs a 50 knot sUAS intruder in the scenario where both aircraft follow right-of-way rules and attempt to stay inside of a RAC corridor. There are four GPS uncertainties, four climb/descent rates, two pilot response times, and three maneuver restrictions for each of the geometry categories. The four GPS uncertainties are RTK, WAAS, SPS GPS, and GPS MAX. Climb rates are 250fpm, 500fpm, 750fpm, and 1000fpm. Pilot response times of one second and five seconds. Maneuver restrictions of horizontal-only, vertical-only, and unrestricted.

B1.1.1 Head-on

Table 97. RAC corridor sUAS vs sUAS Following Rules, Head-on, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	821	1477	821	1493	837	1493	952	1608
vertical-only	771	1444	919	1575	968	1625	1592	2248
unrestricted	657	1313	771	1428	788	1444	952	1625
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	821	1477	821	1493	837	1493	952	1608
vertical-only	607	1280	640	1296	657	1313	968	1641
unrestricted	607	1264	624	1280	640	1296	837	1493
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	821	1477	821	1493	837	1493	952	1608
vertical-only	509	1165	607	1264	607	1280	771	1444
unrestricted	493	1165	591	1264	607	1264	771	1428
1000fpm desc	**RTK (0.03m 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	821	1477	821	1493	837	1493	952	1608
vertical-only	493	1149	509	1165	591	1264	657	1313
unrestricted	493	1149	493	1165	591	1231	640	1313

B.1.1.2 Overtaking

Table 98. RAC corridor sUAS vs sUAS Following Rules, Overtaking, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**

250fpm desc	RTK (0.03m, 0.1m)		WAAS (1m, 2.2m)		SPS (1.72m, 3.42m)		MAX (8m, 13m)	
horizontal-only	361	558	361	558	361	558	411	624
vertical-only	411	624	493	689	542	739	1083	1280
unrestricted	361	558	361	558	361	558	394	591
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	411	624
vertical-only	312	509	345	542	361	558	591	788
unrestricted	345	542	361	558	361	558	378	575
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	411	624
vertical-only	279	460	312	509	312	509	427	624
unrestricted	312	509	329	525	345	542	361	558
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	411	624
vertical-only	263	460	279	460	279	476	361	558
unrestricted	279	476	312	509	312	509	361	558

A.3.3. Not Following Right-of-Way Rules

These results are for a 35 knot sUAS ownship vs a 50 knot sUAS intruder in the scenario where the intruder aircraft does not follow the right-of-way rules but attempts to stay inside of the RAC corridor. There are four GPS uncertainties, four climb/descent rates, two pilot response times, and three maneuver restrictions for each of the geometry categories. The four GPS uncertainties are RTK, WAAS, SPS GPS, and GPS MAX. Climb rates are 250fpm, 500fpm, 750fpm, and 1000fpm. Pilot response times of one second and five seconds. Maneuver restrictions of horizontal-only, vertical-only, and unrestricted.

B.1.2 Head-on

Table 99. RAC corridor sUAS vs sUAS Not Following Rules, Head-on, Required Detection Range in Feet.

Pilot Response Time	1	5	1	5	1	5	1	5
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	968	1625	985	1625	985	1641	1116	1772
vertical-only	1149	1805	1428	2100	1575	2231	2740	3413
unrestricted	985	1625	985	1641	1083	1723	1132	1789
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	968	1625	985	1625	985	1641	1116	1772
vertical-only	788	1444	936	1592	968	1641	1608	2281

unrestricted	640	1313	771	1428	788	1460	1132	1789
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	968	1625	985	1625	985	1641	1116	1772
vertical-only	640	1313	755	1428	788	1444	1280	1936
unrestricted	624	1280	640	1313	657	1329	1132	1789
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	968	1625	985	1625	985	1641	1116	1772
vertical-only	607	1280	640	1296	657	1313	985	1657
unrestricted	607	1264	624	1296	640	1296	952	1608

B.1.2 Overtaking

Table 100. RAC corridor sUAS vs sUAS Not Following Rules, Overtaking, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	1723	1920	1772	1969	1772	1969	2117	2330
vertical-only	411	624	509	722	509	722	870	1067
unrestricted	476	673	624	821	673	870	1067	1264
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	1723	1920	1772	1969	1772	1969	2117	2330
vertical-only	312	509	345	542	361	558	525	722
unrestricted	312	509	361	558	411	624	673	870
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	1723	1920	1772	1969	1772	1969	2117	2330
vertical-only	279	476	312	509	312	509	443	640
unrestricted	296	493	312	509	312	509	509	722
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	1723	1920	1772	1969	1772	1969	2117	2330
vertical-only	279	460	296	493	312	509	378	575
unrestricted	279	460	296	493	312	509	411	624

B.2 Single and Multiple sUAS vs Crewed (KU)

B.2.1 Moving Corridor Single sUAS

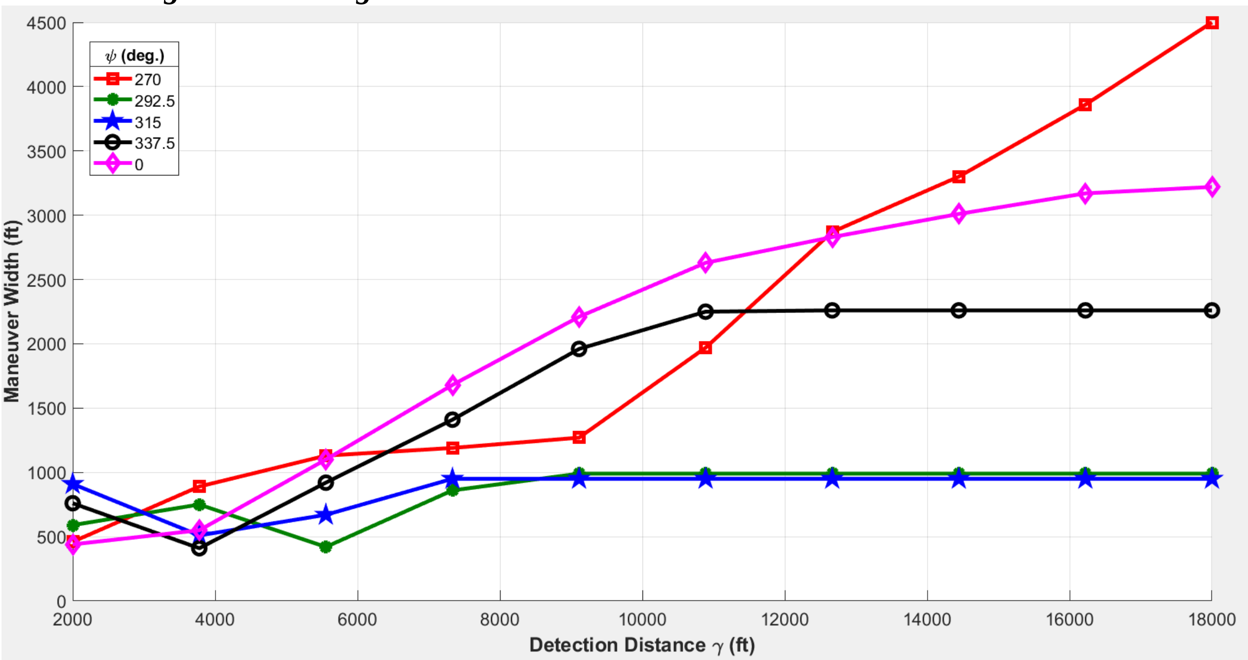


Figure 165. 145 ft/s Overtaking single sUAS.

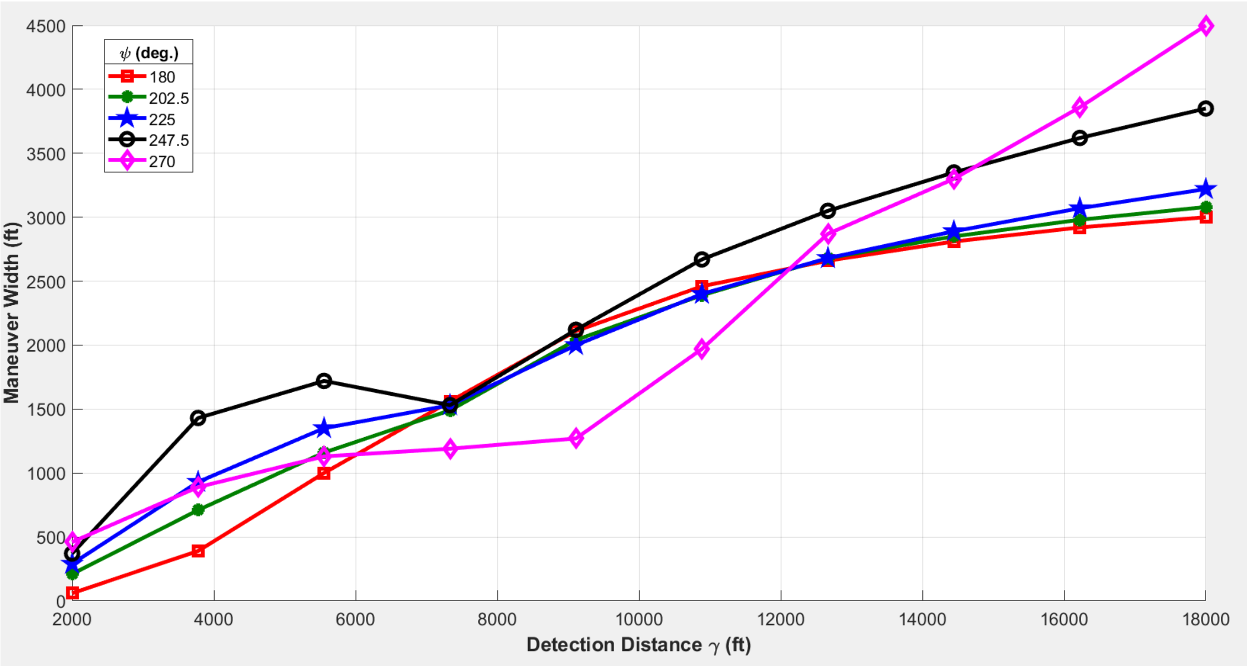


Figure 166. 145 ft/s Head On Converging Single sUAS.

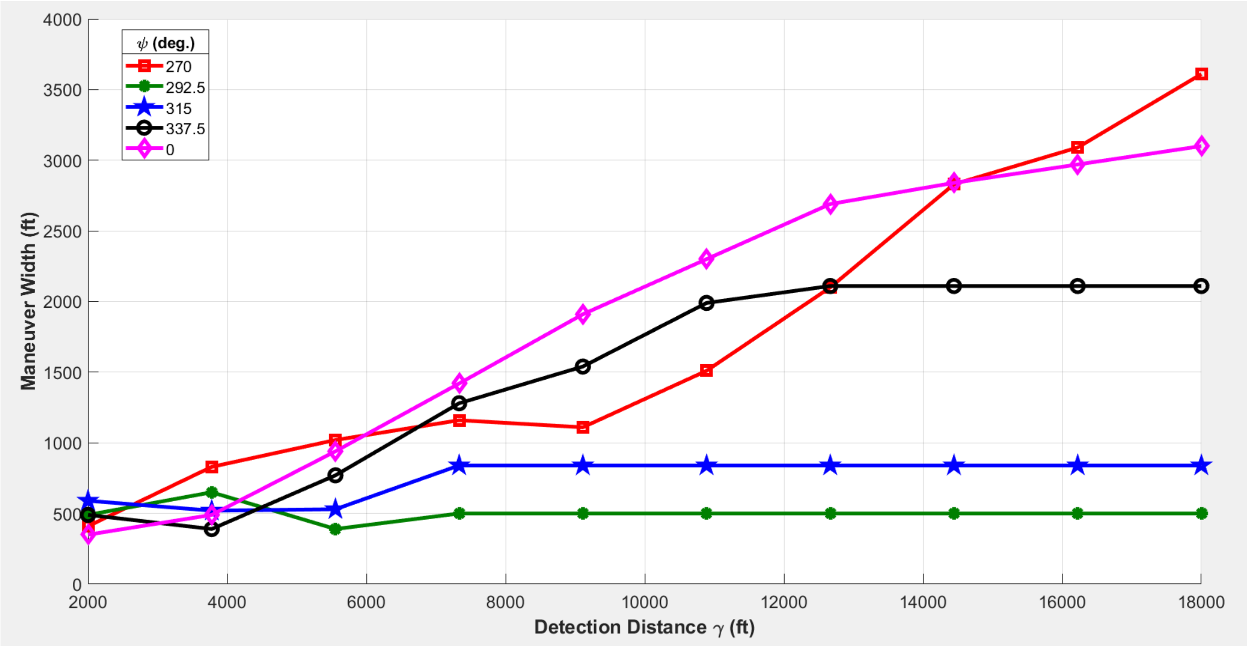


Figure 167. 170 ft/s Overtaking single sUAS.

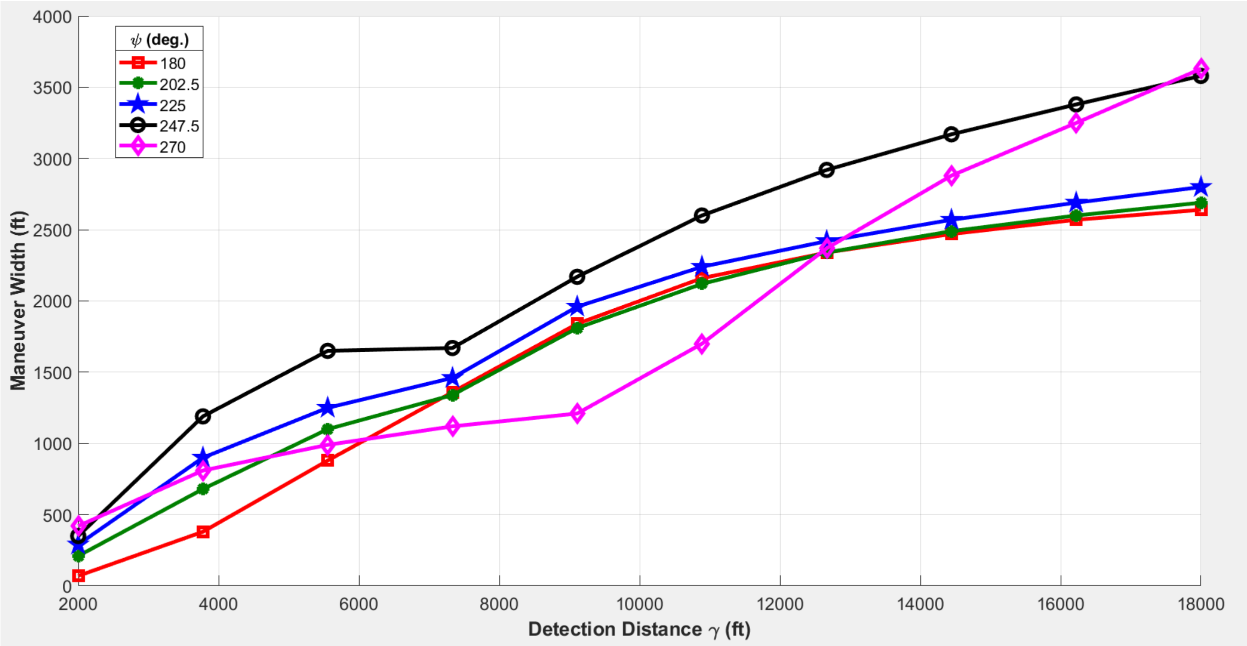


Figure 168. 170 ft/s Head On Converging Single sUAS.

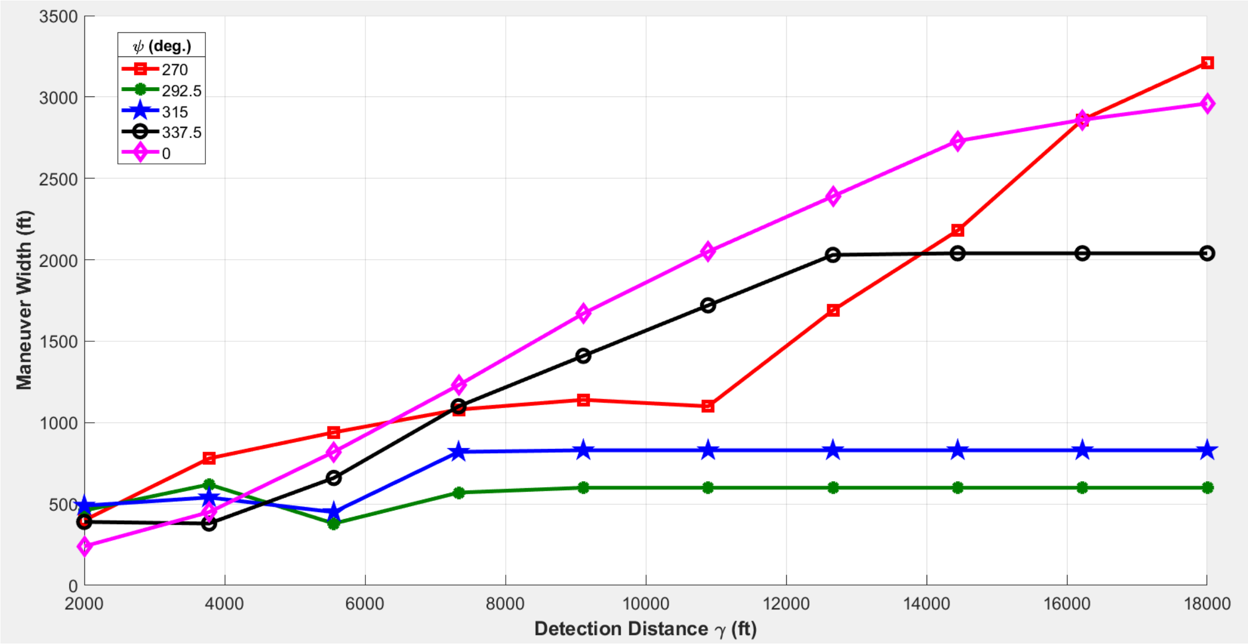


Figure 169. 195 ft/s Overtaking single sUAS.

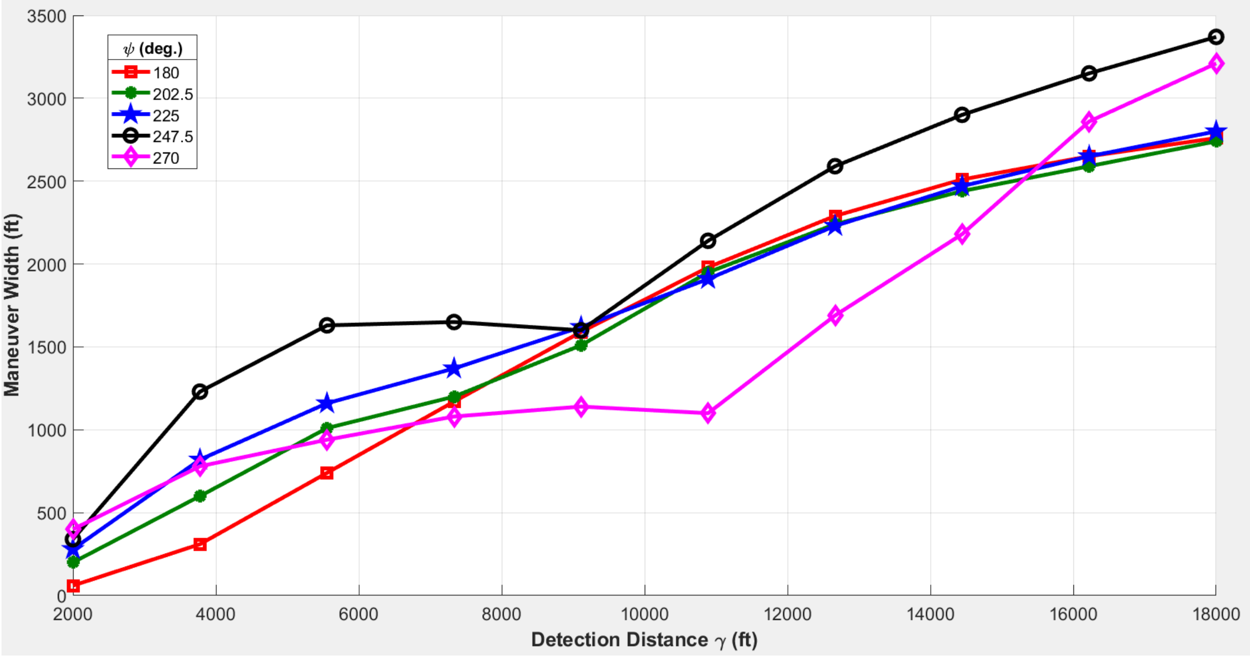


Figure 170. 195 ft/s Head On Converging Single sUAS.

B.2.2 Moving Corridor Multiple sUAS

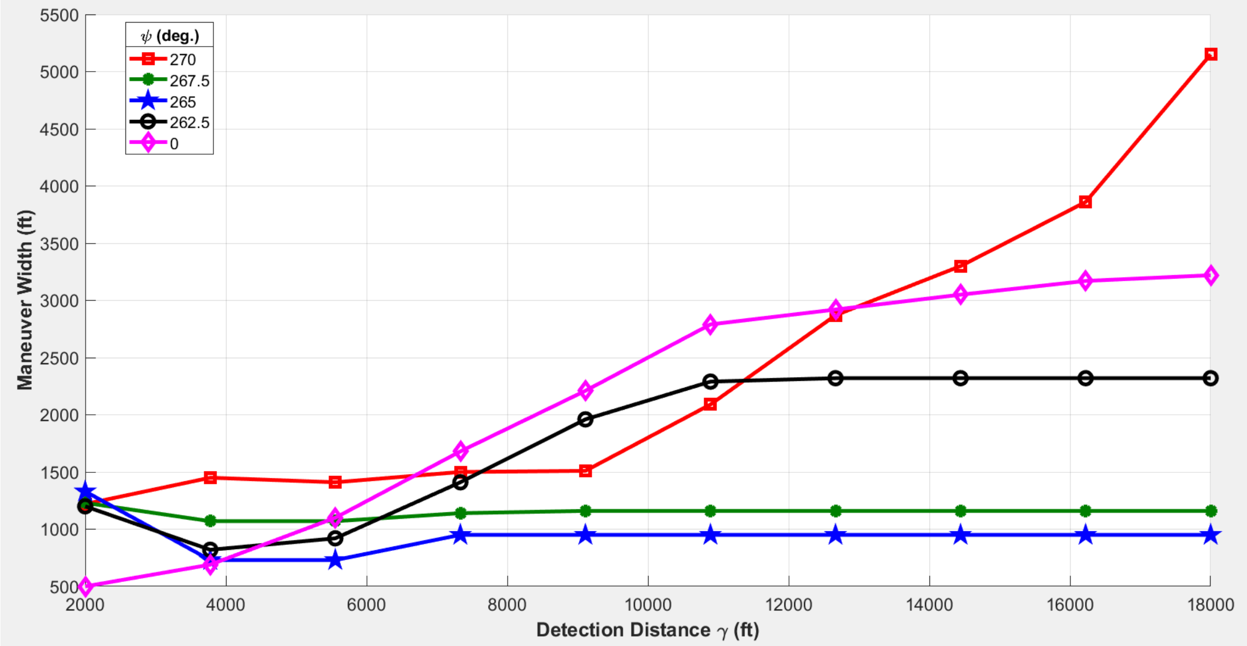


Figure 171. 145 ft/s Overtaking Multi sUAS.

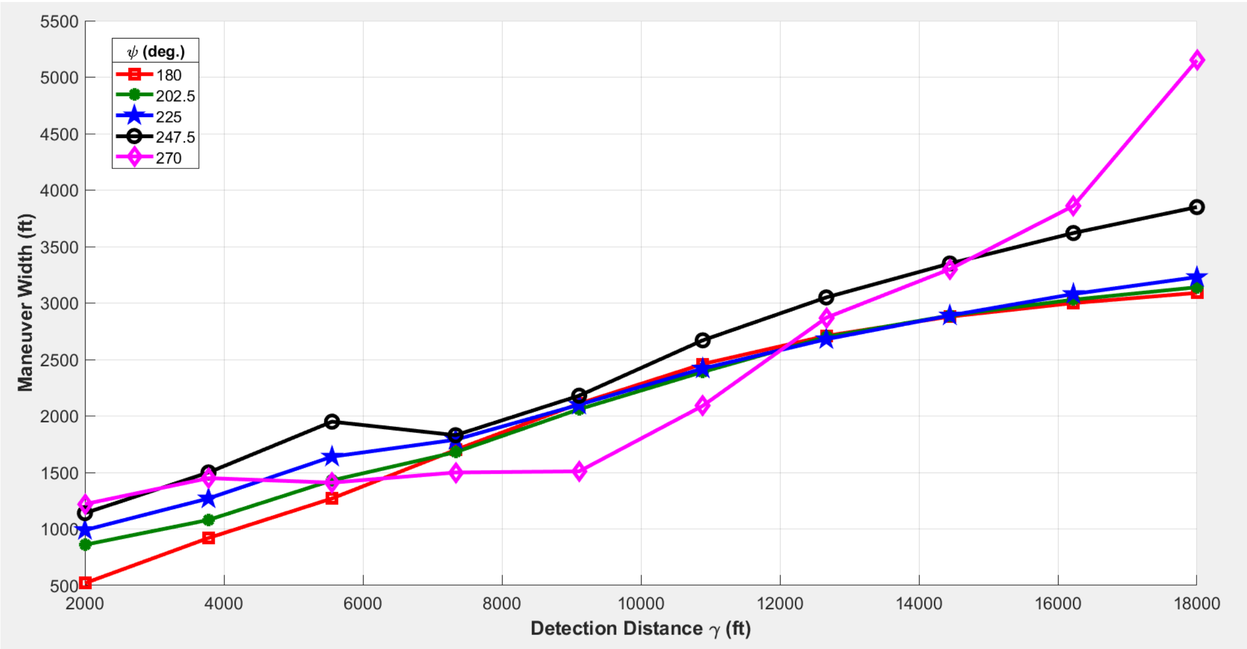


Figure 172. 145 ft/s Head On Converging Multi sUAS.

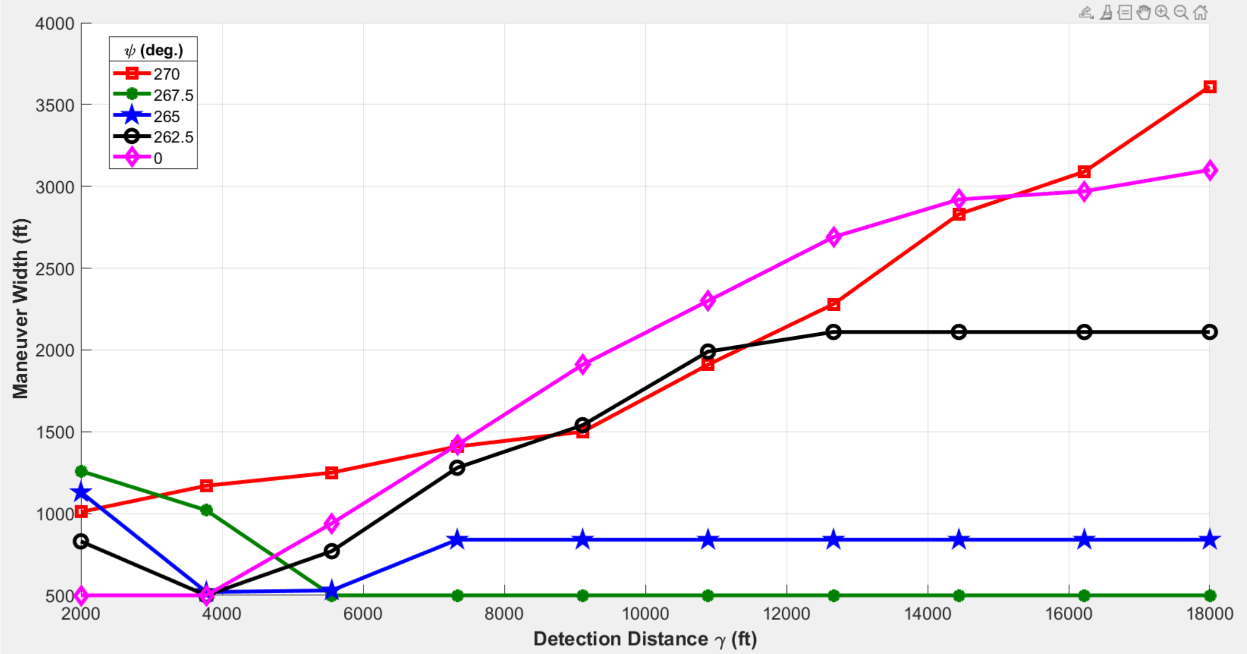


Figure 173. 170 ft/s Overtaking Multi sUAS.

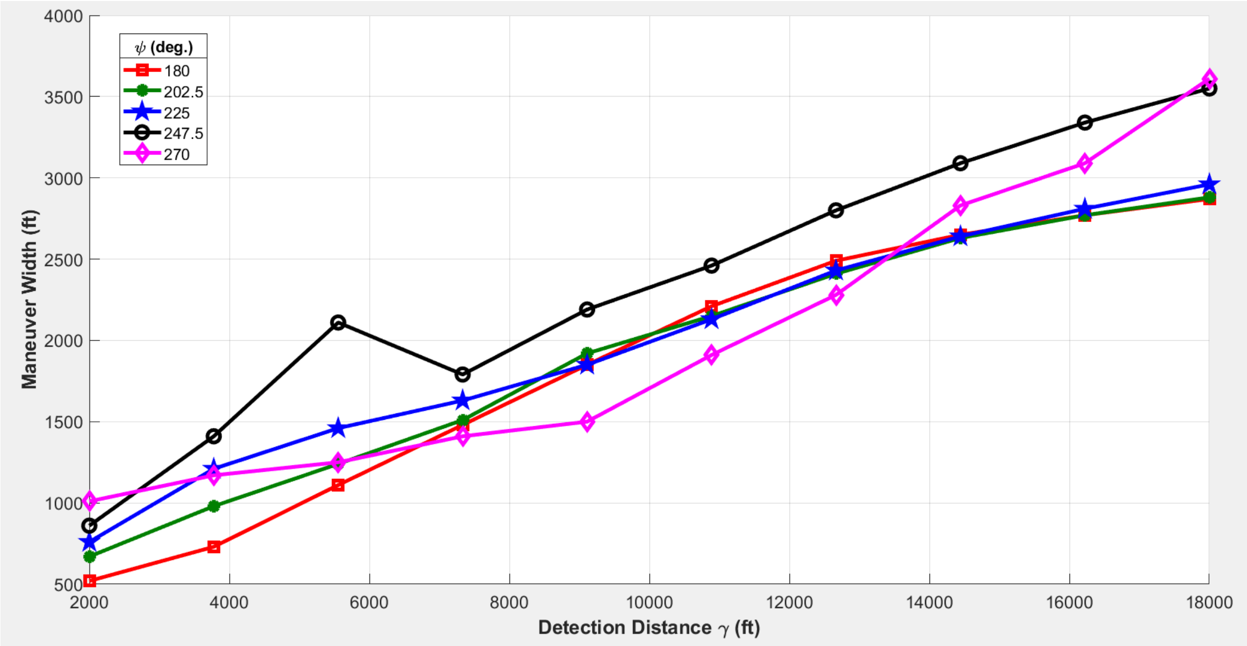


Figure 174. 170 ft/s Head On Converging Multi sUAS.

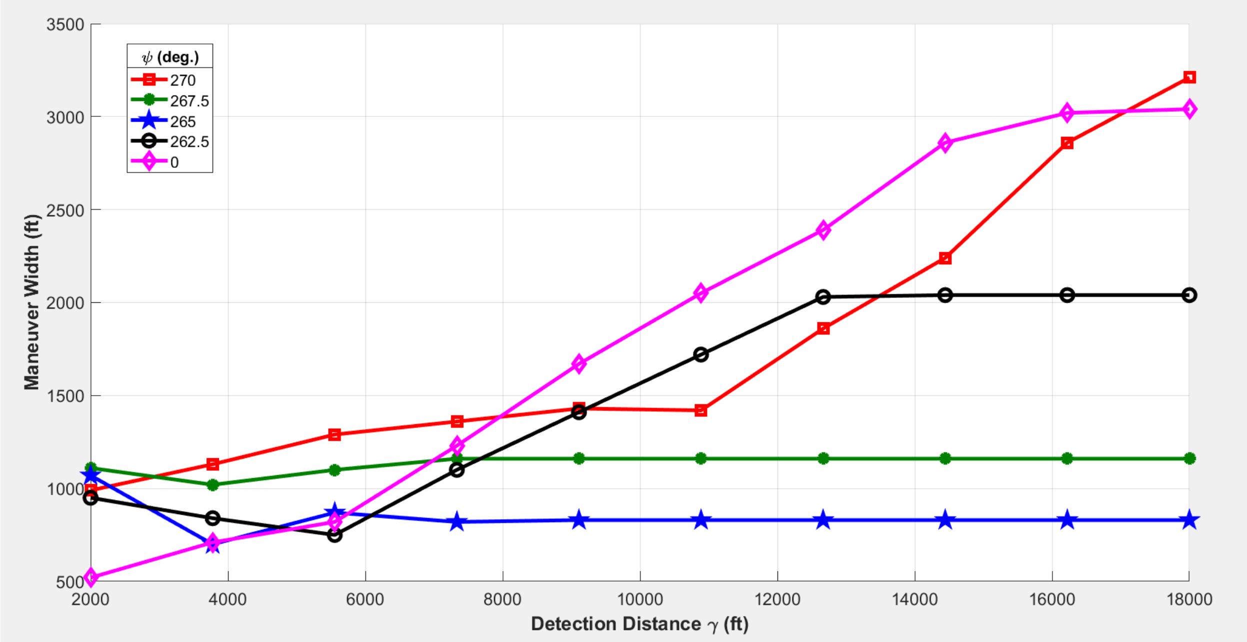


Figure 175. 195 ft/s Overtaking Multi sUAS.

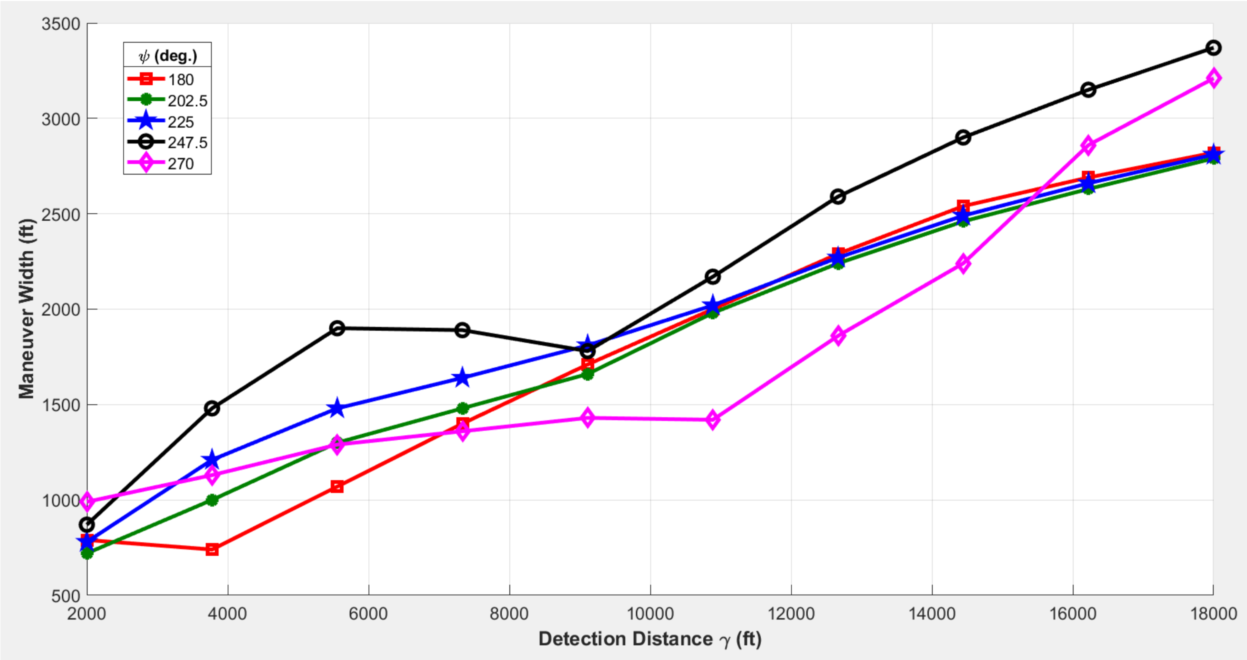


Figure 176. 195 ft/s Head On Converging Multi sUAS.

B.2.3 Moving Corridor Single sUAS Loiter Guidance

The first few graphs show the manuever width required for loiter guidance in the moving corridor single sUAS scenario. In the second section, the first figure for each of the respective scenarios in this appendix shows the effect of using the loiter guidance on all angles. The second figure for each of these sections removes two angles (180 degrees and 202.5 degrees removed for the head on converging scenarios) and (337.5 degrees and 360 degrees removed for the overtaking scenarios). The angles were removed because loiter guidance does not work well for those angles. This means that morphing potential needs to be used instead. At every other angle, loiter guidance does a better job than MPF does in the same scenario.

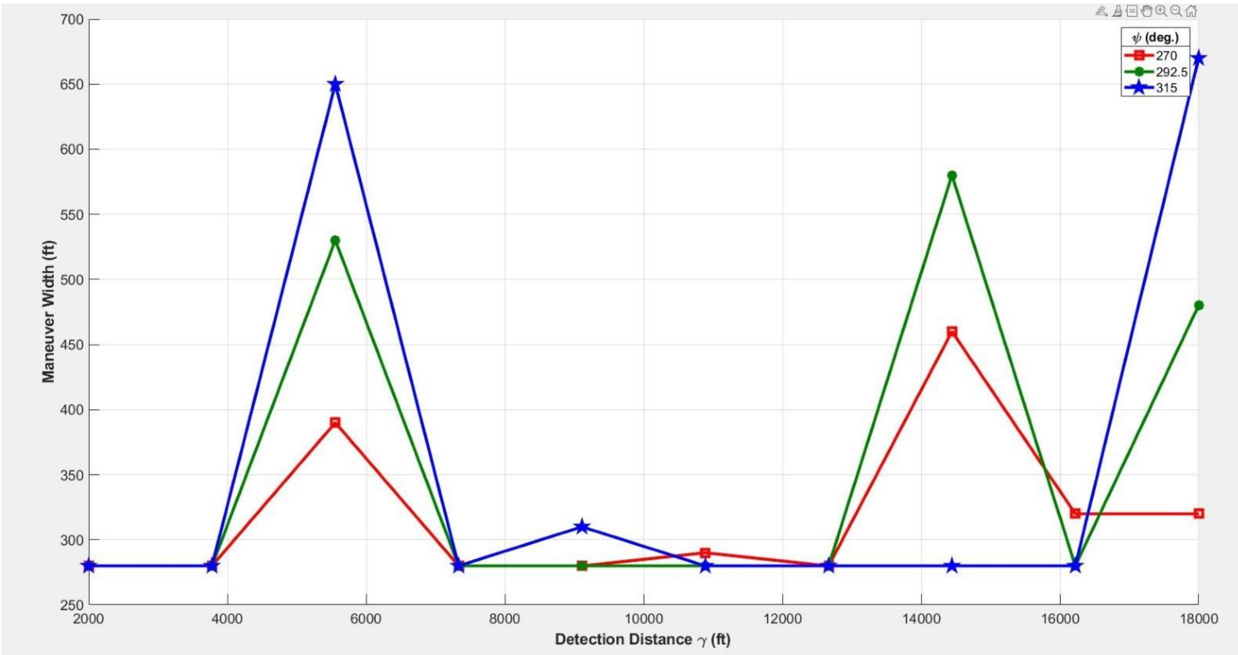


Figure 177. 145 ft/s Overtaking.

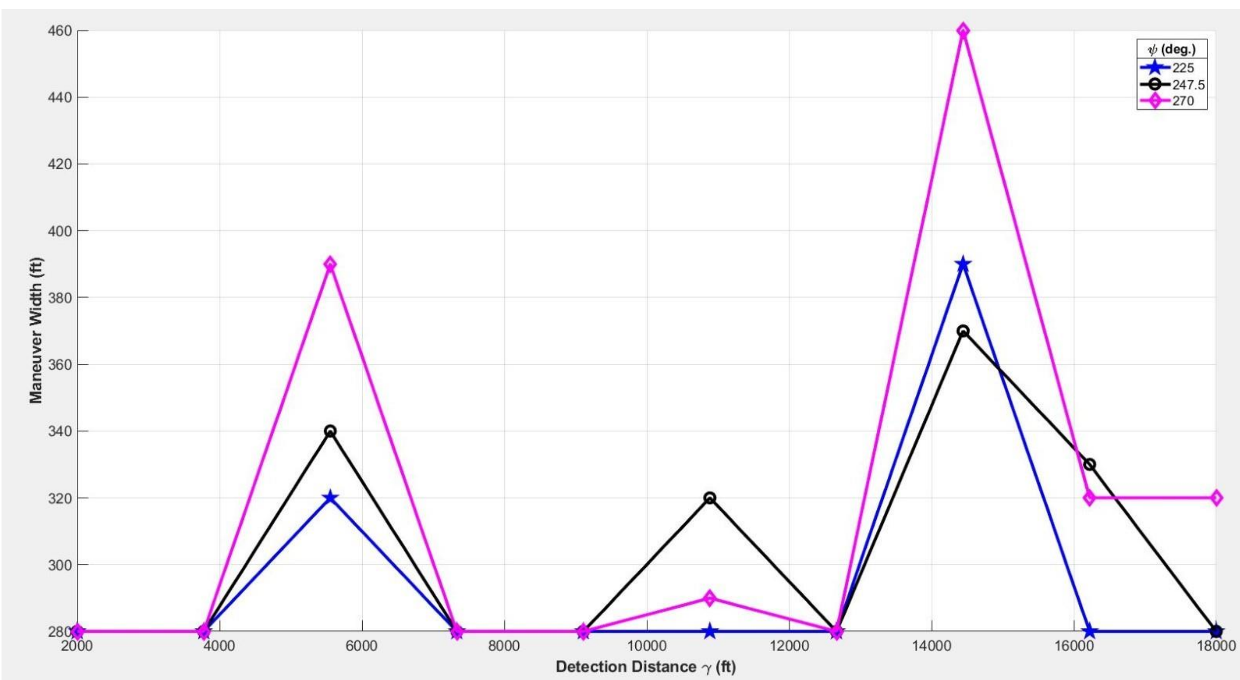


Figure 178. 145 ft/s Head On Converging.

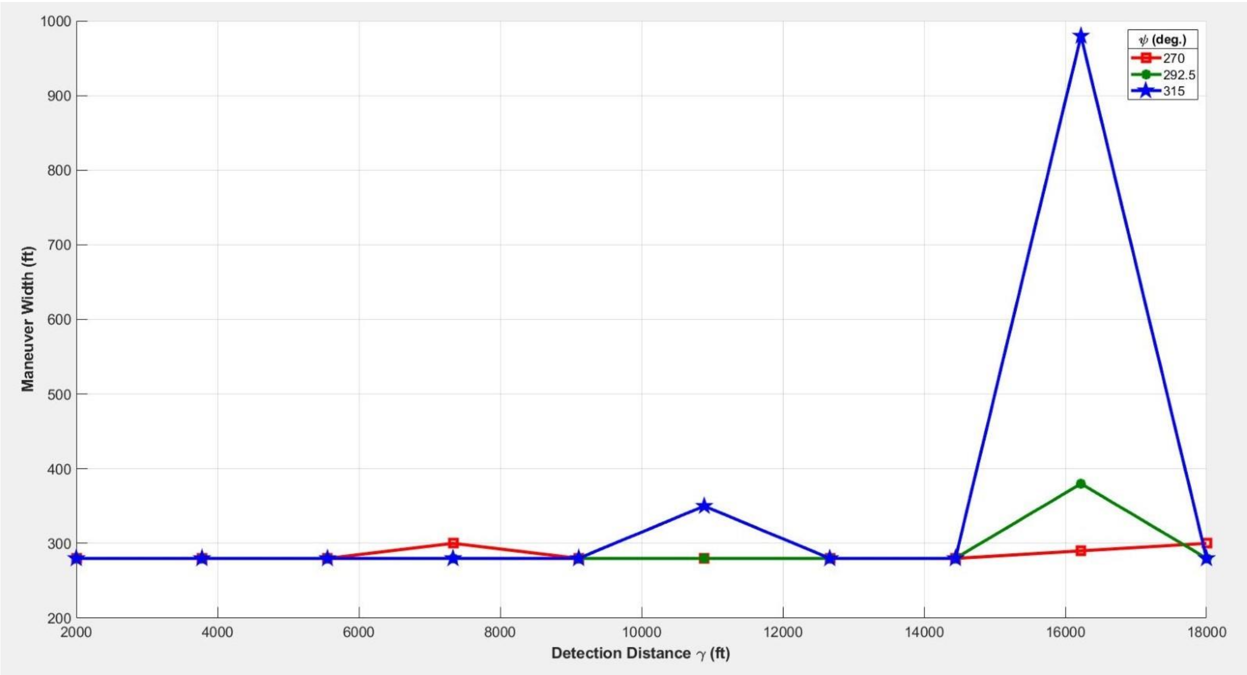


Figure 179. 170 ft/s Overtaking.

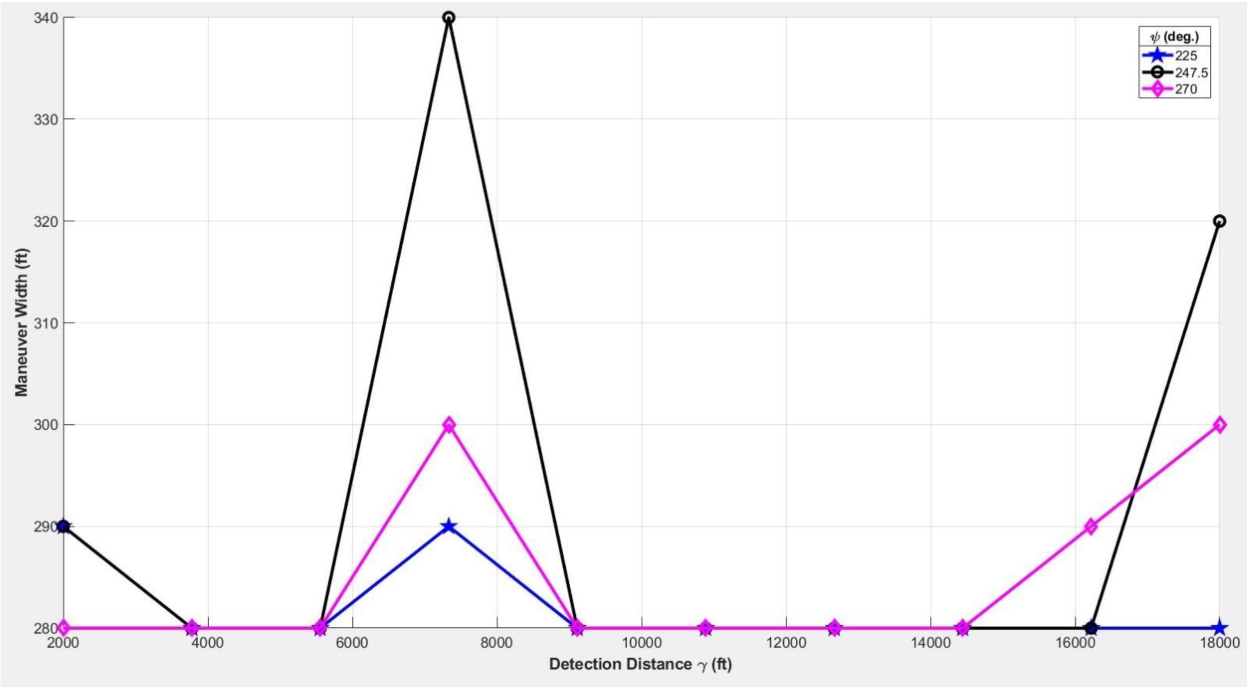


Figure 180. 170 ft/s Head On Converging.

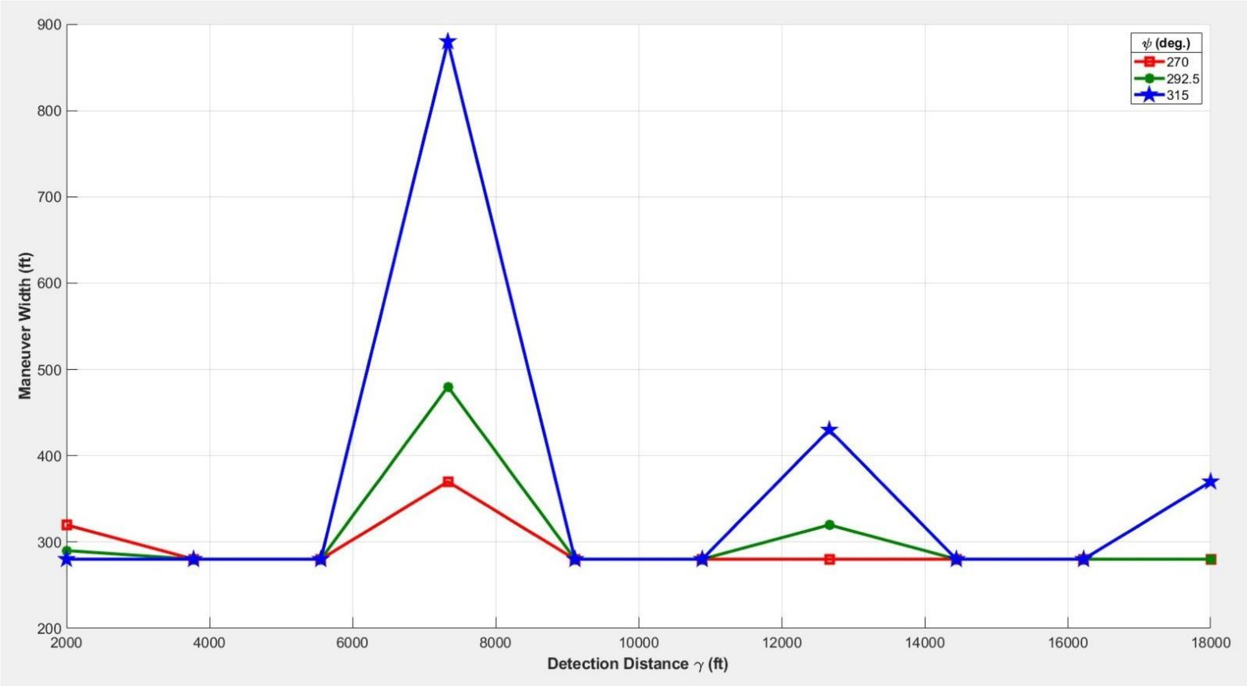


Figure 181. 195 ft/s Overtaking.

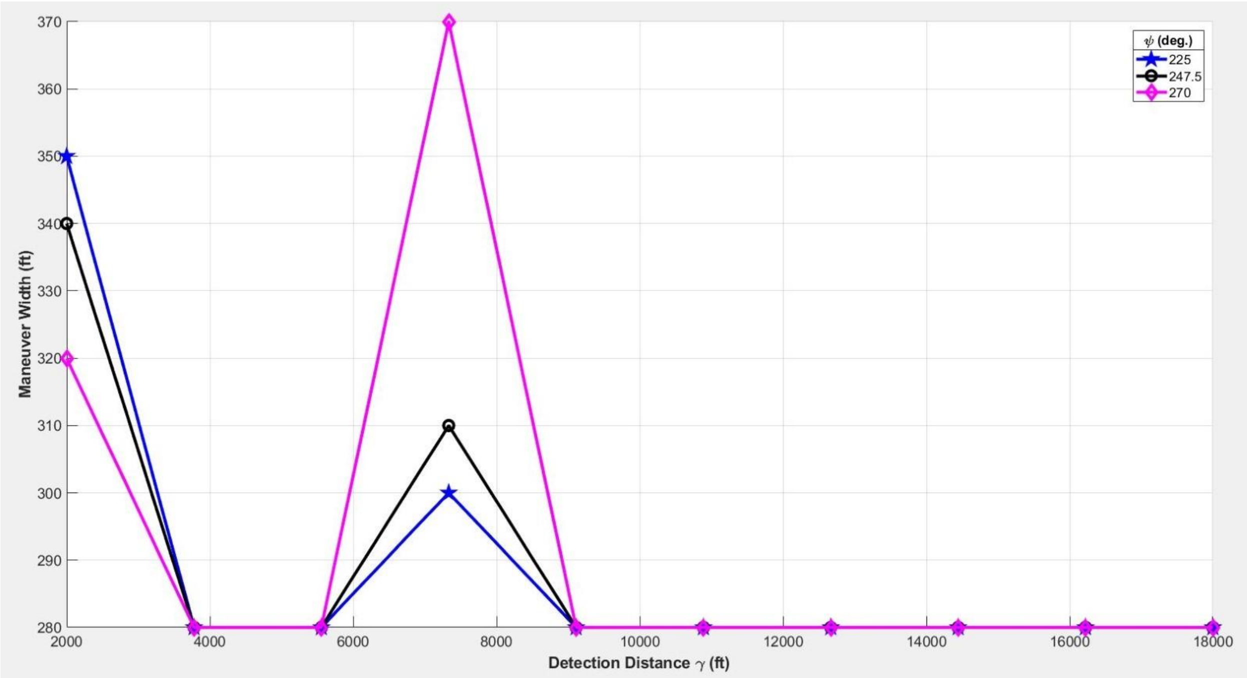


Figure 182. 195 ft/s Head On Converging.

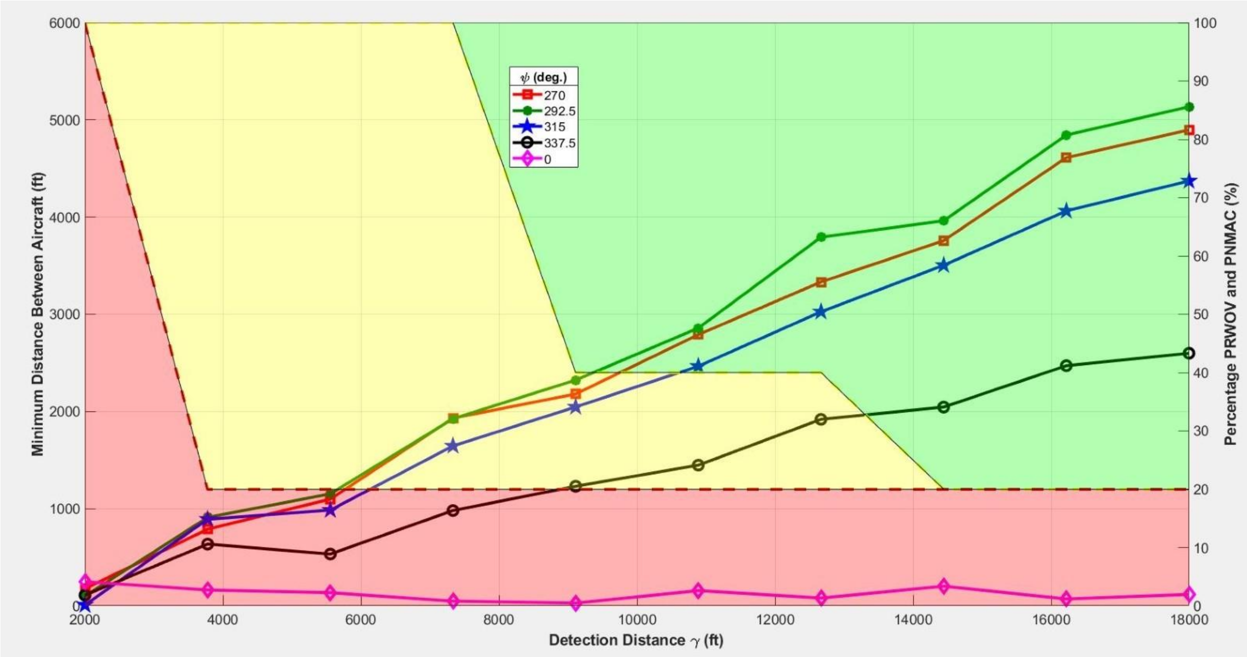


Figure 183. 145 ft/s Overtaking Loiter Guidance.

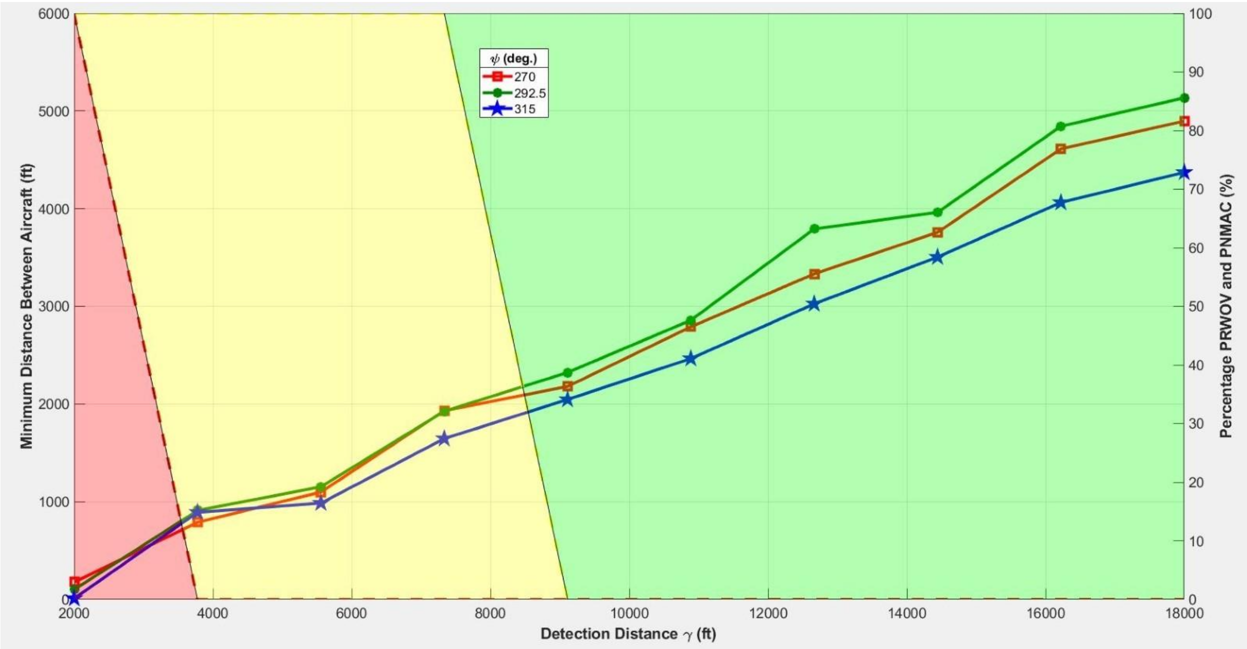


Figure 184. 145 ft/s Overtaking Loiter Guidance with MPF.

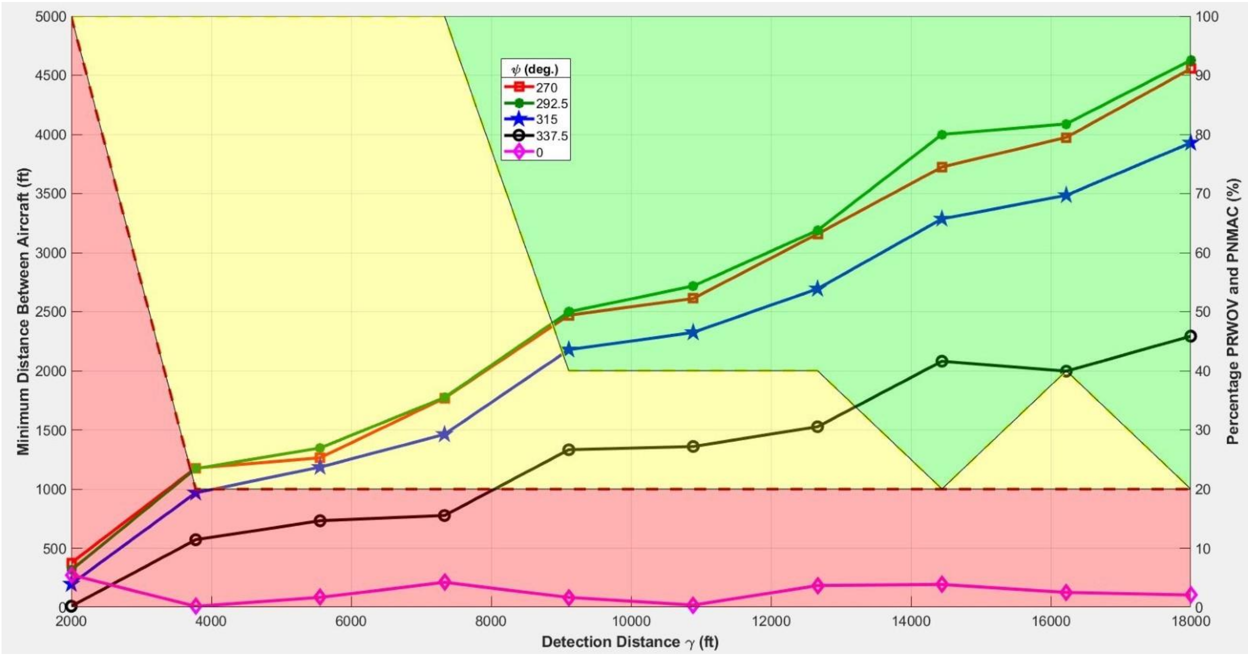


Figure 185. 170 ft/s Overtaking Loiter Guidance.

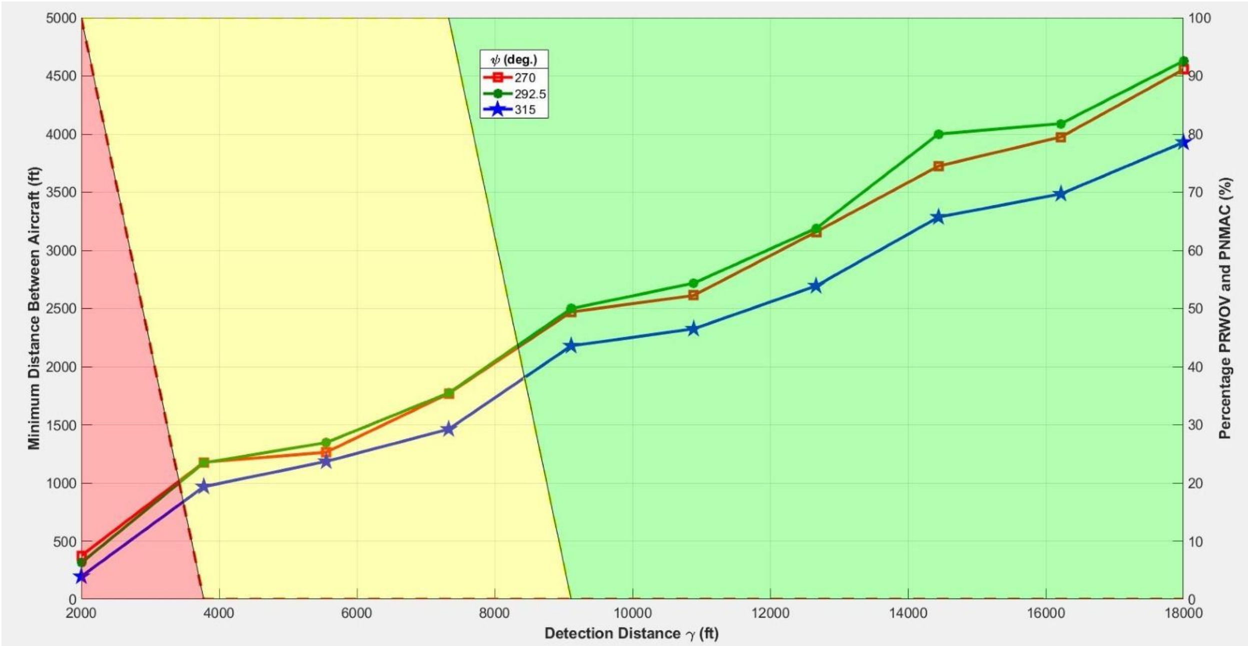


Figure 186. 170 ft/s Overtaking Loiter Guidance with MPF.

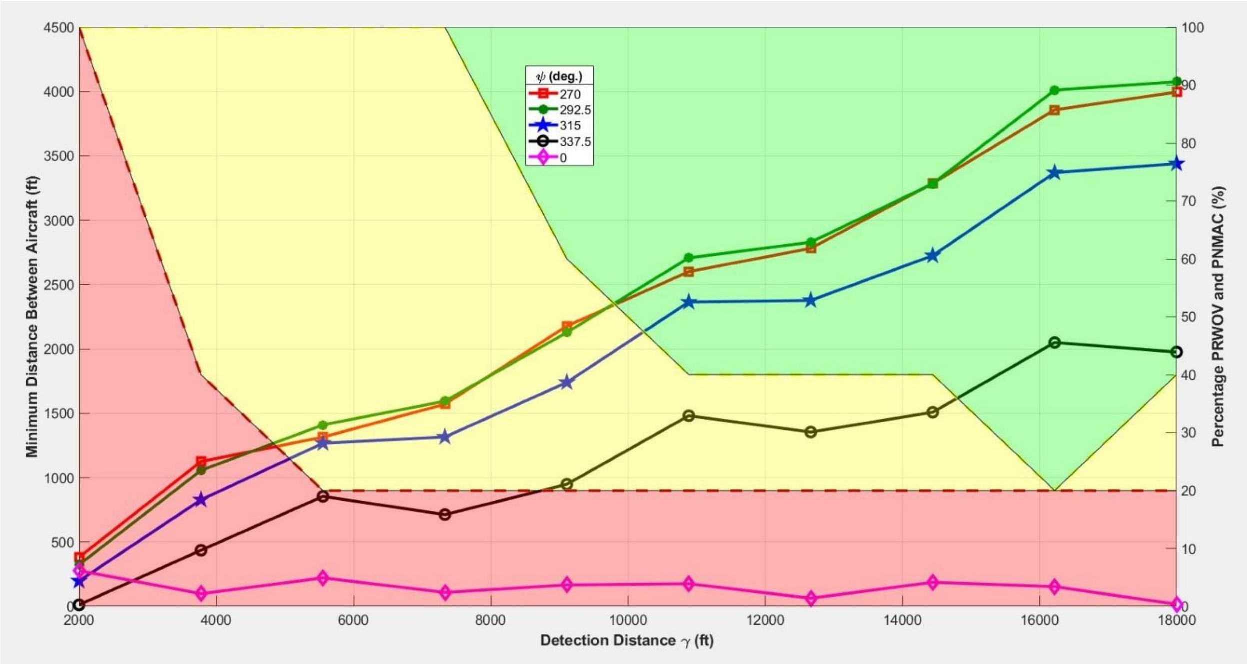


Figure 187. 195 ft/s Overtaking Loiter Guidance.

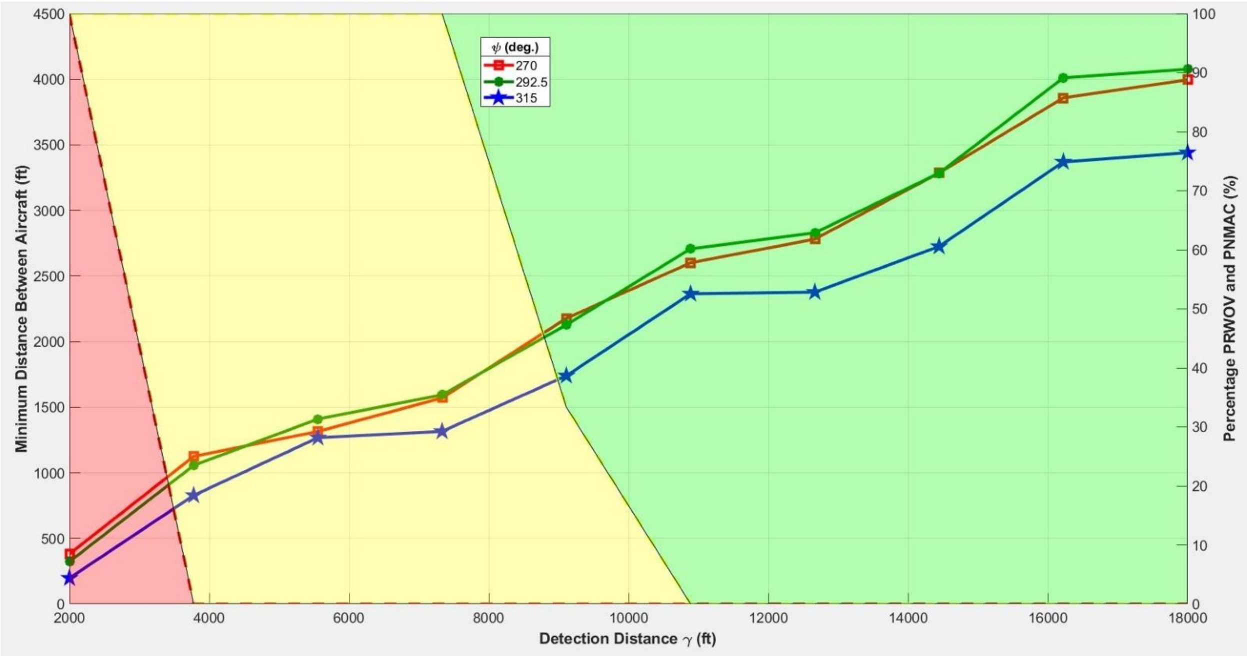


Figure 188. 195 ft/s Overtaking Loiter Guidance with MPF.

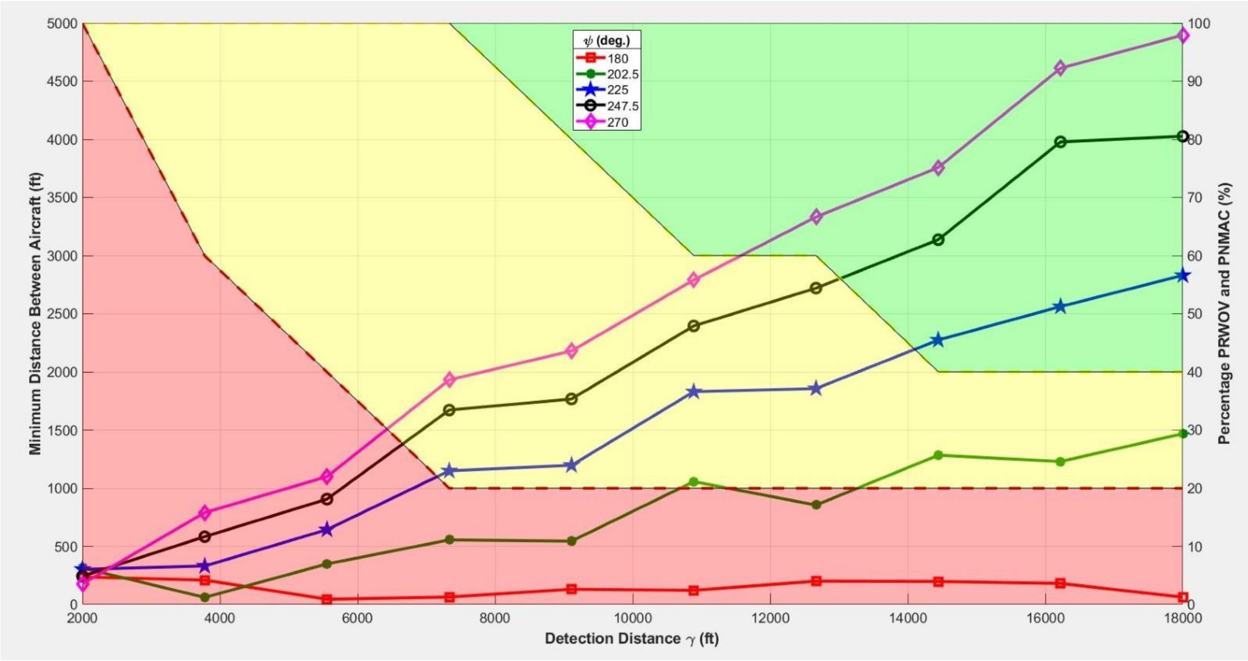


Figure 189. 145 ft/s Head On Converging Loiter Guidance.

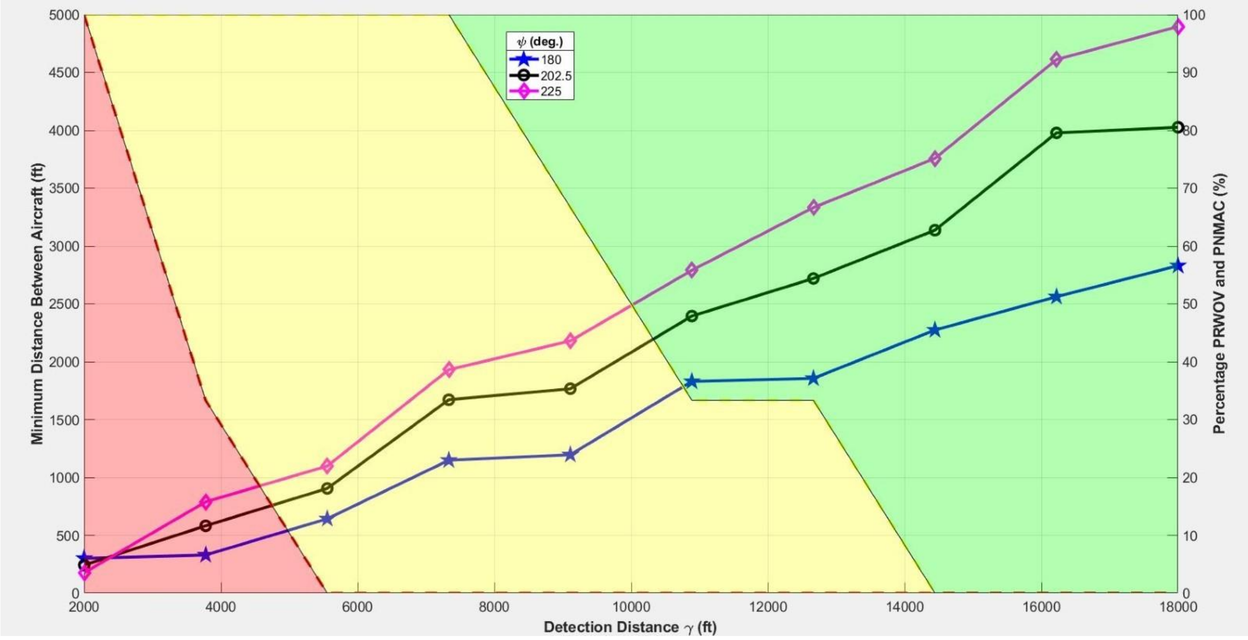


Figure 190. 145 ft/s Head On Converging Loiter Guidance With MPF.

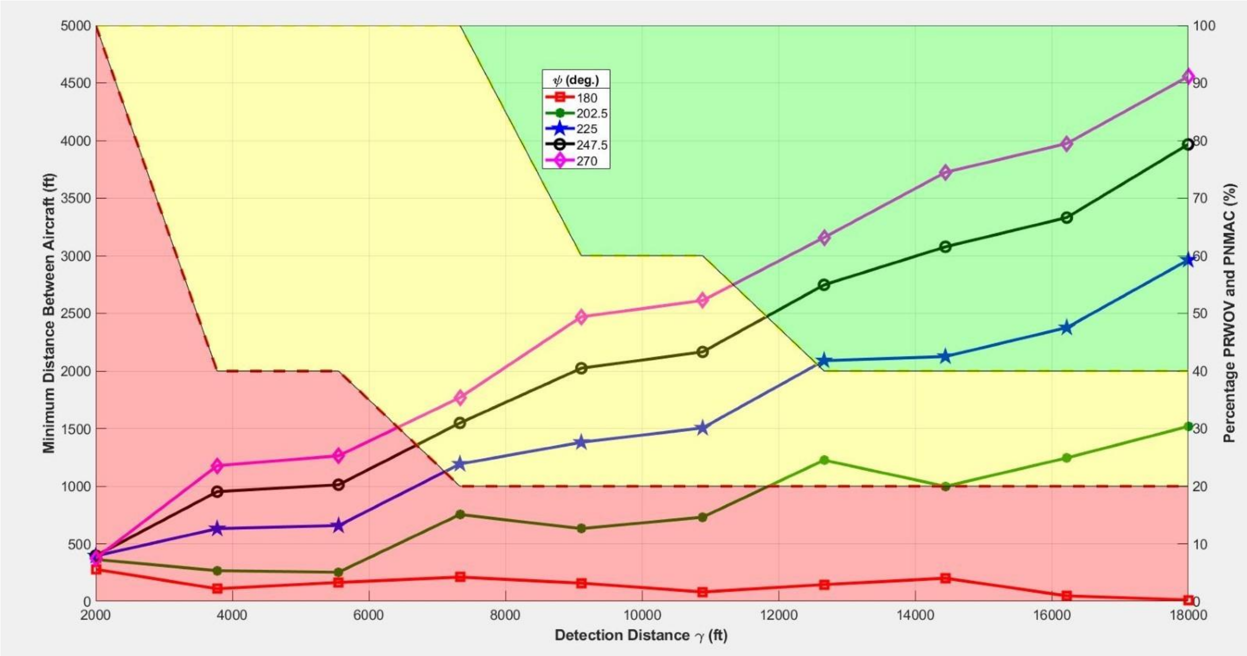


Figure 191. 170 ft/s Head On Converging Loiter Guidance.

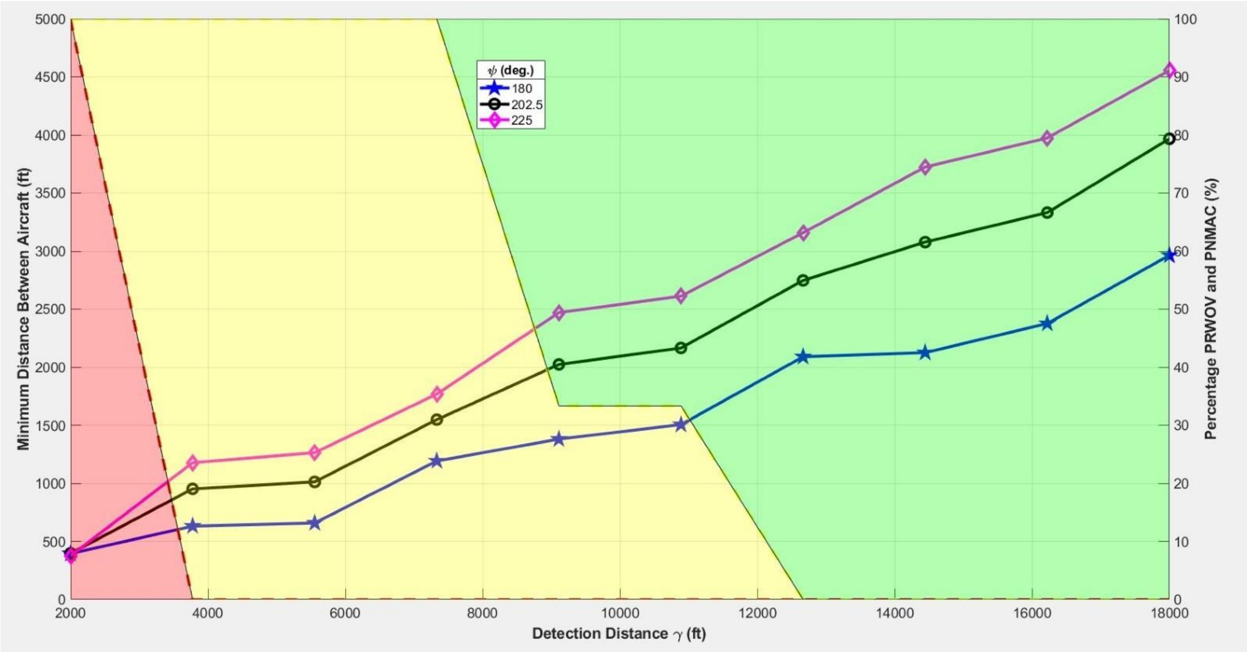


Figure 192. 170 ft/s Head On Converging Loiter Guidance With MPF.

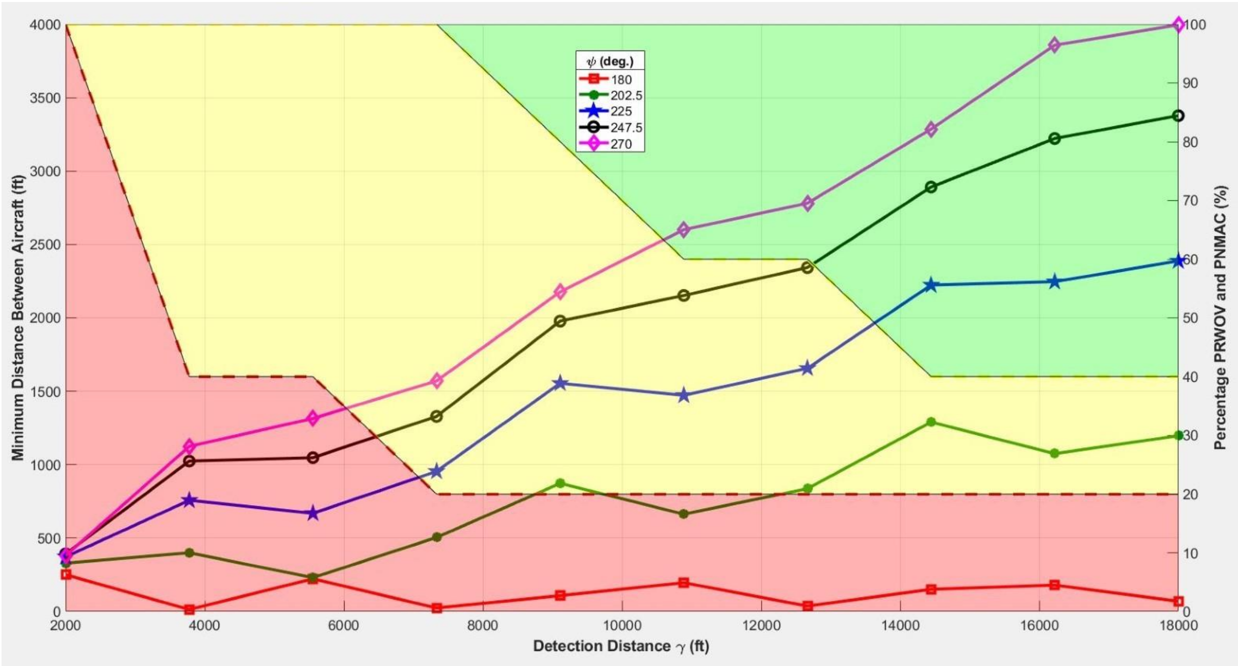


Figure 193. 195 ft/s Head On Converging Loiter Guidance.

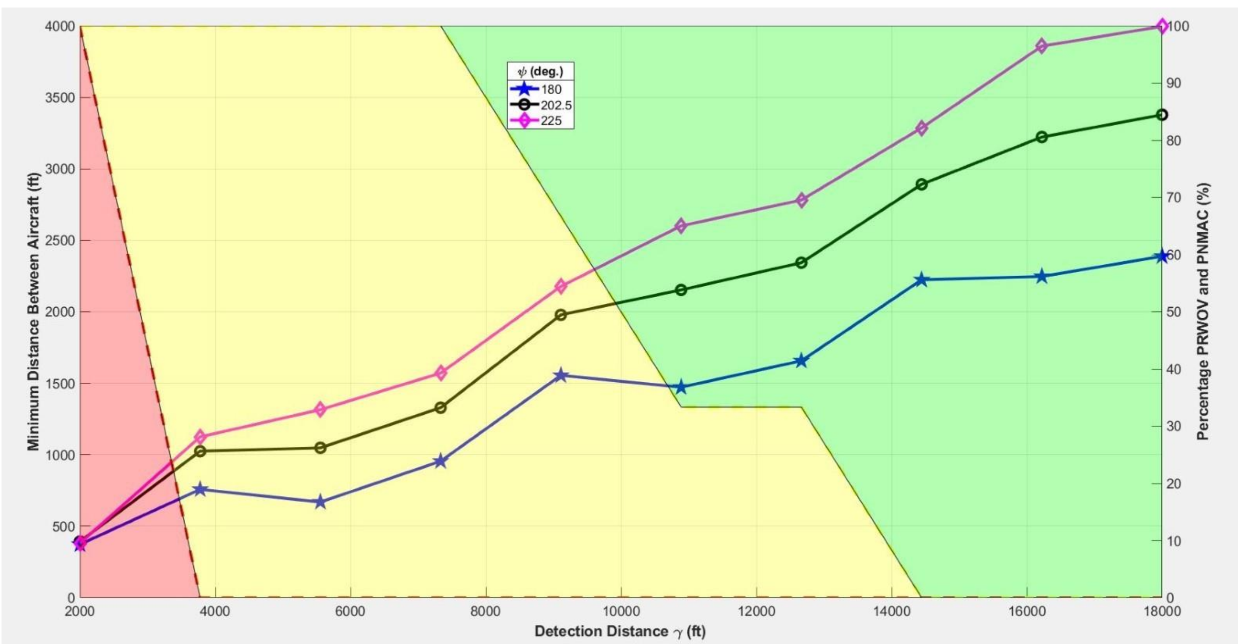


Figure 194. 195 ft/s Head On Converging Loiter Guidance With MPF.

B.2.4 Survey Pattern Single sUAS

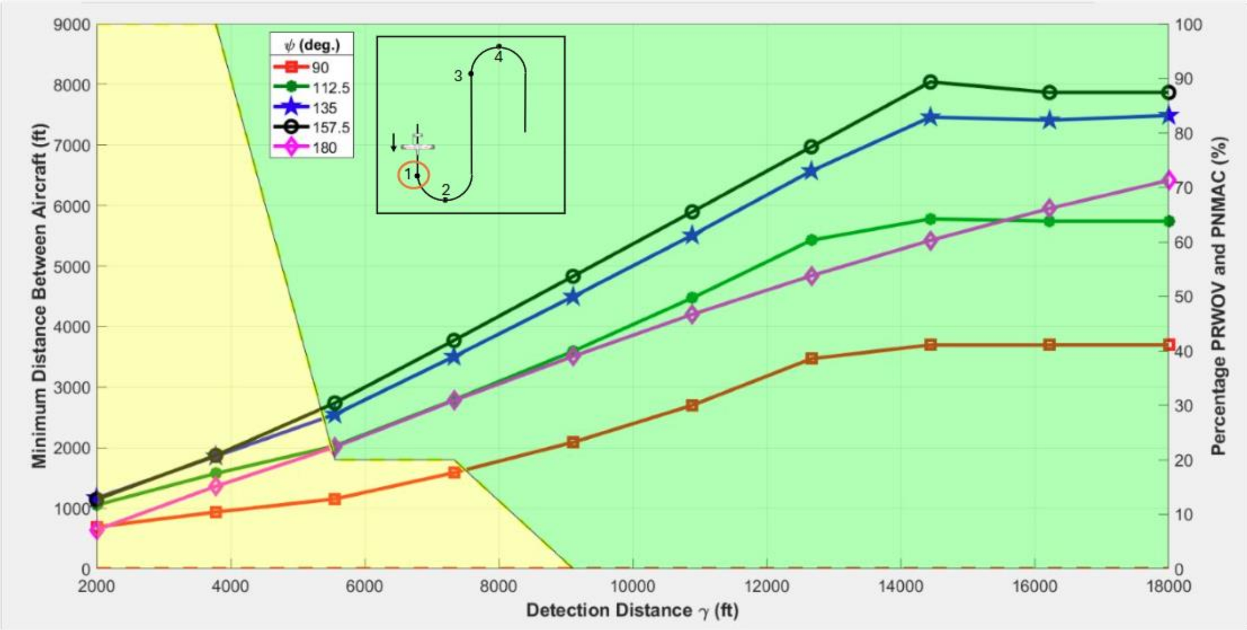


Figure 195. 145 ft/s Survey Single sUAS Point 1.

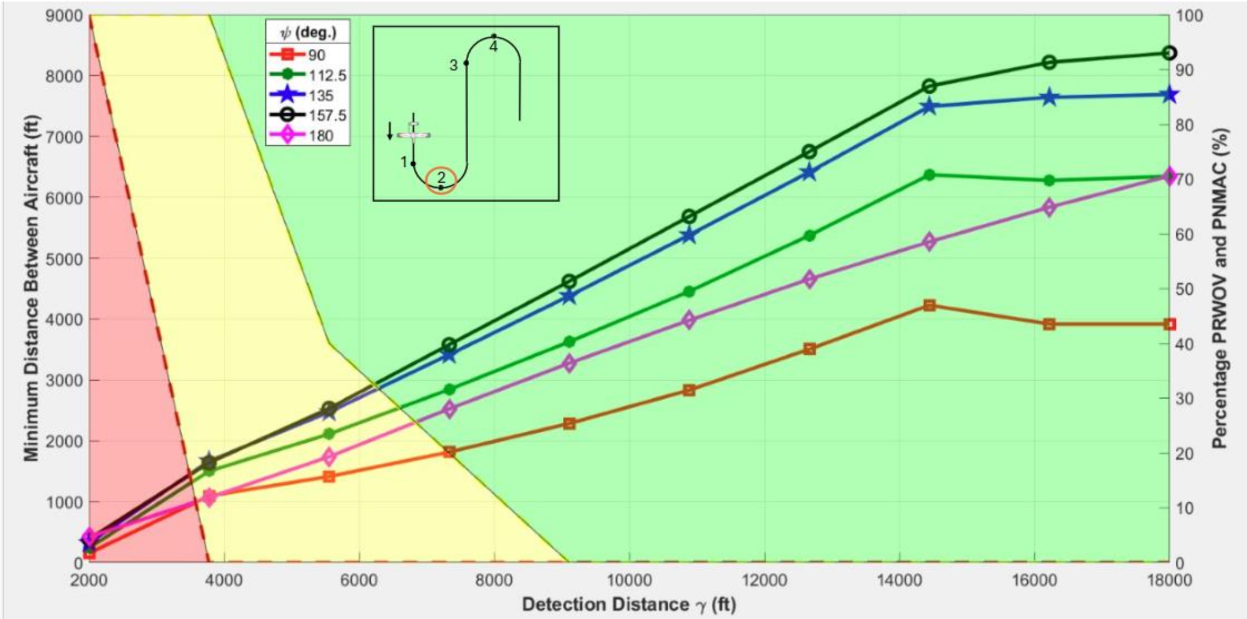


Figure 196. 145 ft/s Survey Single sUAS Point 2.

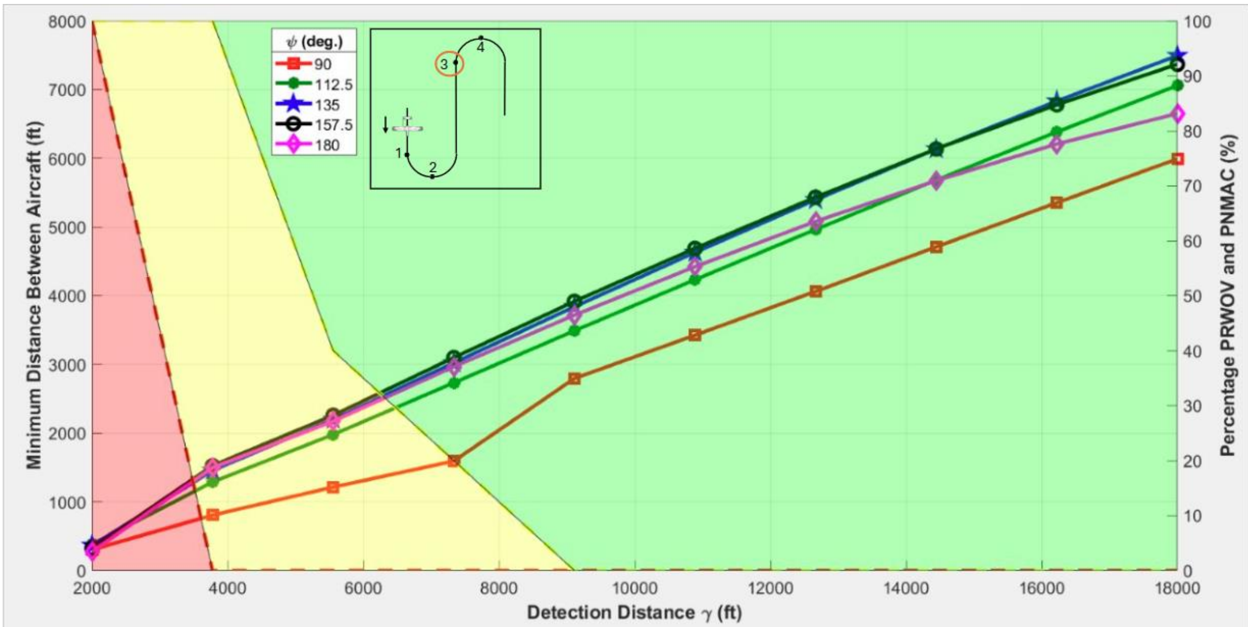


Figure 197. 145 ft/s Survey Single sUAS Point 3.

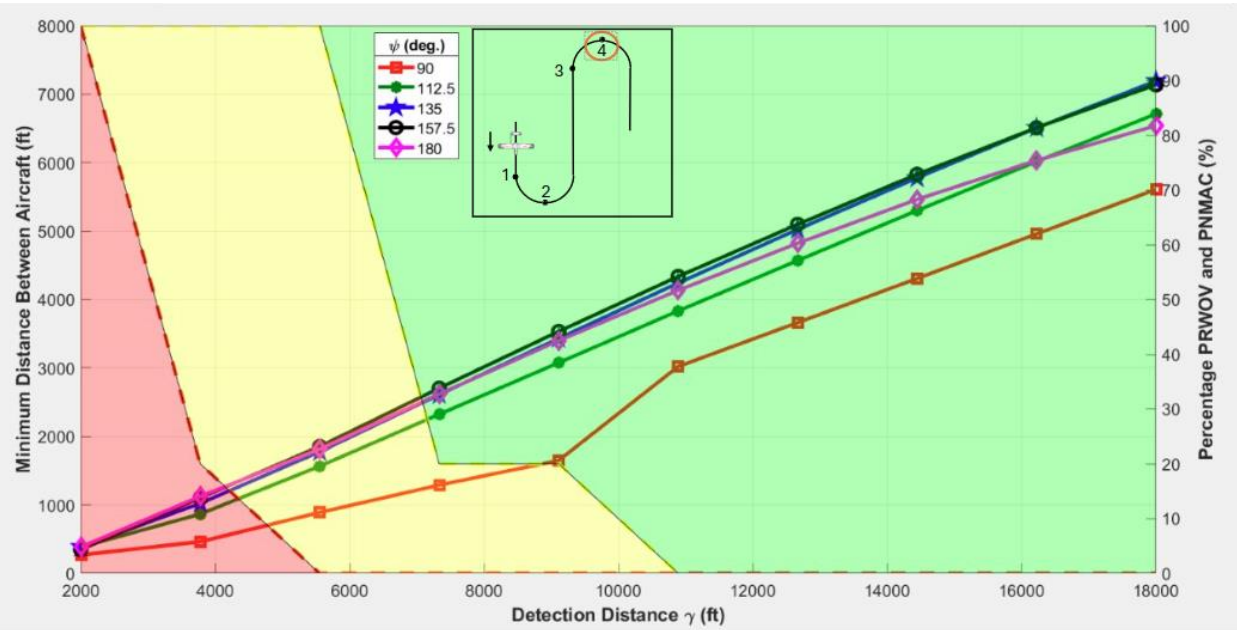


Figure 198. 145 ft/s Survey Single sUAS Point 4.

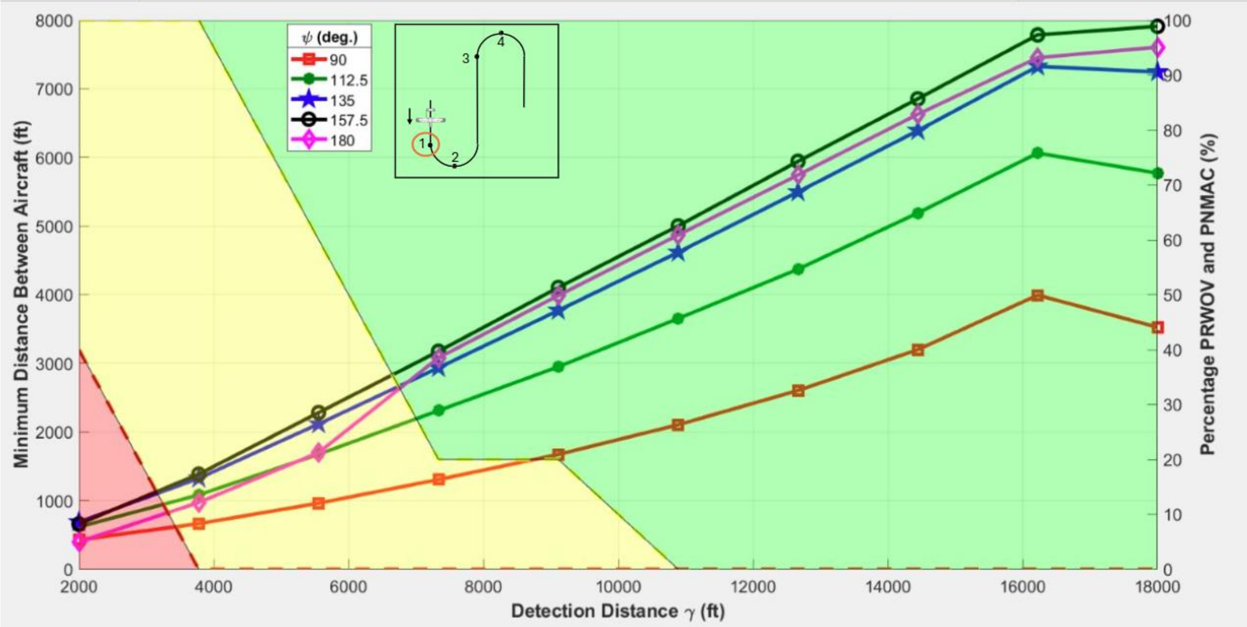


Figure 199. 170 ft/s Survey Single sUAS Point 1.

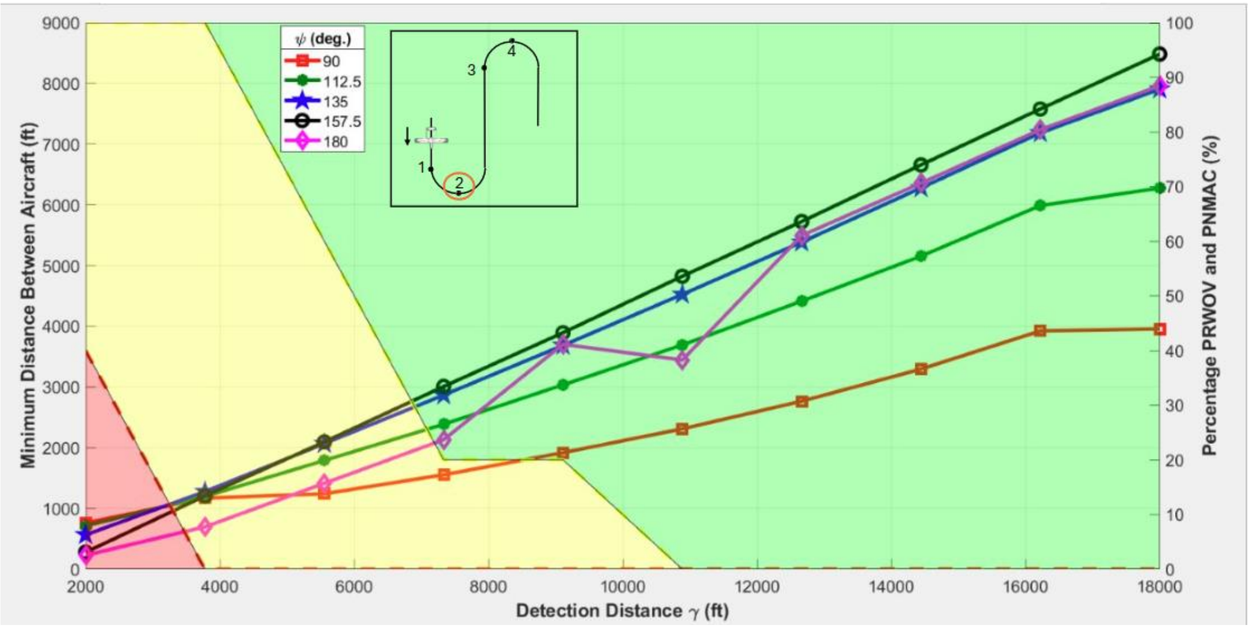


Figure 200. 170 ft/s Survey Single sUAS Point 2.

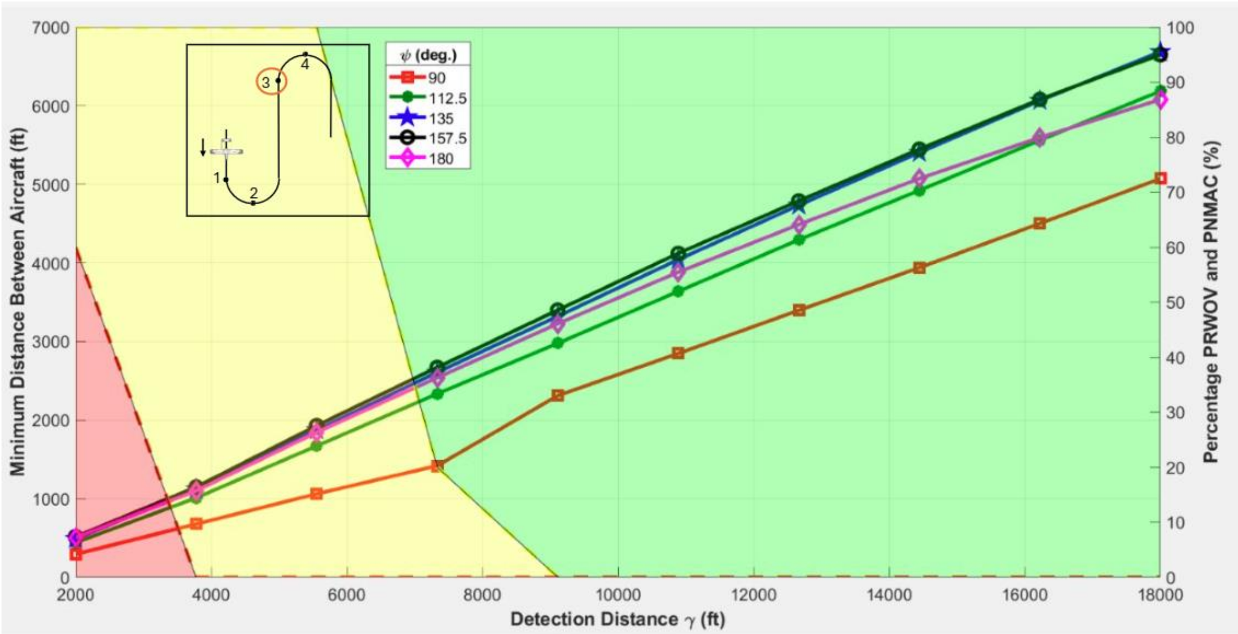


Figure 201. 170 ft/s Survey Single sUAS Point 3.

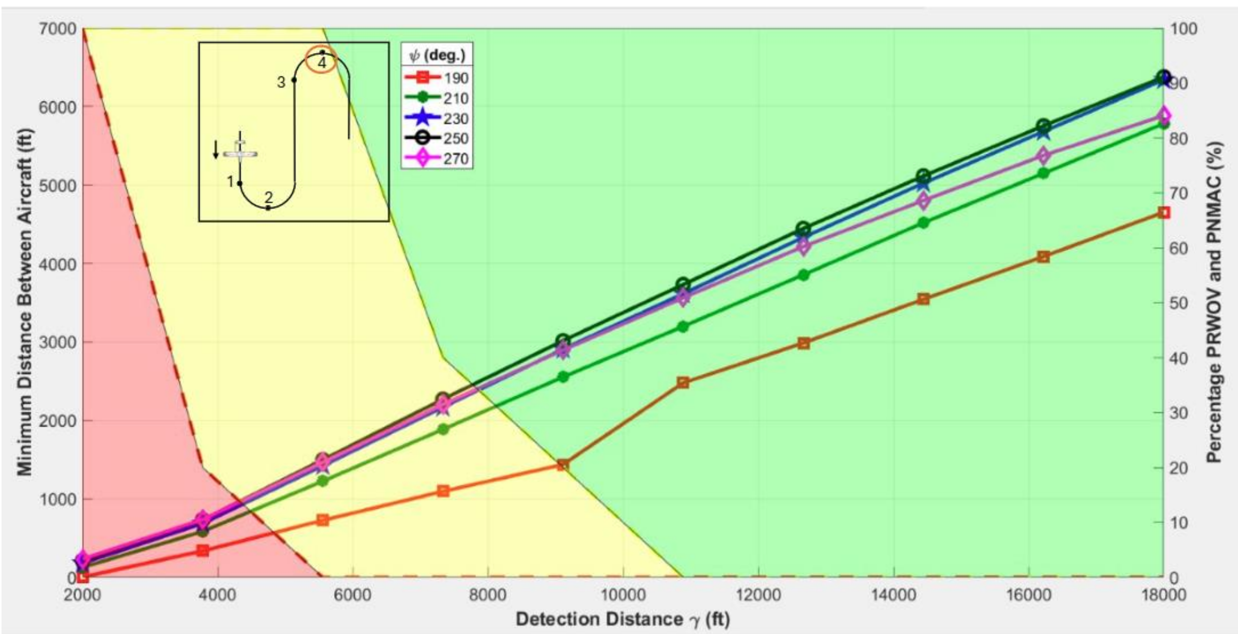


Figure 202. 170 ft/s Survey Single sUAS Point 4.

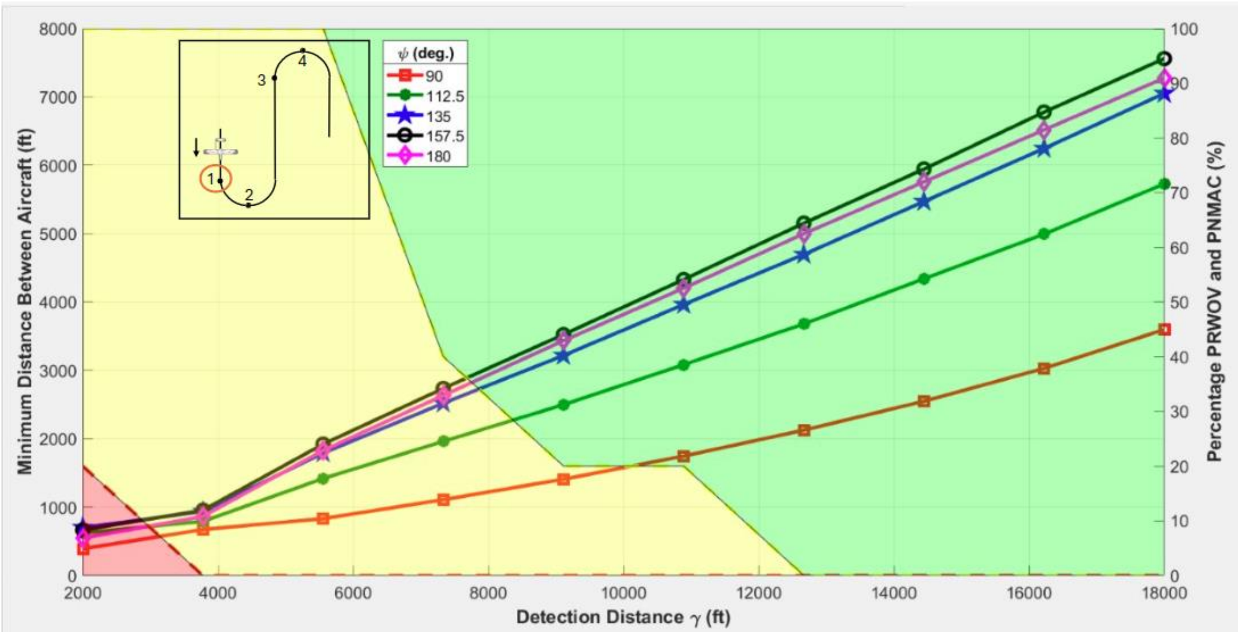


Figure 203. 195 ft/s Survey Single sUAS Point 1.

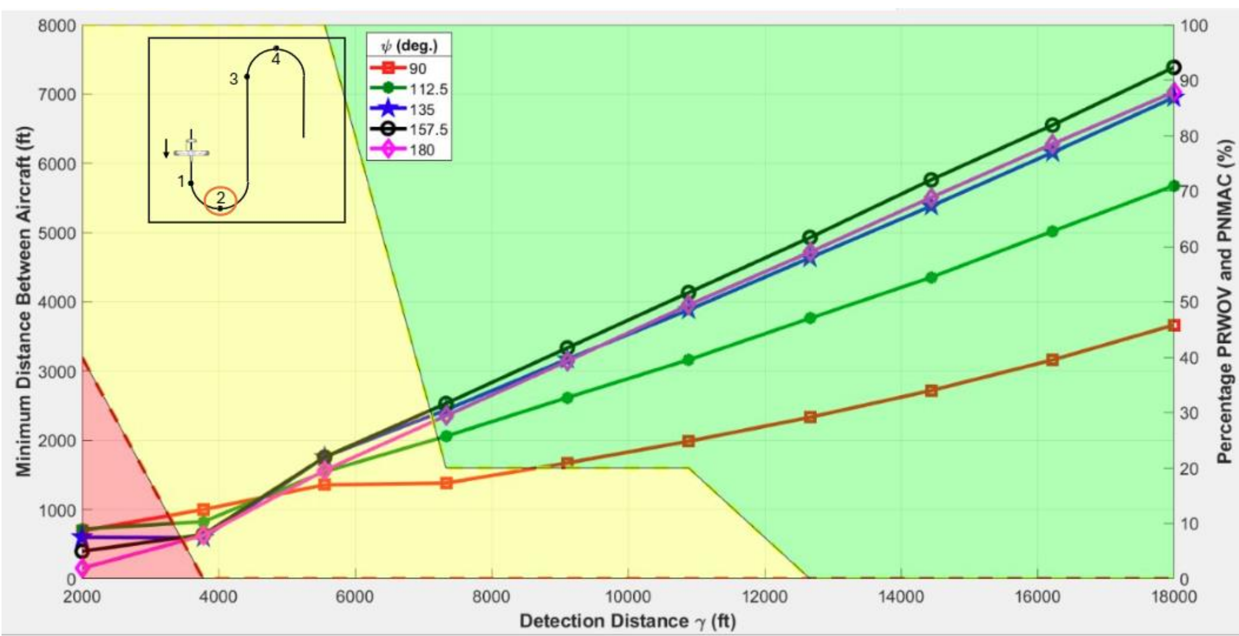


Figure 204. 195 ft/s Survey Single sUAS Point 2.

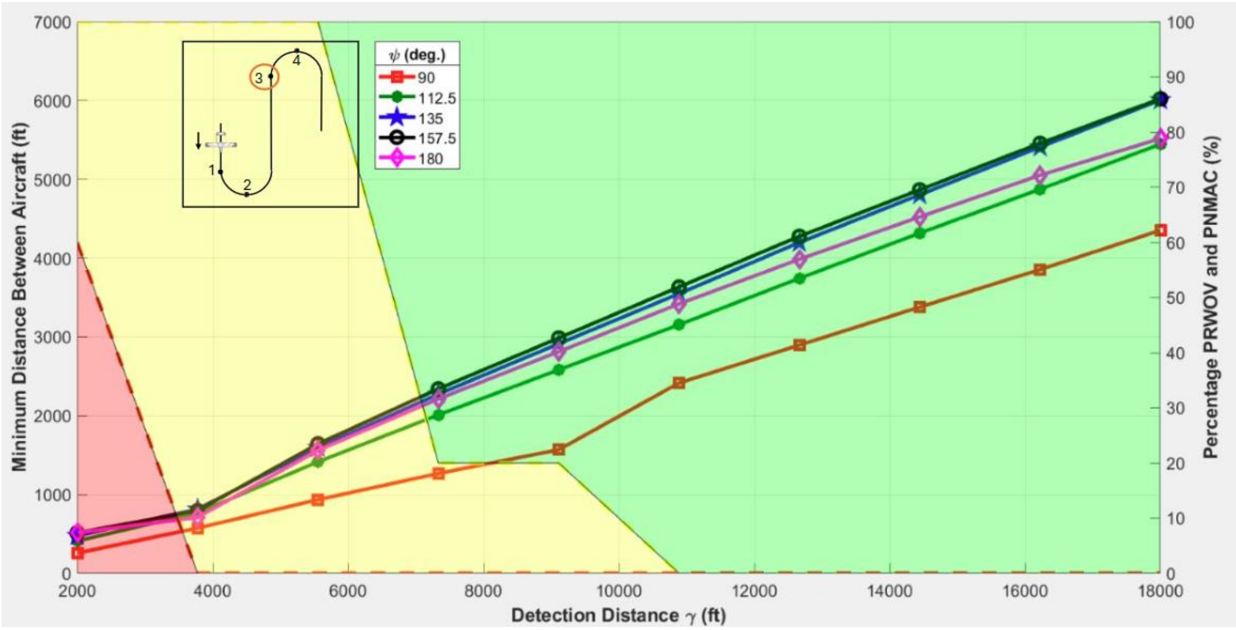


Figure 205. 195 ft/s Survey Single sUAS Point 3.

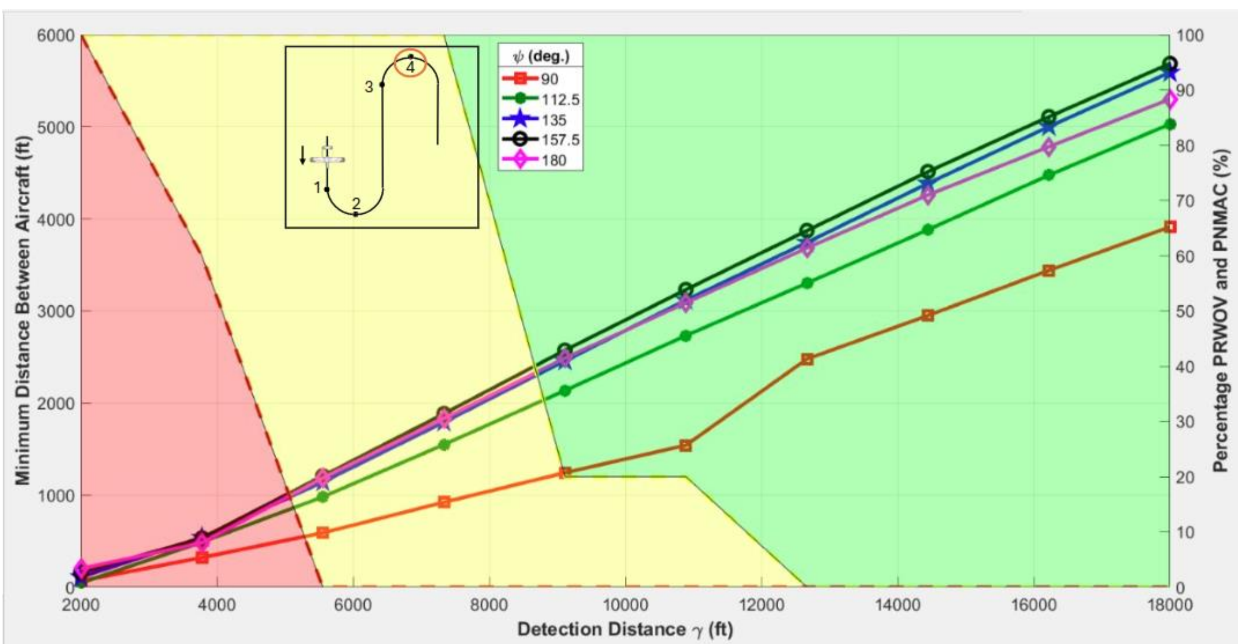


Figure 206. 195 ft/s Survey Single sUAS Point 4.

B.2.5 Survey Pattern Multiple sUAS

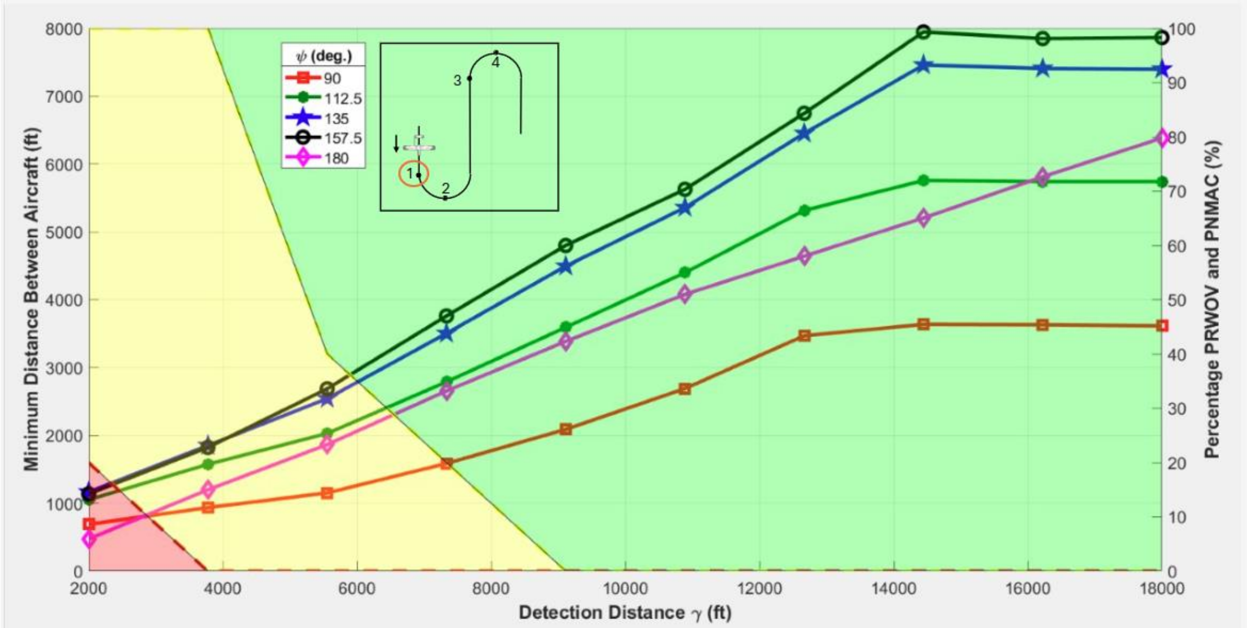


Figure 207. 145 ft/s Survey Multiple sUAS Point 1.

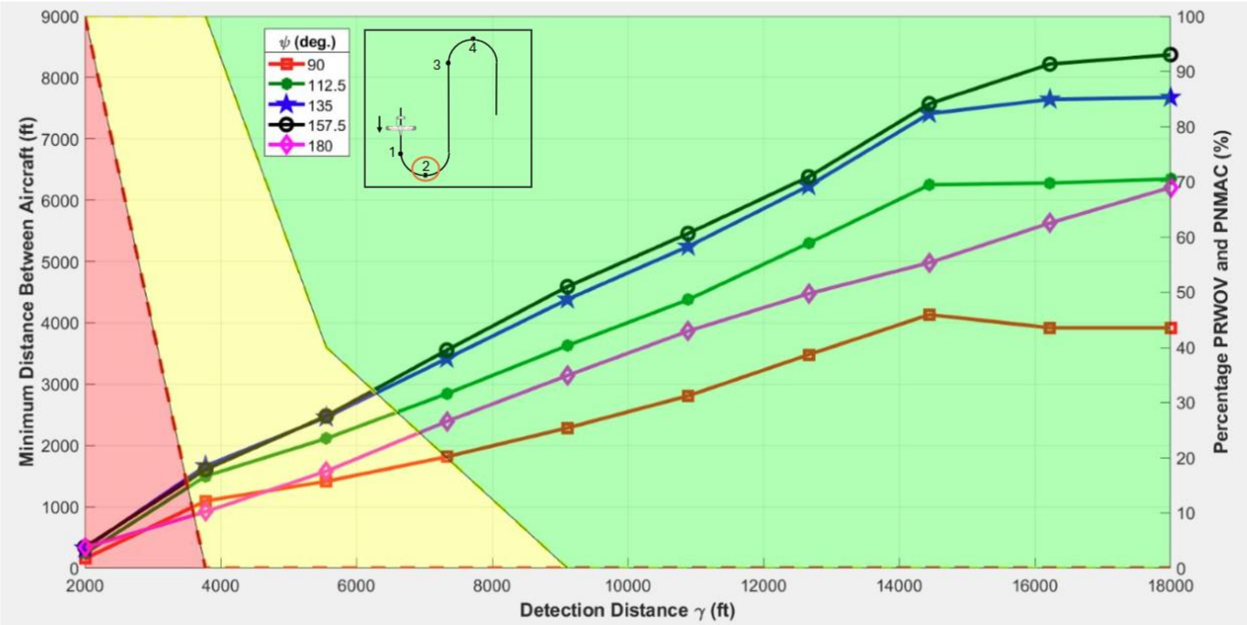


Figure 208. 145 ft/s Survey Multiple sUAS Point 2.

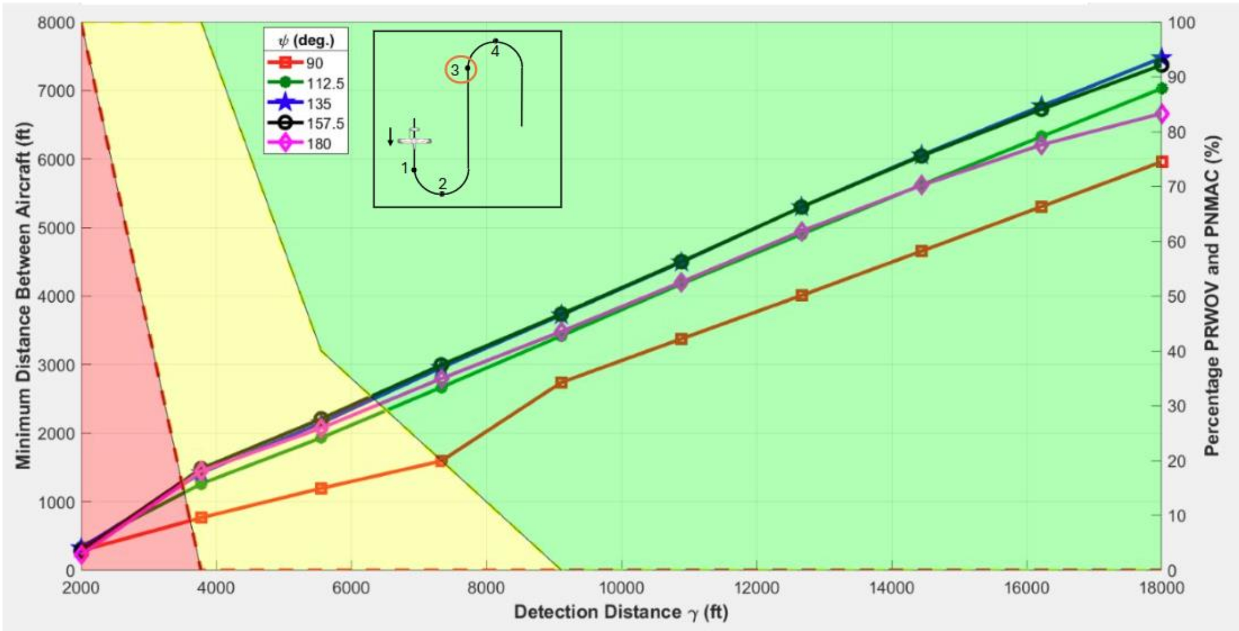


Figure 209. 145 ft/s Survey Multiple sUAS Point 3.

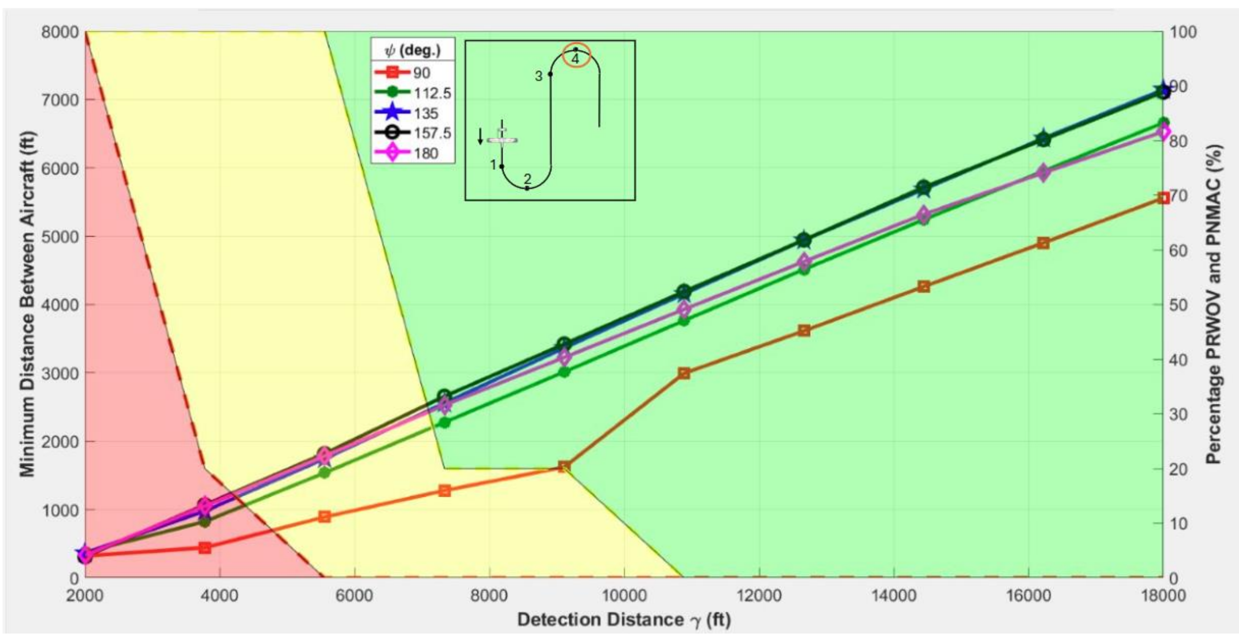


Figure 210. 145 ft/s Survey Multiple sUAS Point 4.

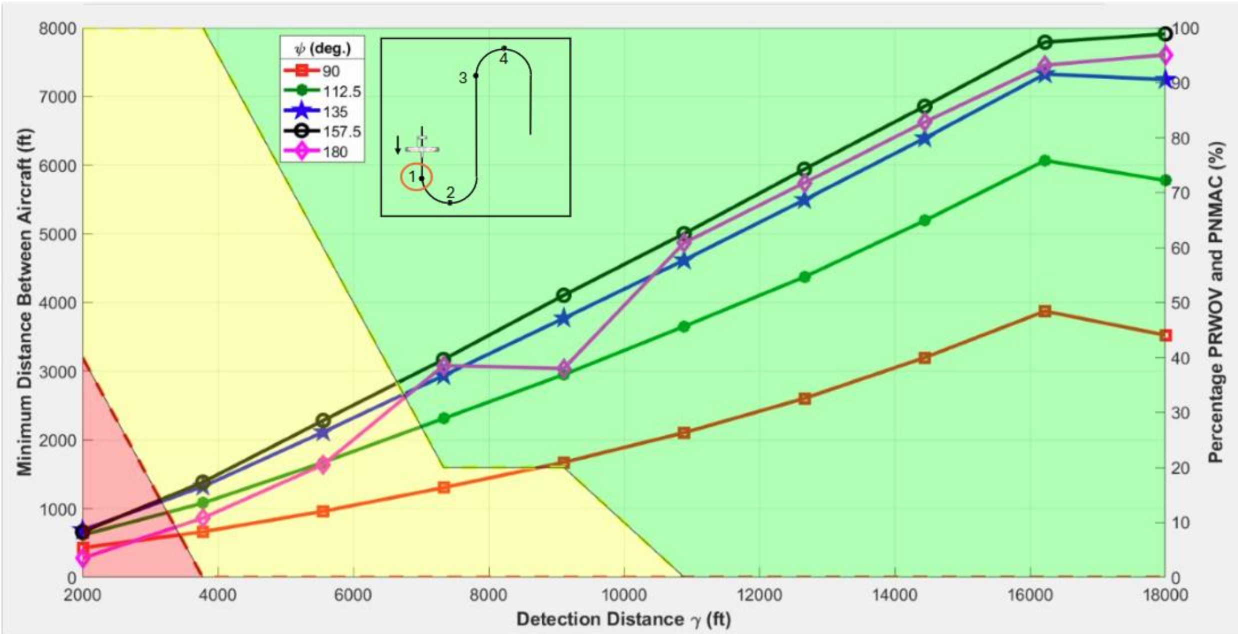


Figure 211. 170 ft/s Survey Multiple sUAS Point 1.

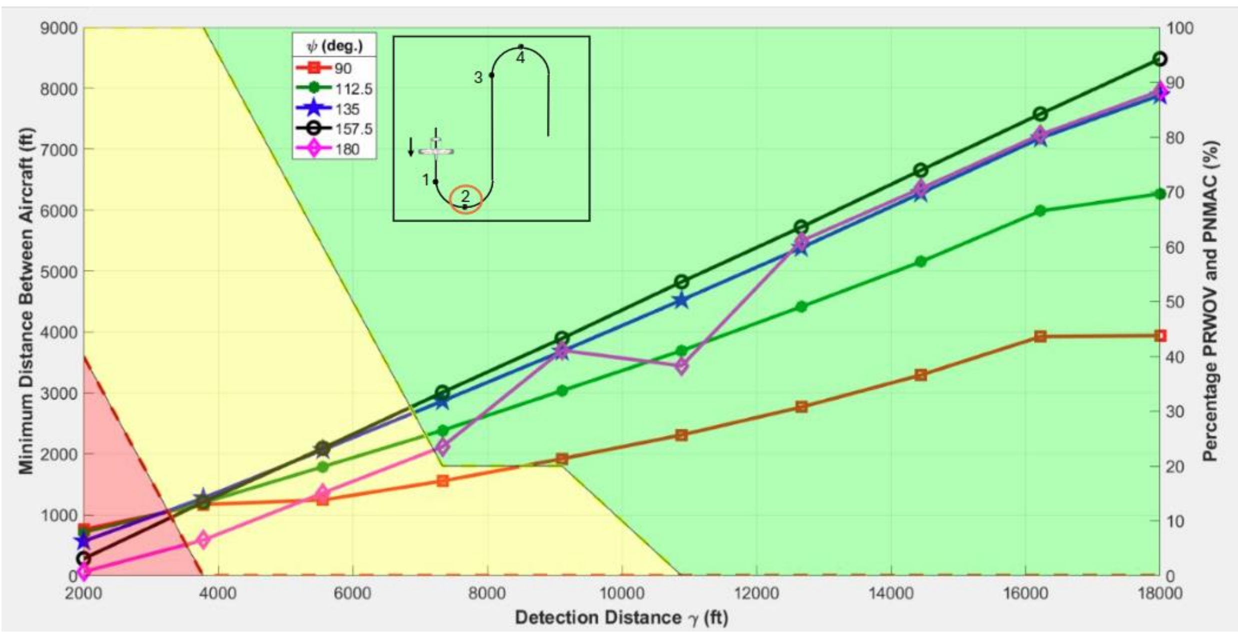


Figure 212. 170 ft/s Survey Multiple sUAS Point 2.

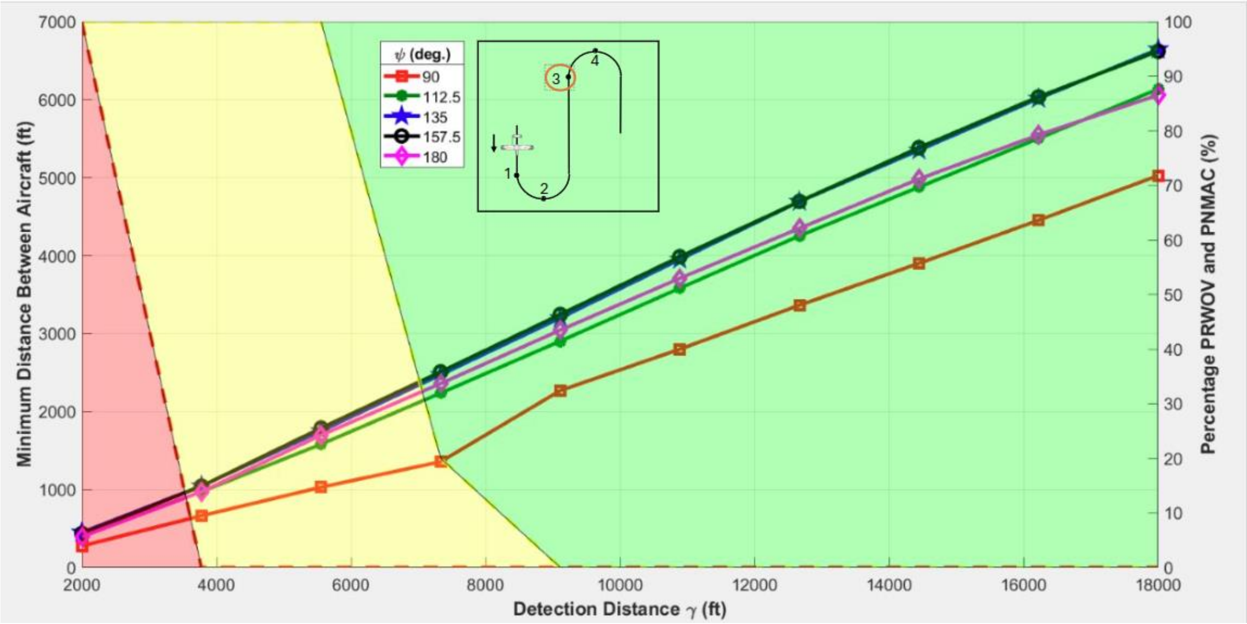


Figure 213. 170 ft/s Survey Multiple sUAS Point 3.

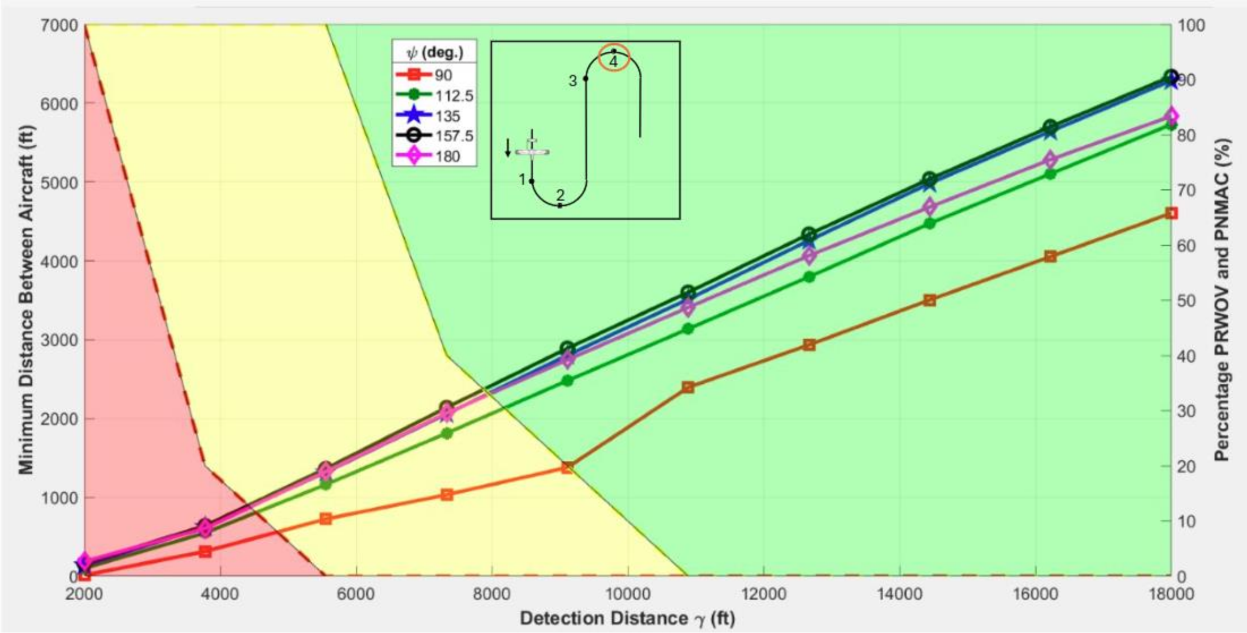


Figure 214. 170 ft/s Survey Multiple sUAS Point 4.

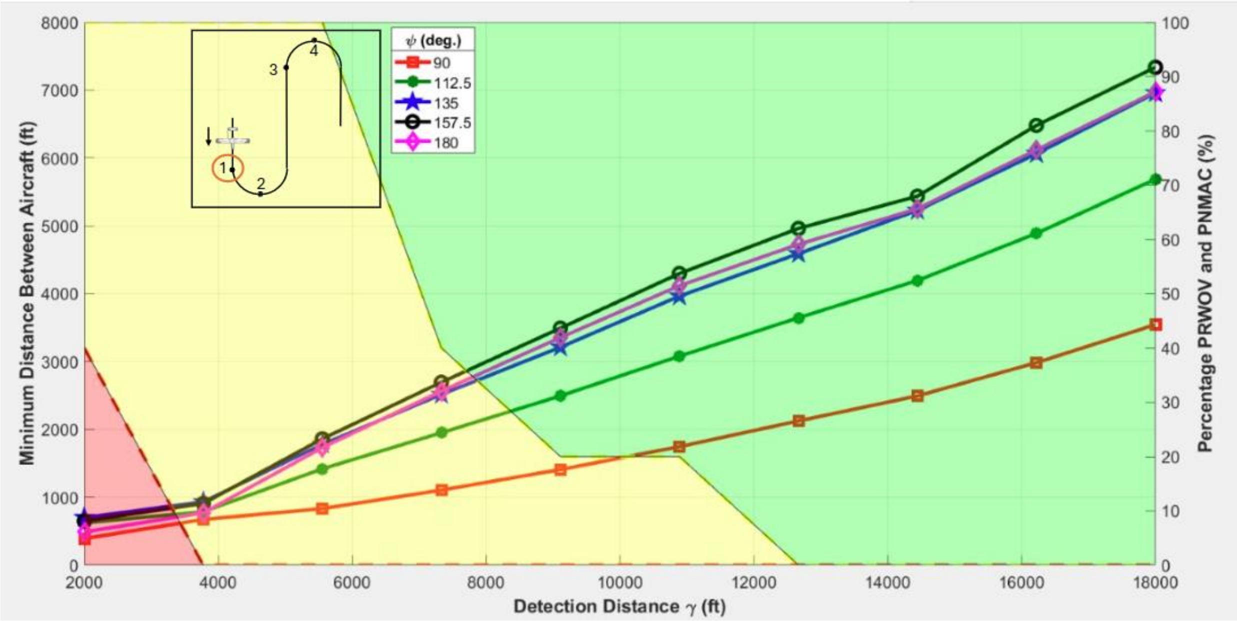


Figure 215. 195 ft/s Survey Multiple sUAS Point 1.

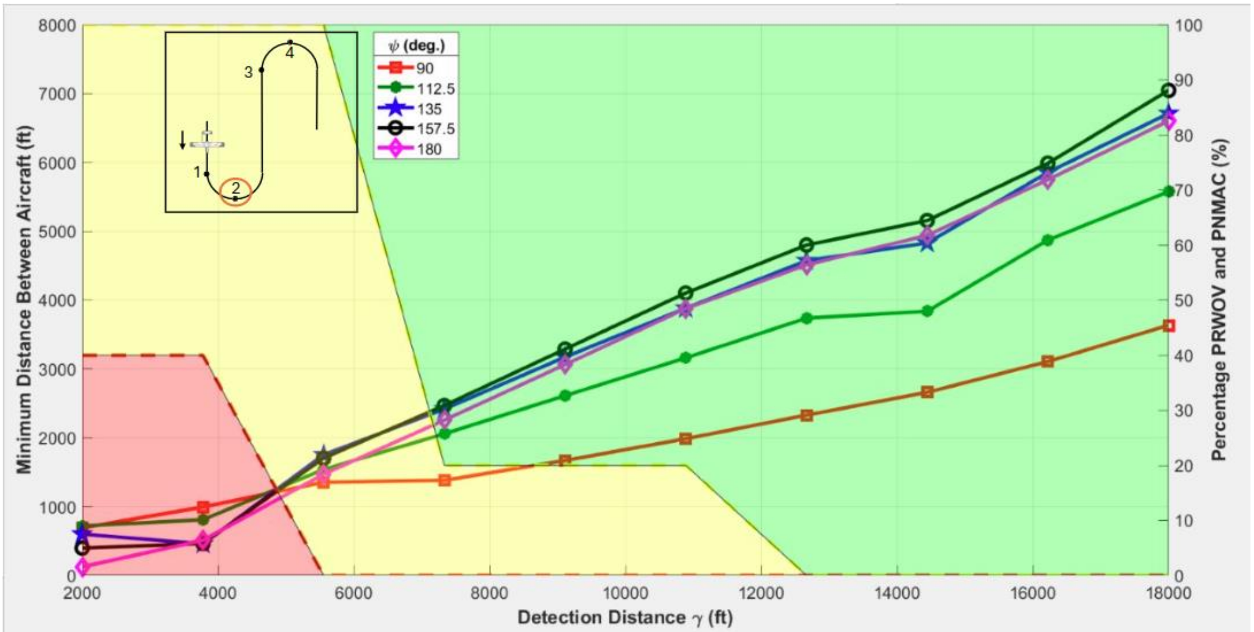


Figure 216. 195 ft/s Survey Multiple sUAS Point 2.

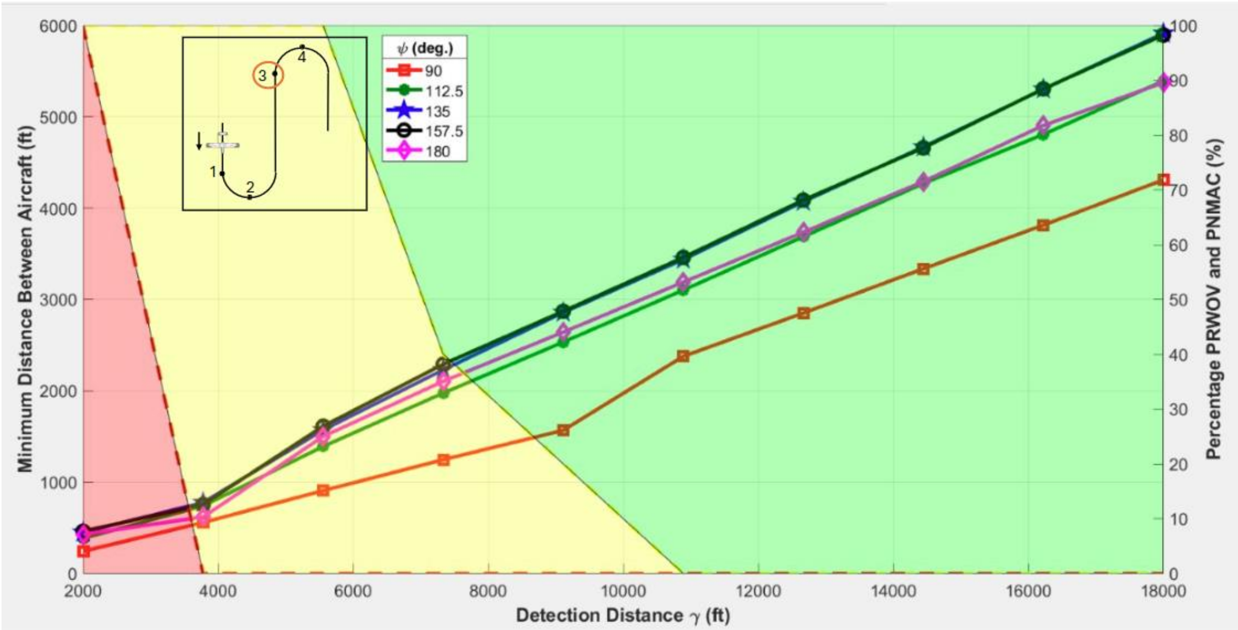


Figure 217. 195 ft/s Survey Multiple sUAS Point 3.

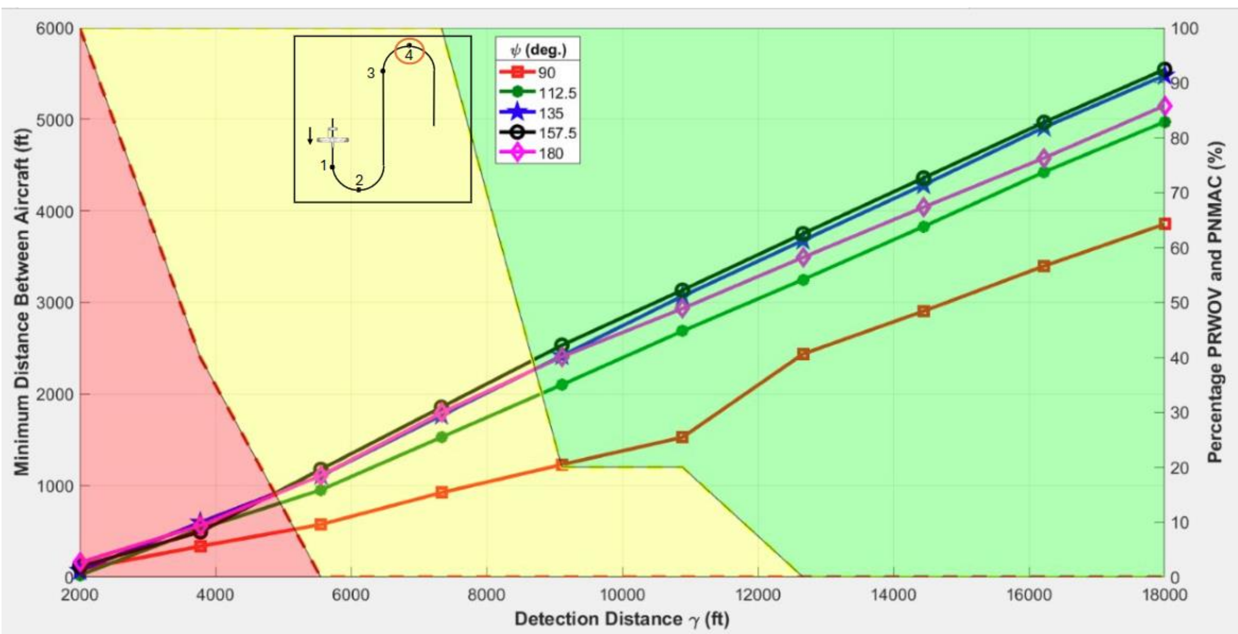


Figure 218. 195 ft/s Survey Multiple sUAS Point 4.

B.3 Saturation Point Results

Table 101. RAC Saturation Point Results.

UAS-on-UAS Incidents - Use Case #1: Powerline Inspection					
UASs released 10-20 seconds apart					
Average of 5 trials		Number of UASs			
		5	10	25	50
	sMACs (1ft)	0.00	1.00	4.00	8.40
	sNMACs (100ft)	0.40	2.20	12.00	30.80
	sWC Violations (500ft)	1.80	8.60	40.00	108.40
	Closest Distance (ft)	41.32	5.33	0.00	0.00
	Mean	1532.04	2272.85	2290.13	2796.27
	Median	1234.73	1949.07	2231.19	2368.74
	Mode	965.87	664.53	486.93	264.00
	Time (seconds) in potential conflict	1827.10	6851.20	28736.90	75913.00
	Average MACs	0.00	0.10	0.16	0.17
	Average sNMACs	0.08	0.22	0.48	0.62
	Average WC	0.36	0.86	1.60	2.17
	Average time in potential conflict	365.42	685.12	1149.48	1518.26

UAS-on-UAS Incidents - Use Case #2: Package Delivery					
UASs released 10-20 seconds apart					
Average of 5 trials		Number of UASs			
		5	10	25	50
	sMACs (2ft)	0.0	0.8	1.6	2.2
	sNMACs (50ft)	0.8	3.2	7	12.2
	sWC Violations (100ft)	0.8	3.4	9	15.6
	Closest Distance (ft)	65.74	66.24	8.96	1.55
	Mean	3691.76	3894.32	4456.20	4617.92
	Median	3402.25	3667.51	4397.11	4583.30
	Mode	2851.27	2946.69	3851.89	1822.56
	Time (seconds) in potential conflict	1445.00	5322.40	21571.70	47813.30
	Average MACs	0.00	0.08	0.06	0.04
	Average sNMACs	0.16	0.32	0.28	0.24
	Average WC	0.16	0.34	0.36	0.31
	Average time in potential conflict	289.00	532.24	862.87	956.27

These data indicate the saturation point lies somewhere between five and ten. The team re-ran the trials at this more focused window, shown in Table 101.

Table 102. Additional RAC Saturation Point Results.

UAS-on-UAS Incidents - Use Case #1: Powerline Inspection					
UASs released 10-20 seconds apart					
Average of 5 trials		Number of UASs			
		6	7	8	9
	sMACs (2ft)	0.2	0.8	0.8	0.8
	sNMACs (50ft)	0.8	1.6	1.6	2.6
	sWC Violations (100ft)	3	4.8	7.2	10.2
	Closest Distance (ft)	28.28	22.45	22.42	12.54
	Mean	1784.39	1915.55	2019.26	2080.57
	Median	1317.82	1481.38	1542.20	1562.80
	Mode	739.20	897.60	704.00	774.40

	Time (seconds) in potential conflict	2653.10	3615.40	4648.40	5759.50
	Average MACs	0.03	0.11	0.10	0.09
	Average NMACs	0.13	0.23	0.20	0.29
	Average WC	0.50	0.69	0.90	1.13
	Average time in potential conflict	442.18	516.49	581.05	639.94

Table IV

UAS-on-UAS Incidents - Use Case #2: Package Delivery

UASs released 10-20 seconds apart

Average of 5 trials		Number of UASs			
		6	7	8	9
	sMACs (2ft)	0	0	0	0
	sNMACs (50ft)	0.4	0.8	0.8	0.8
	sWC Violations (100ft)	0.4	0.8	1	1.4
	Closest Distance (ft)	136.85	109.07	109.07	71.16
	Mean	3770.71	3790.07	3728.93	3847.40
	Median	3518.56	3747.79	3649.98	3733.88
	Mode	1974.06	2792.99	2747.00	3125.92
	Time (seconds) in potential conflict	1863.00	2723.40	3542.10	4444.00
	Average MACs	0.00	0.00	0.00	0.00
	Average NMACs	0.07	0.11	0.10	0.09
	Average WC	0.07	0.11	0.13	0.16
	Average time in potential conflict	310.50	389.06	442.76	493.78

APPENDIX C – REMOTE ID – ROUND 3

C.1 sUAS vs sUAS (UND)

C.1.1 Following Right-of-Way Rules

These results are for a 35 knot sUAS ownship vs a 50 knot sUAS intruder in the scenario where both aircraft follow right-of-way rules. There are four GPS uncertainties, four climb/descent rates, two pilot response times, two update rates, and three maneuver restrictions for each of the geometry categories. The four GPS uncertainties are RTK, WAAS, SPS GPS, and GPS MAX. Climb rates are 250fpm, 500fpm, 750fpm, and 1000fpm. Pilot response times of one second and five seconds. Update rates of 0.2s, 1s, 3s, and 5s. Maneuver restrictions of horizontal-only, vertical-only, and unrestricted.

C.1.1.1 0.2s Update Rate

C.1.1.1.1 Head-on

Table 103. Remote ID sUAS vs sUAS Following Rules, Head-on, 0.2s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	640	1296	640	1296	640	1296	673	1329
vertical-only	722	1395	837	1493	919	1592	1526	2182
unrestricted	640	1296	640	1296	640	1296	673	1329
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	640	1296	640	1296	640	1296	673	1329
vertical-only	558	1231	607	1264	640	1296	952	1625
unrestricted	558	1231	607	1264	624	1296	673	1329
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	640	1296	640	1296	640	1296	673	1329
vertical-only	509	1165	542	1198	558	1231	722	1395
unrestricted	509	1165	542	1198	558	1231	673	1329
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	640	1296	640	1296	640	1296	673	1329
vertical-only	476	1132	509	1165	525	1182	640	1296
unrestricted	493	1165	509	1165	525	1198	640	1296

C.1.1.1.2 Converging from Right

Table 104. Remote ID sUAS vs sUAS Following Rules, Converging from Right, 0.2s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	739	1395	739	1395	739	1395	788	1428
vertical-only	1132	1772	1362	2002	1460	2100	2543	3199
unrestricted	689	1346	755	1395	771	1395	804	1444
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	739	1395	739	1395	739	1395	788	1428
vertical-only	722	1362	854	1510	936	1592	1542	2199
unrestricted	607	1264	673	1329	706	1362	821	1460
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	739	1395	739	1395	739	1395	788	1428
vertical-only	607	1264	673	1329	722	1362	1198	1838
unrestricted	575	1231	607	1264	640	1296	837	1477
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	739	1395	739	1395	739	1395	788	1428
vertical-only	558	1198	607	1264	640	1296	968	1608
unrestricted	542	1198	575	1231	607	1247	788	1428

C.1.1.1.3 Overtaking

Table 105. Remote ID sUAS vs sUAS Following Rules, Overtaking, 0.2s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	329	525	329	525	329	525	361	558
vertical-only	427	624	509	706	558	755	952	1165
unrestricted	312	509	329	525	329	525	361	558
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	329	525	329	525	329	525	361	558
vertical-only	279	493	329	525	361	558	558	771
unrestricted	312	509	312	509	312	509	345	542
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	329	525	329	525	329	525	361	558
vertical-only	263	460	279	476	279	493	443	640
unrestricted	312	509	312	509	312	509	345	542
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	329	525	329	525	329	525	361	558
vertical-only	230	443	263	460	263	460	361	558
unrestricted	263	460	296	493	312	509	329	525

C.1.1.2 1s Update Rate

C.1.1.2.1 Head-on

Table 106. Remote ID sUAS vs sUAS Following Rules, Head-on, 1s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1313	657	1313	657	1313	673	1329
vertical-only	771	1444	837	1493	952	1625	1592	2248
unrestricted	657	1313	657	1313	657	1313	673	1329
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1313	657	1313	657	1313	673	1329
vertical-only	607	1280	640	1296	657	1313	968	1641
unrestricted	607	1280	640	1296	640	1313	673	1329
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1313	657	1313	657	1313	673	1329
vertical-only	509	1165	607	1264	607	1280	771	1444
unrestricted	509	1165	607	1264	607	1280	673	1329
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1313	657	1313	657	1313	673	1329
vertical-only	493	1149	509	1165	591	1264	657	1313
unrestricted	493	1165	509	1165	591	1264	657	1313

C.1.1.2.2 Converging from Right

Table 107. Remote ID sUAS vs sUAS Following Rules, Converging from Right, 1s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	771	1428	771	1428	771	1428	804	1444
vertical-only	1132	1772	1411	2051	1460	2100	2560	3216
unrestricted	755	1395	788	1428	788	1428	804	1444
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	771	1428	771	1428	771	1428	804	1444
vertical-only	771	1411	919	1559	952	1608	1575	2231
unrestricted	624	1280	739	1395	755	1411	870	1477
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	771	1428	771	1428	771	1428	804	1444
vertical-only	624	1280	739	1395	771	1411	1247	1887
unrestricted	607	1264	624	1280	640	1296	903	1542
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	771	1428	771	1428	771	1428	804	1444
vertical-only	607	1247	624	1280	640	1296	968	1608
unrestricted	591	1247	607	1264	624	1264	804	1444

C.1.1.2.3 Overtaking

Table 108. Remote ID sUAS vs sUAS Following Rules, Overtaking, 1s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	378	575
vertical-only	460	673	525	722	575	771	968	1165
unrestricted	345	542	361	558	361	558	378	575
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	378	575

vertical-only	312	509	361	558	378	575	591	788
unrestricted	329	525	345	542	345	542	361	558
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	378	575
vertical-only	279	460	312	509	312	509	460	673
unrestricted	312	509	329	525	329	525	361	558
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	558	361	558	361	558	378	575
vertical-only	263	460	279	460	279	476	394	591
unrestricted	296	493	312	509	312	509	361	558

C.1.1.3 3s Update Rate

C.1.1.3.1 Head-on

Table 109. Remote ID sUAS vs sUAS Following Rules, Head-on, 3s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	821	1395	821	1395	821	1395	837	1411
vertical-only	854	1444	919	1493	952	1789	1756	2330
unrestricted	821	1395	821	1395	821	1395	837	1411
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	821	1395	821	1395	821	1395	837	1411
vertical-only	771	1362	804	1378	821	1395	968	1805
unrestricted	788	1362	804	1378	804	1395	837	1411
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	821	1395	821	1395	821	1395	837	1411
vertical-only	509	1329	771	1346	771	1362	854	1444
unrestricted	509	1329	771	1346	771	1362	837	1411
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	821	1395	821	1395	821	1395	837	1411
vertical-only	493	1313	509	1329	755	1346	821	1395

unrestricted	493	1329	509	1329	755	1346	821	1395

C.1.1.3.2 Converging from Right

Table 110. Remote ID sUAS vs sUAS Following Rules, Converging from Right, 3s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	854	1428	854	1428	854	1428	886	1444
vertical-only	1296	1854	1411	2215	1608	2264	2724	3298
unrestricted	837	1395	870	1428	870	1428	886	1493
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	854	1428	854	1428	854	1428	886	1444
vertical-only	854	1411	919	1723	952	1772	1739	2313
unrestricted	788	1362	821	1395	837	1411	903	1641
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	854	1428	854	1428	854	1428	886	1444
vertical-only	788	1362	821	1395	854	1411	1329	1887
unrestricted	771	1346	788	1362	804	1378	903	1723
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	854	1428	854	1428	854	1428	886	1444
vertical-only	771	1329	788	1362	804	1378	1050	1772
unrestricted	755	1329	771	1346	788	1346	886	1493

C.1.1.3.3 Overtaking

Table 111. Remote ID sUAS vs sUAS Following Rules, Overtaking, 3s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	673	394	673	394	673	476	673
vertical-only	542	689	607	821	673	837	1034	1264
unrestricted	361	640	361	673	394	673	476	673
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	673	394	673	394	673	476	673
vertical-only	394	542	411	673	476	673	689	837
unrestricted	361	607	361	640	361	640	460	673
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	673	394	673	394	673	476	673
vertical-only	361	542	394	542	394	558	542	722
unrestricted	361	591	361	607	361	607	427	673
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	361	673	394	673	394	673	476	673
vertical-only	361	542	361	542	361	542	493	689
unrestricted	361	542	361	558	361	591	411	673

C.1.1.4 5s Update Rate

C.1.1.4.1 Head-on

Table 112. Remote ID sUAS vs sUAS Following Rules, Head-on, 5s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1395	657	1395	657	1395	673	1411
vertical-only	1116	1444	1165	1493	1214	1953	1920	2248
unrestricted	657	1395	657	1395	657	1395	673	1411
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1395	657	1395	657	1395	673	1411
vertical-only	607	1362	640	1378	657	1395	1231	1969
unrestricted	607	1362	640	1378	640	1395	673	1411
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1395	657	1395	657	1395	673	1411
vertical-only	591	1329	607	1346	607	1362	1116	1444
unrestricted	591	1329	607	1346	607	1362	673	1411
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	657	1395	657	1395	657	1395	673	1411
vertical-only	575	1313	591	1329	591	1346	657	1395
unrestricted	575	1329	591	1329	591	1346	657	1395

C.1.1.4.2 Converging from Right

Table 113. Remote ID sUAS vs sUAS Following Rules, Converging from Right, 5s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	1100	1428	1100	1428	1100	1428	1132	1444
vertical-only	1296	2018	1411	2133	1772	2182	2806	3544
unrestricted	1083	1395	1116	1428	1116	1428	1132	1641
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	1100	1428	1100	1428	1100	1428	1132	1444
vertical-only	1100	1411	1165	1887	1214	1936	1903	2231
unrestricted	788	1362	1067	1395	1083	1411	1149	1805
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	1100	1428	1100	1428	1100	1428	1132	1444
vertical-only	689	1362	1067	1395	1100	1411	1329	2051
unrestricted	640	1346	788	1362	936	1378	1149	1887
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	1100	1428	1100	1428	1100	1428	1132	1444
vertical-only	640	1329	640	1362	854	1378	1214	1936
unrestricted	640	1329	640	1346	689	1346	1132	1641

C.1.1.4.3 Overtaking

Table 114. Remote ID sUAS vs sUAS Following Rules, Overtaking, 5s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	509	771	509	771	509	771	509	771
vertical-only	591	837	706	837	771	936	1083	1329
unrestricted	509	739	509	771	509	771	509	771
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	509	771	509	771	509	771	509	771
vertical-only	509	624	509	771	509	771	771	985
unrestricted	509	706	509	739	509	739	509	771
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	509	771	509	771	509	771	509	771
vertical-only	460	591	509	591	509	657	591	837
unrestricted	509	673	509	706	509	706	509	771
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	509	771	509	771	509	771	509	771
vertical-only	411	591	460	591	476	591	591	771
unrestricted	493	591	509	657	509	673	509	771

C.2 sUAS vs Crewed (UND)

C.2.1 Following Right-of-Way Rules

These results are for a 50 knot sUAS ownship vs a 120 knot Crewed intruder in the scenario where both aircraft follow the right-of-way rules using a small well clear volume. There are four GPS uncertainties, four climb/descent rates, two pilot response times, two update rates, and three maneuver restrictions for each of the geometry categories. The four GPS uncertainties are RTK, WAAS, SPS GPS, and GPS MAX. Climb rates are 250fpm, 500fpm, 750fpm, and 1000fpm. Pilot response times of one second and five seconds. Update rates of 0.2s, 1s, 3s, and 5s. Maneuver restrictions of horizontal-only, vertical-only, and unrestricted.

C.2.1.1 0.2s Update Rate

C.2.1.1.1 Head-on

Table 115. Remote ID sUAS vs Crewed Following Rules, Head-on, 0.2s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6743	7875	6743	7875	6743	7875	6792	7924
vertical-only	19292	NA	NA	NA	NA	NA	NA	NA
unrestricted	6743	7875	6743	7875	6743	7875	6841	7973
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6743	7875	6743	7875	6743	7875	6792	7924
vertical-only	10827	11959	11024	12156	11221	12353	12254	13436
unrestricted	6644	7776	6693	7825	6743	7875	6841	7973
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6743	7875	6743	7875	6743	7875	6792	7924
vertical-only	7973	9105	8121	9252	8268	9400	9006	10138
unrestricted	5709	6841	5808	6890	5808	6939	6103	7235
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6743	7875	6743	7875	6743	7875	6792	7924
vertical-only	6644	7776	6792	7924	6841	7973	7382	8514
unrestricted	5217	6349	5217	6349	5266	6398	5512	6595

C.2.1.1.2 Converging from Left

Table 116. Remote ID sUAS vs Crewed Following Rules, Converging from Left, 0.2s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6546	7284
vertical-only	19095	NA	19538	NA	NA	NA	NA	NA
unrestricted	6497	7235	6497	7235	6497	7235	6546	7284
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6546	7284
vertical-only	10680	11812	10926	12058	11073	12205	12156	13288
unrestricted	6497	7235	6497	7235	6497	7235	6595	7333
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6546	7284
vertical-only	7875	9006	8071	9203	8170	9302	8908	9991
unrestricted	6447	7186	6497	7235	6497	7235	6644	7382
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6546	7284
vertical-only	6595	7727	6693	7825	6792	7875	7333	8465
unrestricted	5709	6447	5808	6497	5857	6595	6201	6939

C.2.1.1.3 Converging from Right

Table 117. Remote ID sUAS vs Crewed Following Rules, Converging from Right, 0.2s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6546	7235	6546	7284	6546	7284	6595	7333
vertical-only	19144	NA	19538	NA	NA	NA	NA	NA
unrestricted	6546	7284	6546	7284	6546	7284	6644	7382
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6546	7235	6546	7284	6546	7284	6595	7333
vertical-only	10729	11861	10926	12058	11073	12205	12156	13288
unrestricted	6595	7333	6595	7333	6595	7333	6644	7382
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6546	7235	6546	7284	6546	7284	6595	7333
vertical-only	7924	9056	8071	9203	8170	9252	8859	9991
unrestricted	6497	7235	6546	7235	6546	7284	6693	7382
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6546	7235	6546	7284	6546	7284	6595	7333
vertical-only	6595	7678	6693	7825	6792	7924	7333	8465
unrestricted	5709	6447	5808	6546	5857	6595	6251	6989

C.2.1.1.4 Overtaking

Table 118. Remote ID sUAS vs Crewed Following Rules, Overtaking, 0.2s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**

250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	12845	13534	13091	13829	13288	14026	14666	15355
unrestricted	12648	13337	12943	13632	13091	13829	14420	15158
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	7530	8268	7678	8367	7776	8465	8465	9154
unrestricted	7432	8170	7579	8317	7678	8367	8367	9056
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	5758	6497	5857	6595	5906	6644	6398	7087
unrestricted	5709	6398	5808	6497	5857	6595	6349	7038
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	4873	5611	4971	5660	5020	5709	5365	6103
unrestricted	4823	5562	4922	5611	4971	5709	5315	6004

C.2.1.2 1s Update Rate

C.2.1.2.1 Head-on

Table 119. Remote ID sUAS vs Crewed Following Rules, Head-on, 1s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6792	7924	6792	7924	6792	7924	6792	7924
vertical-only	19292	NA	NA	NA	NA	NA	NA	NA
unrestricted	6792	7924	6792	7924	6792	7924	6989	8121
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	

horizontal-only	6792	7924	6792	7924	6792	7924	6792	7924
vertical-only	10827	11959	11073	12205	11319	12451	12451	13583
unrestricted	6743	7875	6743	7875	6792	7924	7038	8121
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6792	7924	6792	7924	6792	7924	6792	7924
vertical-only	7973	9105	8219	9351	8268	9400	9056	10188
unrestricted	5709	6841	5906	7038	5906	7038	6201	7333
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6792	7924	6792	7924	6792	7924	6792	7924
vertical-only	6792	7924	6792	7973	6841	7973	7382	8514
unrestricted	5365	6497	5365	6497	5365	6497	5611	6743

C.2.1.2.2 Converging from Left

Table 120. Remote ID sUAS vs Crewed Following Rules, Converging from Left, 1s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6644	7382
vertical-only	19095	NA	19636	NA	NA	NA	NA	NA
unrestricted	6497	7235	6497	7235	6644	7382	6644	7382
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6644	7382
vertical-only	10778	11861	10975	12107	11221	12304	12304	13436
unrestricted	6644	7382	6644	7382	6644	7382	6644	7382
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6644	7382
vertical-only	8071	9154	8121	9252	8219	9302	8957	10089

unrestricted	6497	7235	6497	7235	6644	7382	6644	7382
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6497	7235	6497	7235	6497	7235	6644	7382
vertical-only	6693	7825	6743	7875	6890	7973	7432	8563
unrestricted	5758	6546	5955	6644	5955	6693	6300	7038

C.2.1.2.3 Converging from Right

Table 121. Remote ID sUAS vs Crewed Following Rules, Converging from Right, 1s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6644	7382	6644	7382	6644	7382	6644	7382
vertical-only	19144	NA	19636	NA	NA	NA	NA	NA
unrestricted	6644	7382	6644	7382	6644	7382	6644	7382
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6644	7382	6644	7382	6644	7382	6644	7382
vertical-only	10729	11861	10975	12107	11221	12353	12353	13485
unrestricted	6644	7382	6644	7382	6644	7382	6644	7382
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6644	7382	6644	7382	6644	7382	6644	7382
vertical-only	7973	9056	8170	9302	8170	9302	9006	10138
unrestricted	6644	7382	6644	7382	6644	7382	6841	7530
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6644	7382	6644	7382	6644	7382	6644	7382
vertical-only	6743	7875	6792	7875	6792	7924	7333	8465
unrestricted	5758	6497	5906	6693	5906	6693	6300	7038

C.2.1.2.4 Overtaking

Table 122. Remote ID sUAS vs Crewed Following Rules, Overtaking, 1s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	12943	13632	13239	13977	13436	14125	14715	15453
unrestricted	12747	13436	13091	13780	13239	13977	14567	15256
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	7579	8268	7727	8465	7875	8613	8613	9302
unrestricted	7530	8268	7727	8416	7776	8416	8416	9105
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	5906	6644	5955	6693	5955	6693	6497	7186
unrestricted	5808	6497	5906	6644	5955	6644	6447	7136
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	5020	5709	5069	5758	5069	5808	5463	6152
unrestricted	4922	5611	5020	5709	5069	5808	5463	6152

C.2.1.3 3s Update Rate

C.2.1.3.1 Head-on

Table 123. Remote ID sUAS vs Crewed Following Rules, Head-on, 3s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6989	7924	6989	7924	6989	7924	6989	7924
vertical-only	19686	NA	NA	NA	NA	NA	NA	NA
unrestricted	6989	7924	6989	7924	6989	7924	6989	8563
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6989	7924	6989	7924	6989	7924	6989	7924
vertical-only	11221	12156	11270	12205	11319	12845	12845	13780
unrestricted	6939	7875	6989	7875	6989	7924	7038	8563
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6989	7924	6989	7924	6989	7924	6989	7924
vertical-only	7973	9499	8613	9548	8662	9597	9449	10384
unrestricted	6103	7038	6103	7038	6152	7038	6201	7727
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6989	7924	6989	7924	6989	7924	6989	7924
vertical-only	6989	7924	7038	7973	7038	7973	7825	8760
unrestricted	5365	6890	5365	6890	5365	6890	6054	6989

C.2.1.3.2 Converging from Left

Table 124. Remote ID sUAS vs Crewed Following Rules, Converging from Left, 3s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6841	7382	6841	7382	6841	7382	6841	7382
vertical-only	19489	NA	19636	NA	NA	NA	NA	NA
unrestricted	6841	7382	6841	7382	6841	7382	6841	7382
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6841	7382	6841	7382	6841	7382	6841	7382
vertical-only	11123	12008	11172	12205	11221	12747	12697	13632
unrestricted	6841	7382	6841	7382	6841	7382	6841	7382
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6841	7382	6841	7382	6841	7382	6841	7382
vertical-only	8465	9400	8563	9449	8563	9499	9400	10286
unrestricted	6841	7382	6841	7382	6841	7382	6841	7382
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6841	7382	6841	7382	6841	7382	6841	7382
vertical-only	6890	7825	6939	7973	6989	8416	7727	8662
unrestricted	6152	6939	6300	6939	6300	7087	6497	7382

C.2.1.3.3 Converging from Right

Table 125. Remote ID sUAS vs Crewed Following Rules, Converging from Right, 3s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**

250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6841	7382	6841	7382	6841	7382	6841	7628
vertical-only	19538	NA	19636	NA	NA	NA	NA	NA
unrestricted	6841	7382	6841	7382	6841	7382	6841	7628
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6841	7382	6841	7382	6841	7382	6841	7628
vertical-only	11123	12058	11172	12107	11221	12747	12747	13682
unrestricted	6841	7382	6841	7382	6841	7382	6841	7628
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6841	7382	6841	7382	6841	7382	6841	7628
vertical-only	8367	9449	8563	9499	8613	9499	9400	10335
unrestricted	6841	7382	6841	7628	6841	7628	6841	7924
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6841	7382	6841	7382	6841	7382	6841	7628
vertical-only	6939	7875	6989	7973	6989	8268	7776	8662
unrestricted	6103	6890	6251	7038	6251	7038	6497	7382

C.2.1.3.4 Overtaking

Table 126. Remote ID sUAS vs Crewed Following Rules, Overtaking, 3s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	13288	13829	13288	14321	13780	14371	14912	15453

unrestricted	12993	13780	13239	14026	13534	14321	14863	15601
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	7924	8465	7924	8613	7924	8957	8957	9548
unrestricted	7875	8416	7924	8760	8071	8760	8760	9499
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	6251	6841	6300	6841	6300	6841	6841	7382
unrestricted	6152	6792	6251	6792	6251	6939	6792	7432
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	5217	5758	5217	5906	5217	6152	5758	6300
unrestricted	5168	5906	5266	6004	5266	6152	5709	6398

C.2.1.4 5s Update Rate

C.2.1.4.1 Head-on

Table 127. Remote ID sUAS vs Crewed Following Rules, Head-on, 5s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6989	8317	6989	8317	6989	8317	6989	8317
vertical-only	19686	NA	NA	NA	NA	NA	NA	NA
unrestricted	6989	8317	6989	8317	6989	8317	6989	8317
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6989	8317	6989	8317	6989	8317	6989	8317
vertical-only	11221	12550	11270	12599	11319	12648	12648	13977

unrestricted	6939	8268	6989	8317	6989	8317	7038	8367
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6989	8317	6989	8317	6989	8317	6989	8317
vertical-only	8367	9695	8416	9745	8465	9794	9695	11024
unrestricted	5709	7038	6743	7038	6743	7038	6792	8170
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6989	8317	6989	8317	6989	8317	6989	8317
vertical-only	6989	8317	7038	8367	7038	8367	8219	8514
unrestricted	5562	6890	5562	6890	5562	6890	5611	6989

C.2.1.4.2 Converging from Left

Table 128. Remote ID sUAS vs Crewed Following Rules, Converging from Left, 5s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6890	7628	6890	7628	6890	7628	7382	7628
vertical-only	19489	NA	19636	NA	NA	NA	NA	NA
unrestricted	6890	7628	6890	7628	7382	7628	7382	7628
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6890	7628	6890	7628	6890	7628	7382	7628
vertical-only	11123	12402	11172	12501	11221	12550	12501	13829
unrestricted	7382	7628	7382	7628	7382	7628	7382	7628
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	6890	7628	6890	7628	6890	7628	7382	7628
vertical-only	8317	9597	8317	9646	8367	9695	9597	10876
unrestricted	6890	7628	6890	7628	7382	7628	7382	7628
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	

horizontal-only	6890	7628	6890	7628	6890	7628	7382	7628
vertical-only	6890	8219	6939	8268	6989	8317	8121	9351
unrestricted	6497	7284	6497	7382	6693	7382	6890	7628

C.2.1.4.3 Converging from Right

Table 129. Remote ID sUAS vs Crewed Following Rules, Converging from Right, 5s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	7382	7628	7382	7628	7382	7628	7382	7628
vertical-only	19538	NA	19636	NA	NA	NA	NA	NA
unrestricted	7382	7628	7382	7628	7382	7628	7382	7628
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	7382	7628	7382	7628	7382	7628	7382	7628
vertical-only	11123	12451	11172	12501	11221	12550	12550	13878
unrestricted	7382	7628	7382	7628	7382	7628	7382	7875
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	7382	7628	7382	7628	7382	7628	7382	7628
vertical-only	8317	9646	8367	9695	8367	9695	9597	10926
unrestricted	7382	7628	7382	7628	7382	7628	7382	8268
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	7382	7628	7382	7628	7382	7628	7382	7628
vertical-only	6939	8268	6989	8317	6989	8317	8170	9203
unrestricted	6447	7284	6693	7382	6693	7382	6890	7628

C.2.1.4.4 Overtaking

Table 130. Remote ID sUAS vs Crewed Following Rules, Overtaking, 5s Update Rate, Required Detection Range in Feet.

Pilot Response Time	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
250fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	13632	13632	13632	14567	13632	14567	15453	15650
unrestricted	13337	13928	13632	14518	13632	14518	15109	15995
500fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	8268	8957	8268	9154	8268	9154	9154	10040
unrestricted	8219	8957	8268	9105	8268	9105	9105	9843
750fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	6497	7333	6497	7382	6497	7382	6939	7382
unrestricted	6447	7186	6447	7333	6497	7333	7038	7776
1000fpm desc	**RTK (0.03m, 0.1m)**		**WAAS (1m, 2.2m)**		**SPS (1.72m, 3.42m)**		**MAX (8m, 13m)**	
horizontal-only	NA	NA	NA	NA	NA	NA	NA	NA
vertical-only	5611	6447	5611	6497	5611	6497	5709	6497
unrestricted	5562	6300	5562	6447	5562	6447	6054	6644

APPENDIX D – SMALL NMAC

To evaluate an appropriate volume for small UAS Near Mid-Air Collision (sNMAC) distances, the research team tested the results of traffic interactions across several volume intervals defined between a 50 ft. radius and the conventional aircraft and larger UAS standard of 500 ft. radius. This is restricted, however, to sUAS vs. sUAS interactions with both aircraft following right-of-way rules. The safety standard when dealing with crewed aircraft remains the same.

To reduce computational loads, tests used 50ft radial increments horizontally and ~10ft increments vertically (Figure 219). The objective of this testing was intended to establish a balance between the size of the volume and efficiency, especially in the confines of very low altitudes. A worse case uncertainty is assumed for these simulations and a spherical value of 39.37ft(12m) was used. A radius of 50ft encompasses much of the potential GPS positional error that is not augmented by methods such as RTK or WAAS. At the other end, the full NMAC volume may be unusable for small UAS navigating the low altitudes where obstacles such as tree lines or telephone poles may force much closer navigation than normal air navigation above 500ft AGL.

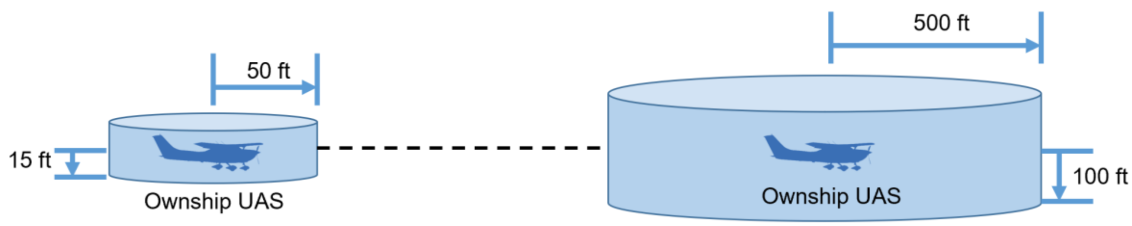


Figure 219. Volume bounds tested for best sNMAC between small UAS.

To test the candidate sNMAC volumes, the above encounter sets were run for each sNMAC volume size and the required detection ranges for each set were compared against each other to see the sNMAC volume sizes effect on required detection range.

Since sNMAC is only used for sUAS vs sUAS interactions, two sUAS fixed-wing aircraft were used with varying performance limitations within expected ranges for sUAS. The maneuvering airspeed of the aircraft was limited to 40 to 80 knots and the climb/descent rates were limited to 500fpm and 1000fpm. For the tests a worst case scenario is assumed with the slowest configuration for the ownship (40 knots) and the fastest for the intruder (80 knots). The overall configuration and performance limits of the aircraft are shown in Table 131.

Table 131. Parameters for all sNMAC volume configuration simulations.

Ownship Cruise Speed	48 kts
Intruder Cruise Speed	80 kts
Ownship Maneuvering Speed	38kts, 78 kts
Vertical Speed limits	500 and 1000 ft/min
Horizontal maneuver	110°
Bank Angle Limit	45°
Pilot Response Delay	5 s
Track Update Rate	1 s
Location Uncertainty	12 m (~40 ft)

In total, 1.044 million traffic encounters were simulated for the tested sNMAC volumes using the above-mentioned increments and ranges.

D.1 Head-on

Limiting the ownship aircraft to its slower iteration at 38 knots and a 500 ft/min climb and descent rate, the encounters against an 80-knot intruder resulted in required detection ranges of 2000 to 3000 feet, in Figure 220 given sNMAC ranges of 50 to 500 feet horizontally. The results are best read where the 0% probability intersects the horizontal axis while looking for unusual behaviors or slopes further up. In these cases, the lines show a rapid, near vertical decline in the probability of sNMAC violation. This pattern will be repeated in other test results.

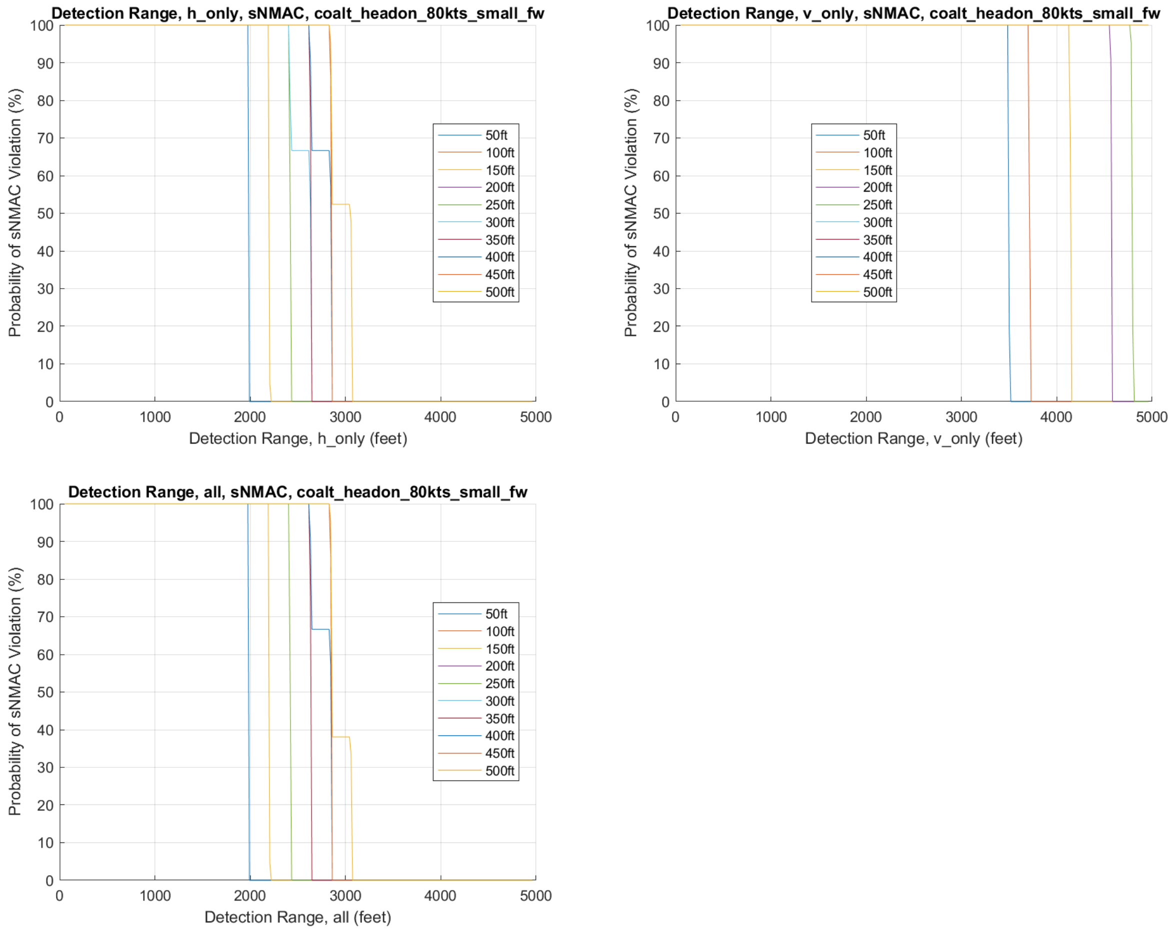


Figure 220. sNMAC volume test for head-on geometries, with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left).

At this slower vertical performance and large positional uncertainty, vertical-only maneuvering is worse than horizontal-only and requires a larger detection range. Increasing the vertical performance to 1000fpm improves its performance to a required detection range of 2500 to 4000ft range but it still lags behind horizontal-only due to the large GPS uncertainty. Using a nominal GPS uncertainty would result in the vertical-only maneuvering performing better at the higher vertical performance of 1000fpm.

Taking the same results but displaying as a function of detection range vs sNMAC distance, we see the required detection range has a linear relationship, as shown in Figure 221.

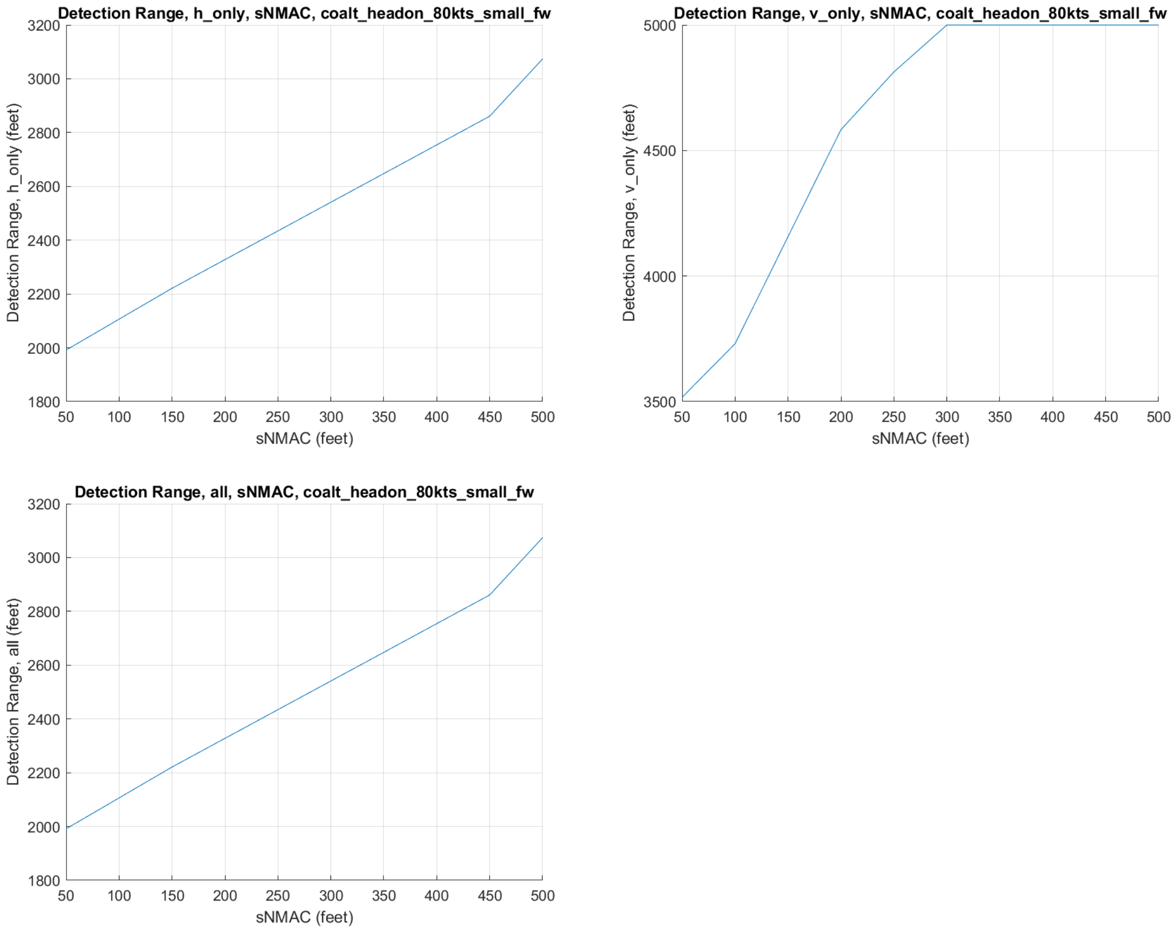


Figure 221**.** Zero probability plot for sNMAC volume test for head-on geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left).

D.2 Converging

A similar result as the head-on geometries can be observed for the converging geometries with the 38knots and 500ft/min ownship results requiring a similar 2000 to 3000ft range for horizontal-only maneuvering, as shown in Figure 222 and 223. Increasing the vertical performance to 1000ft/min results in a similar range of 2500ft to ~4000ft with the same reasoning as head-on.

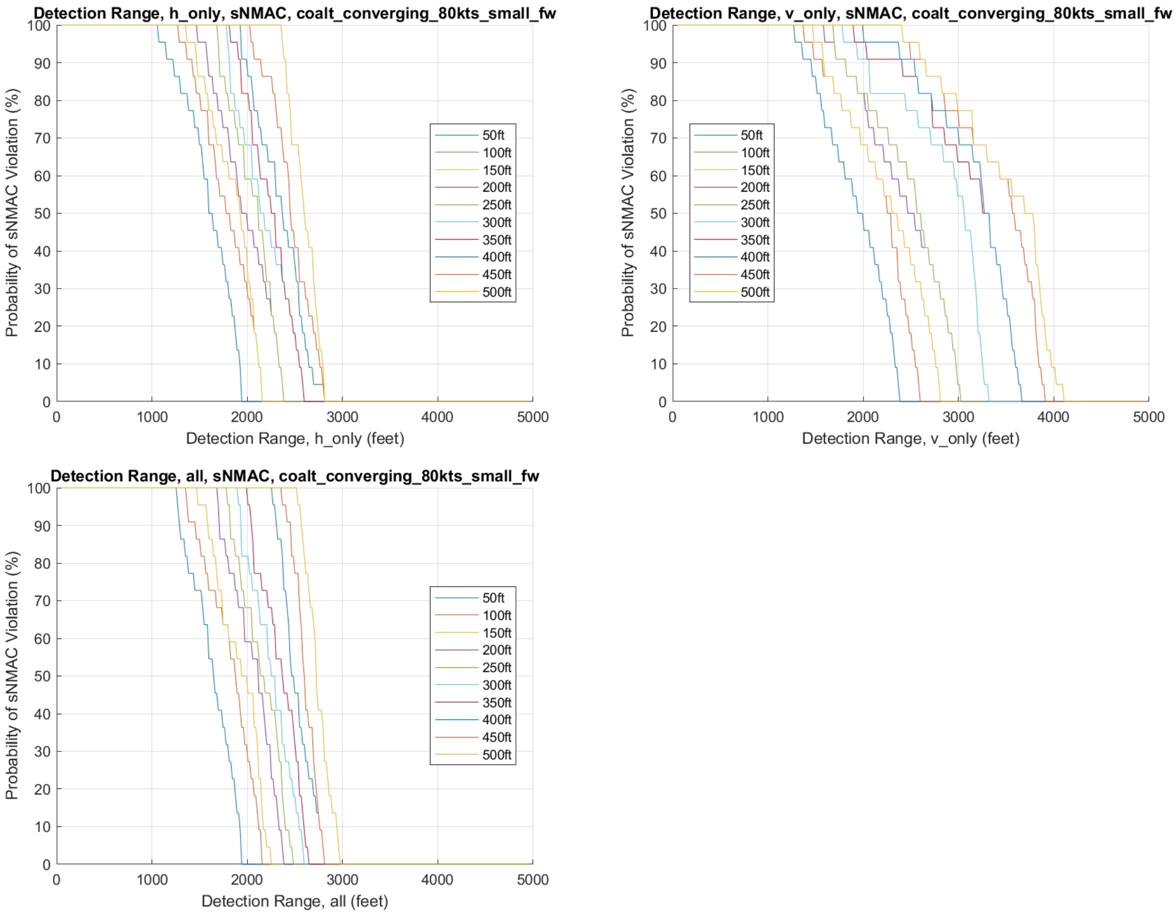


Figure 222**.** sNMAC volume test for converging geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left).

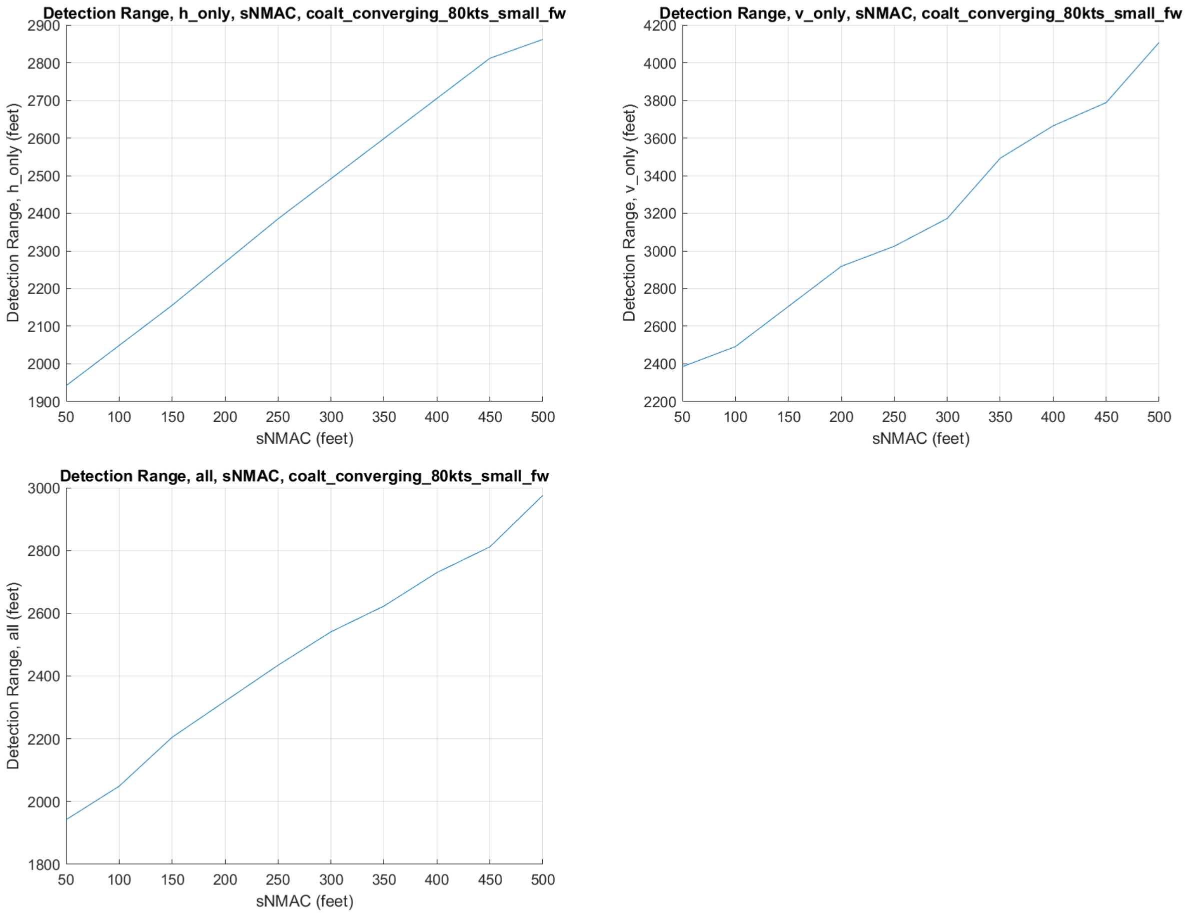


Figure 223. Zero probability plot for sNMAC volume test for converging geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left).

D.3 Overtaking

Due to both sUAS following right-of-way rules, the required detection range for overtaking geometries with the 38 knots and 500ft/min ownship is relatively small since the faster intruder will pass on the right. In this case the horizontal-only results showed a 500 to 1500ft required detection range with the vertical-only showing a 1500 to 3000ft required detection range, as shown in Figure 224 and Figure 225. Increasing the vertical performance to 1000ft/min reduces the vertical-only range to 1000 to 2000ft.

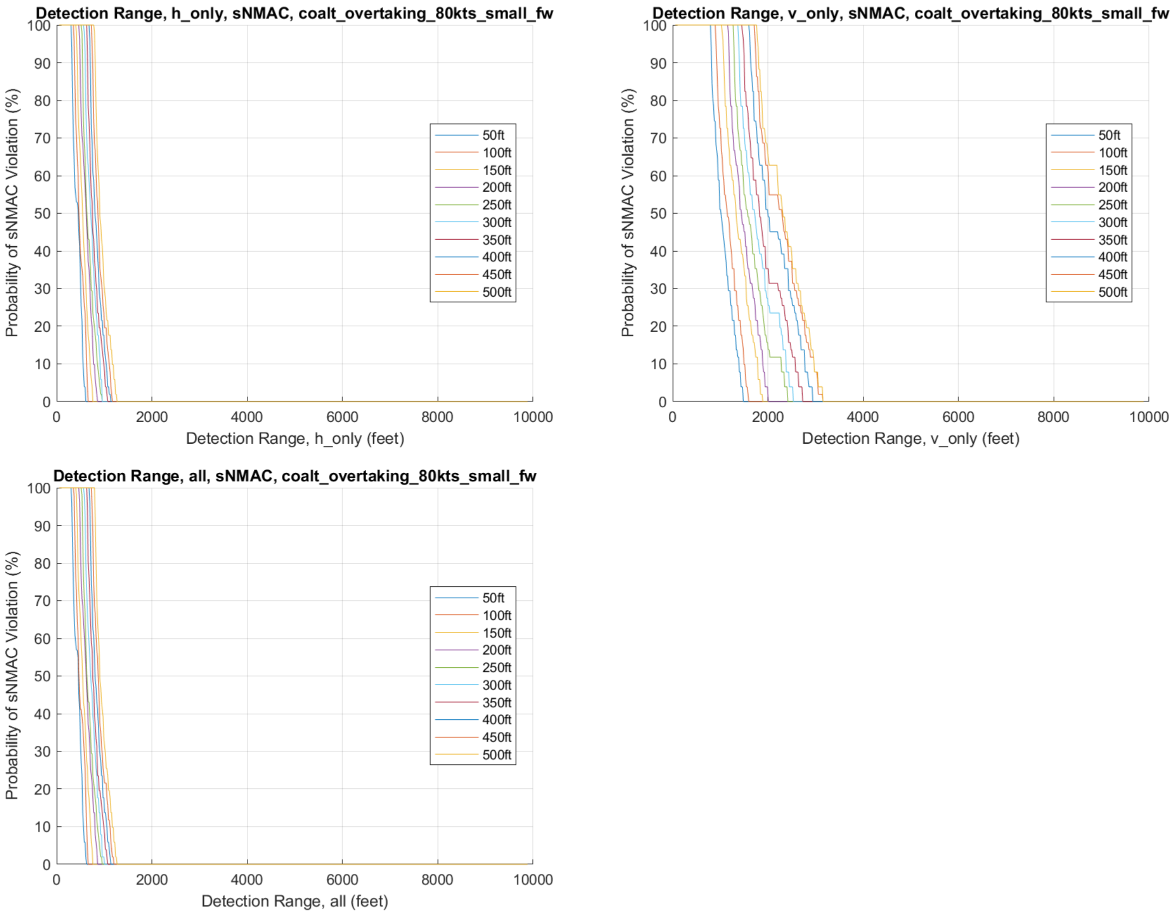


Figure 224. sNMAC volume test for overtaking geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left).

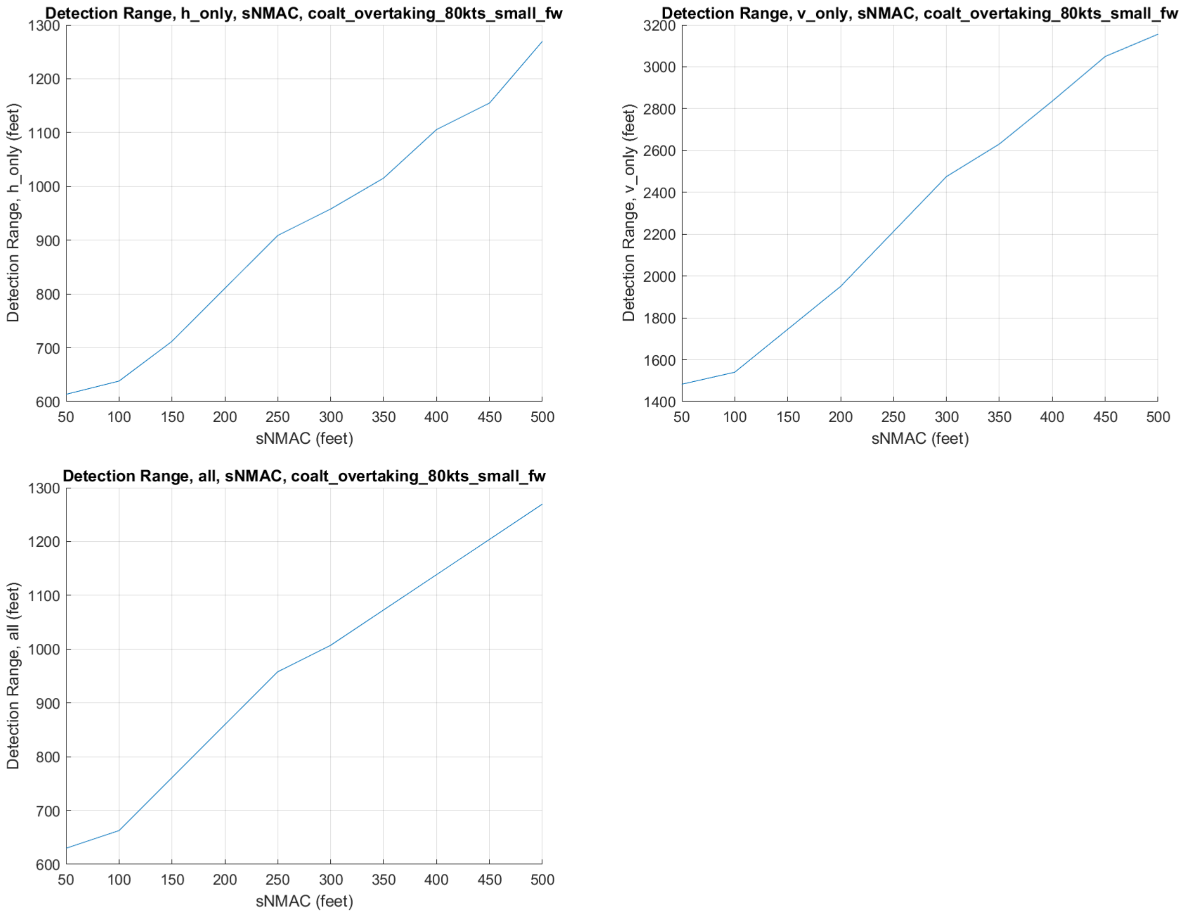


Figure 225. Zero probability plots for sNMAC volume test for overtaking geometries with horizontally only maneuvering (upper left), vertically only maneuvering (upper right), and horizontal and vertical maneuvering (lower left).

APPENDIX E – FIXED AIRCRAFT AVOIDANCE MANEUVER

To allow for direct comparison of the results with horizontal-only maneuver restrictions, each of the encounters performed a fixed maneuver relative to the ownships heading or relative bearing of the intruder.

This heading change was relative to the ownships heading for head-on and converging scenarios and relative to the relative bearing of the intruder for overtaking scenarios. For the overtaking scenario, a fixed heading change relative to the ownships heading change did not work for all geometries in the overtaking encounter set, so a fixed heading change from intruder relative bearing was used.

E.1 Single heading change

Initial testing used a fixed heading change relative to the ownships current heading which resulted in good performance for the head-on and converging geometries but failed to reach a satisfactory result for overtaking geometries.

For head-on geometries, the aircraft was able to avoid the well clear volume by performing a fixed turn to the right of 40 to 160 degrees with the optimal turn being around 115-120 degrees, as shown in Figure 226.

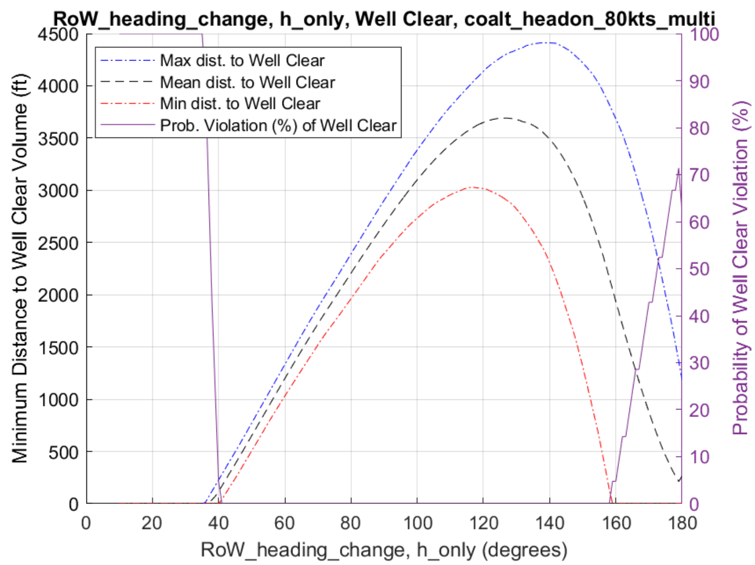


Figure 226. Fixed heading change relative to Ownships heading for head-on geometries.

For converging from left geometries, the aircraft was able to avoid the well clear volume by performing a fixed turn to the left of 95+ degrees with the best turn being 180 degrees, as shown in Figure 227.

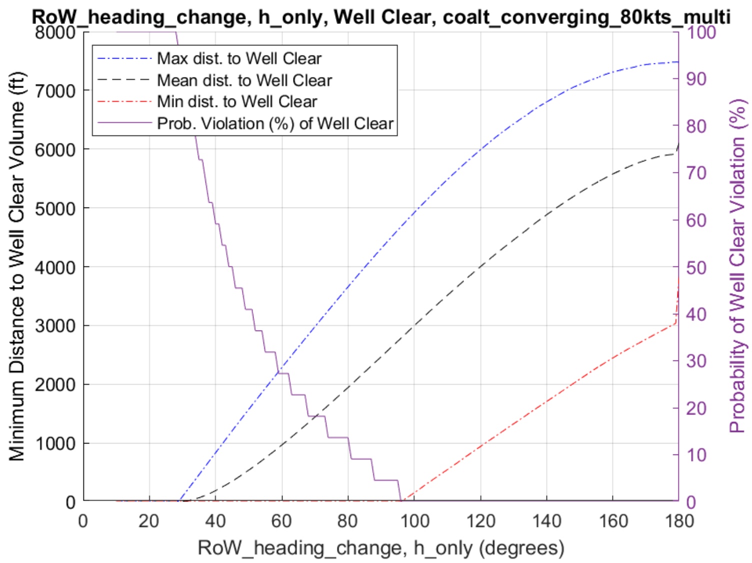


Figure 227. Fixed heading change relative to Ownships heading for converging from left geometries.

For converging from right geometries, the aircraft was able to avoid the well clear volume by performing a fixed turn to the left of 75+ degrees with the best turn being 180 degrees, as shown in Figure 228.

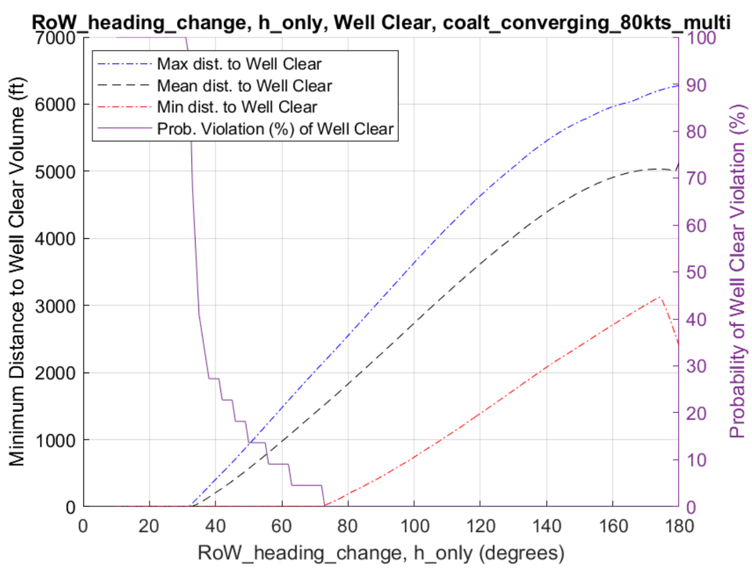


Figure 228. Fixed heading change relative to Ownships heading for converging from right geometries.

For overtaking geometries, the aircraft was able unable to avoid the well clear volume for all geometries in the encounter set by performing a fixed turn, as shown in Figure 229.

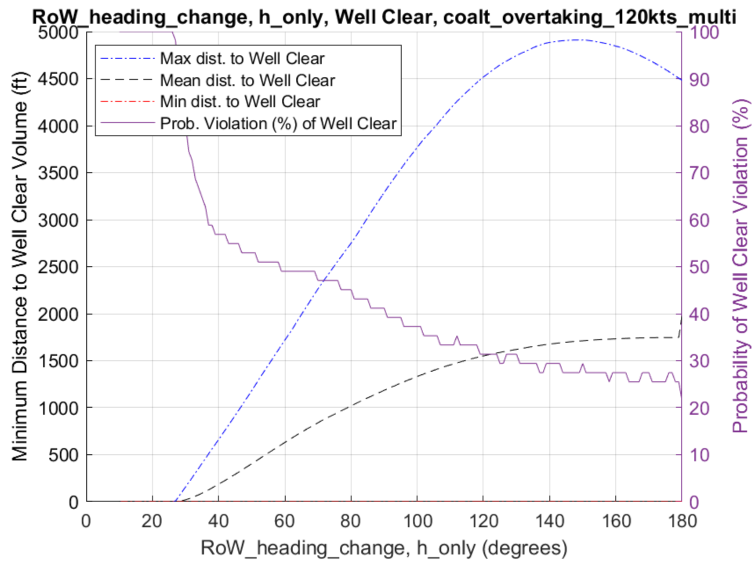


Figure 229. Fixed heading change relative to Ownships heading for overtaking geometries.

The most optimal heading change from the data below was not chosen since this commonly resulted in performing a near 180-degree heading change which is not a realistic or optimal maneuver. A fixed maneuver of 110-degrees to ownship heading was chosen since it provided decent performance while also not deviating too much from the ownships current heading.

E.2 Relative heading change (Overtaking)

For the overtaking scenarios, a fixed heading change relative to the ownships was not enough to maintain a safe distance, so a fixed heading change relative to the relative bearing of the intruder was used. In the case of sUAS vs sUAS no single fixed heading change worked for all geometries within a reasonable detection range, so it was determined that horizontal-only maneuvering for overtaking in sUAS vs sUAS interactions is not the best type of maneuver for this scenario. For the case of sUAS vs Crewed, a larger detection range is realistically required so a fixed maneuver was found. As shown in Figure 230, the aircraft was able to maintain a safe distance to the well clear volume if it performed a fixed heading change of 50 to 70 degrees to the left of the intruders relative bearing. A fixed maneuver of 60 degrees to the left of the intruders relative bearing was used since this was in the middle of the range.

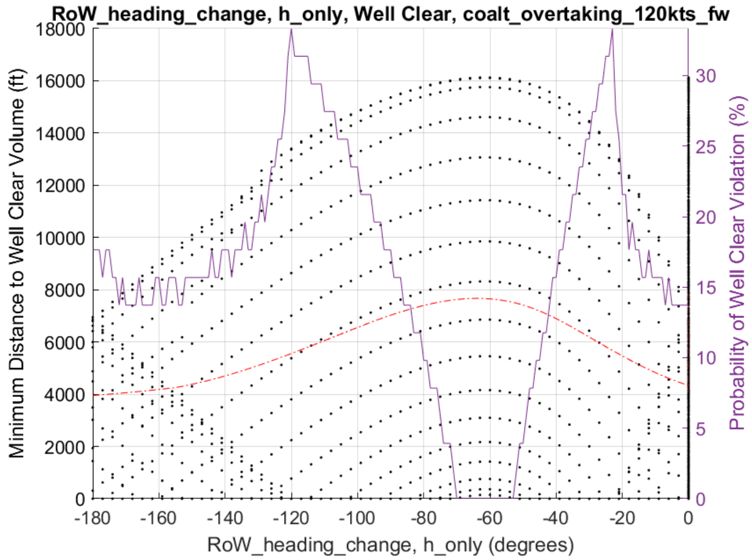


Figure 230. Fixed heading change relative to intruder relative bearing for overtaking geometries with 7,500m detection range.

APPENDIX F - GPS ACCURACY AND HORIZONTAL VS. VERTICAL MANEUVER PRIORITY

At the suggested sNMAC size and the size ultimately used during testing, the GPS uncertainty has a tangible effect on what type of maneuver, horizontal-only vs vertical-only, is best for a given encounter. The relative size of the uncertainty compared to the initial sNMAC volume is shown in **Error! Reference source not found.** and the relative size of the GPS uncertainties vs the sNMAC volume used for testing is shown in Table .

Table 132. Relative Size of GPS Uncertainty vs initial sNMAC volume.

GPS Receiver	Relative Size Horizontal	Relative Size Vertical
RTK	0.2%	2.2%
WAAS	6.56%	48.13%
SPS	11.28%	74.8%
MAX	52.5%	284.33%

Table 133. Relative Size of GPS Uncertainty vs sNMAC volume used for testing.

GPS Receiver	Relative Size Horizontal	Relative Size Vertical
RTK	0.1%	1.32%
WAAS	3.28%	28.88%
SPS	5.64%	44.88%
MAX	26.25%	170.6%

RTK, an application of differential GPS, ingests a correction data stream from a surveyed location. The position uncertainty falls to frequent centimeter accuracy, though conservative estimates place horizontal uncertainty at 0.03m and vertical uncertainty at 0.1m [3].

WAAS enabled GPS is the most common technology and usually approaches less than 10m of uncertainty. Here, a series of ground stations adjust for variations in measurements of orbital GPS vehicles through the atmosphere. This enables vertical GPS navigation for crewed aircraft to Category 1 instrument approaches. A reasonable estimate of uncertainty from surveys is 1m horizontal and 2.2m vertical [4].

The SPS GPS represents the average unaided performance of a GPS receiver with a larger uncertainty than a WAAS enabled GPS but below the reasonable upper bound [5].

The fourth and least accurate technology is unaided GPS navigations reasonable upper bound, increasingly infrequent given the proliferation of RTK receivers in UAS equipment and at least WAAS enabled GPS equipment in crewed aircraft [5].

F.1 Following Right-of-Way Rules

For the case of sUAS vs sUAS interactions, the best maneuver depends on the vertical performance and the GPS uncertainty of the ownship. If the ownship has good vertical performance and reasonable GPS uncertainty, vertical-only is the best maneuver. In the case of low vertical performance or high GPS uncertainty, horizontal-only is the best maneuver.

In the case of sUAS vs Crewed interactions, the large difference in aircraft performance and the larger small well clear volume, the best maneuver is more certain for the geometries compared to the sUAS vs sUAS scenarios. Horizontal-only is the best maneuver in the case of converging and head-on geometries and vertical-only is the best for overtaking scenarios.

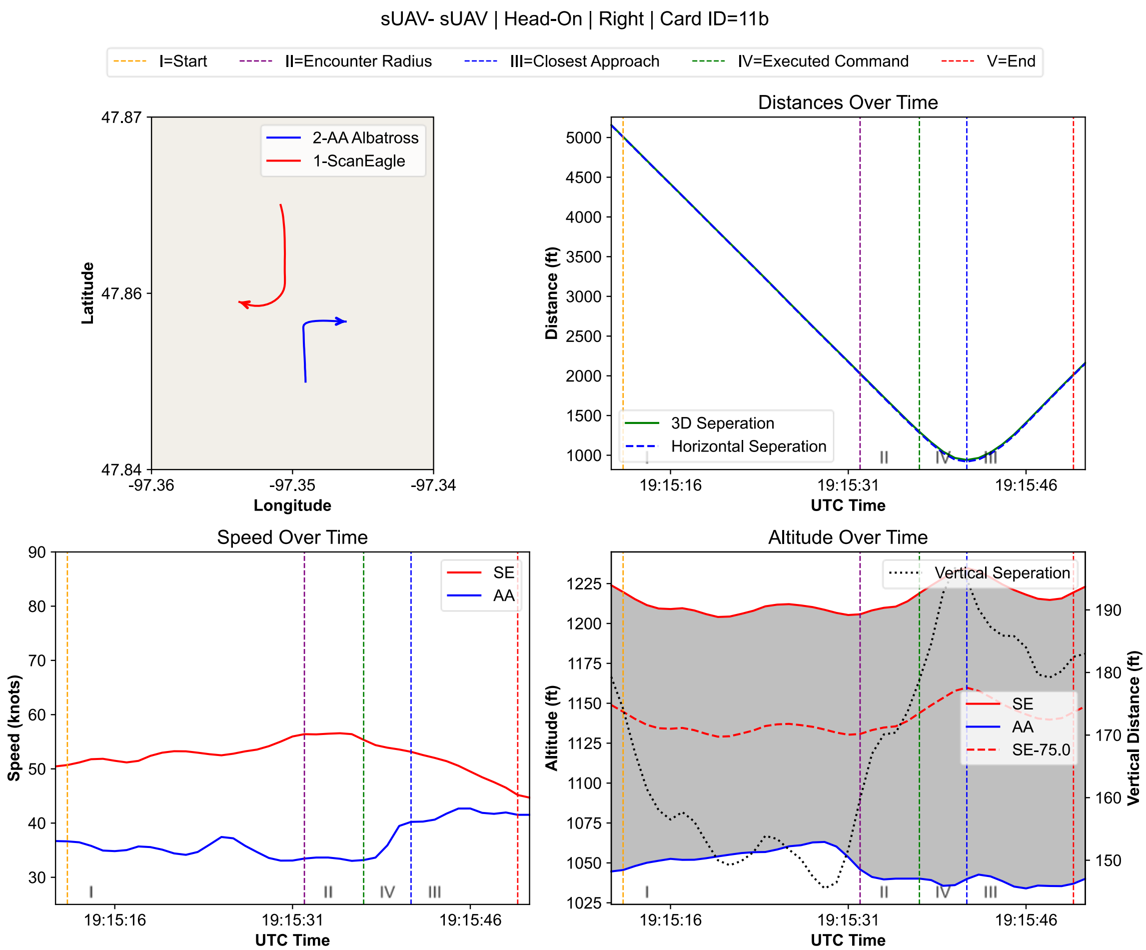
F.2 Not Following Right-of-Way Rules

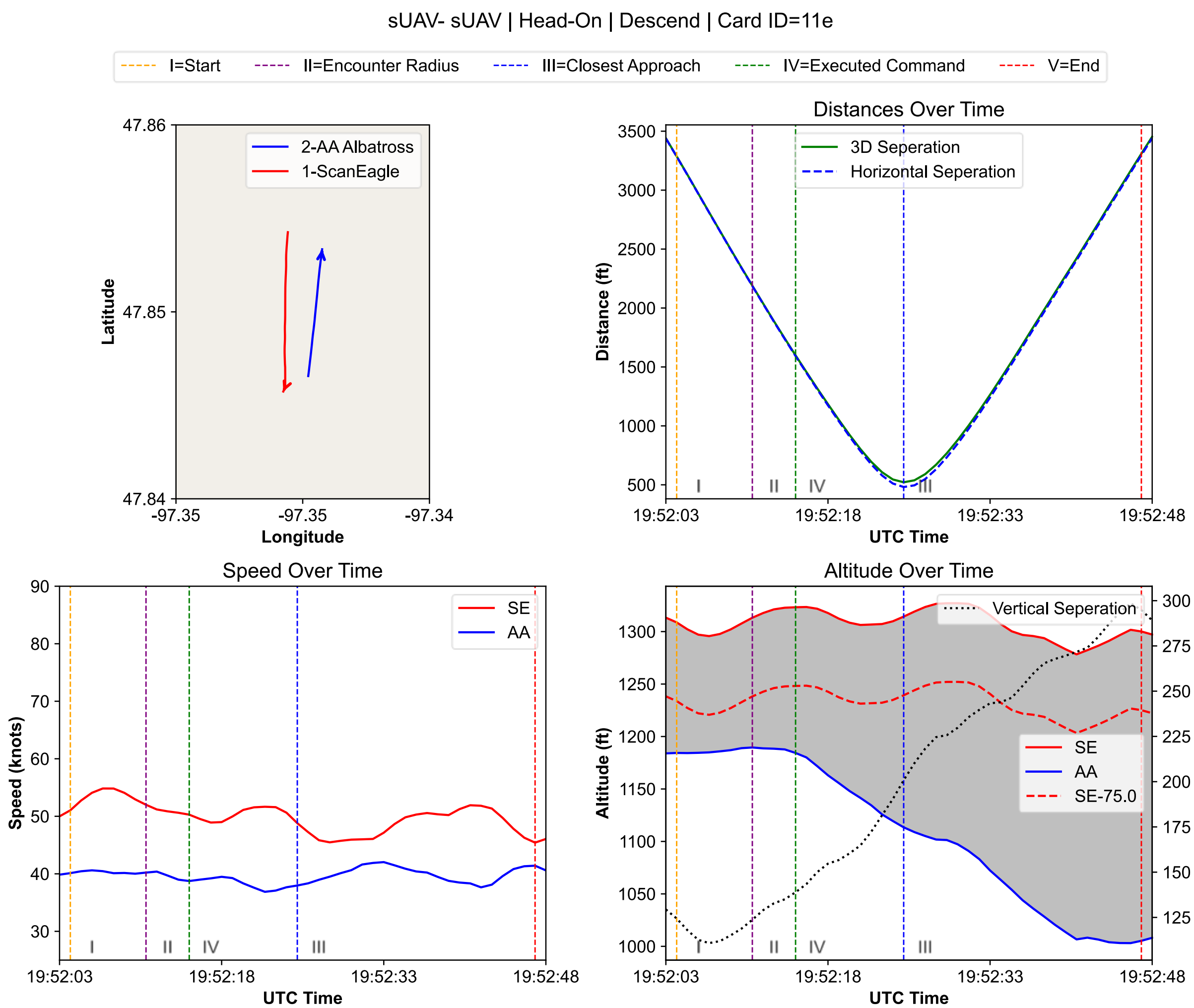
Comparing sUAS vs sUAS scenarios when the intruder follows and does not follow right-of-way rules, the main difference is the not following right-of-way rules has a shift towards horizontal-only performing better in horizontal-only for converging and head-on geometries. In the case of overtaking, the best maneuver for not following right-of-way rules is vertical-only.

APPENDIX G – FLIGHT TEST ANALYSIS

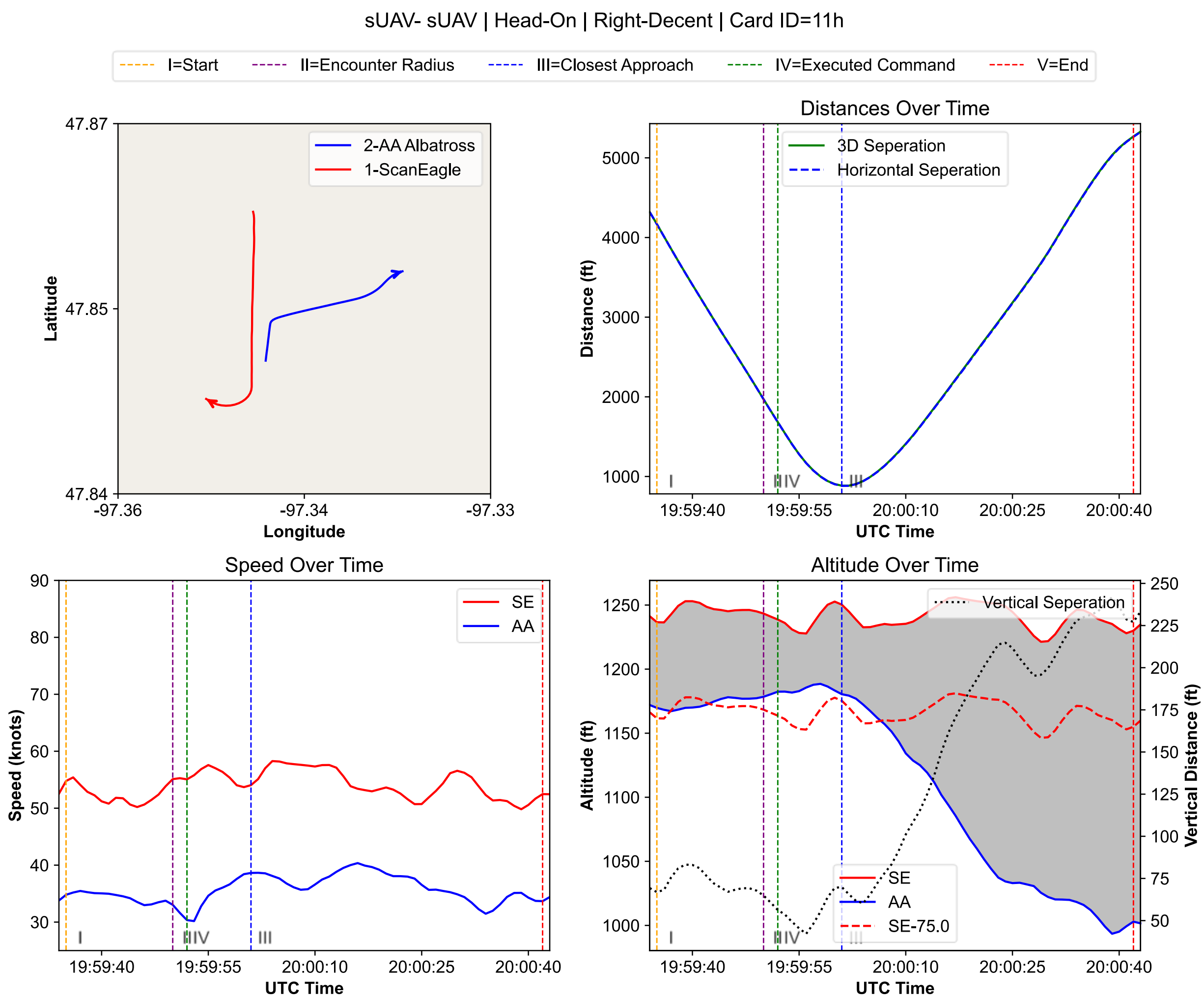
UND – Round 1, Round and Round 3

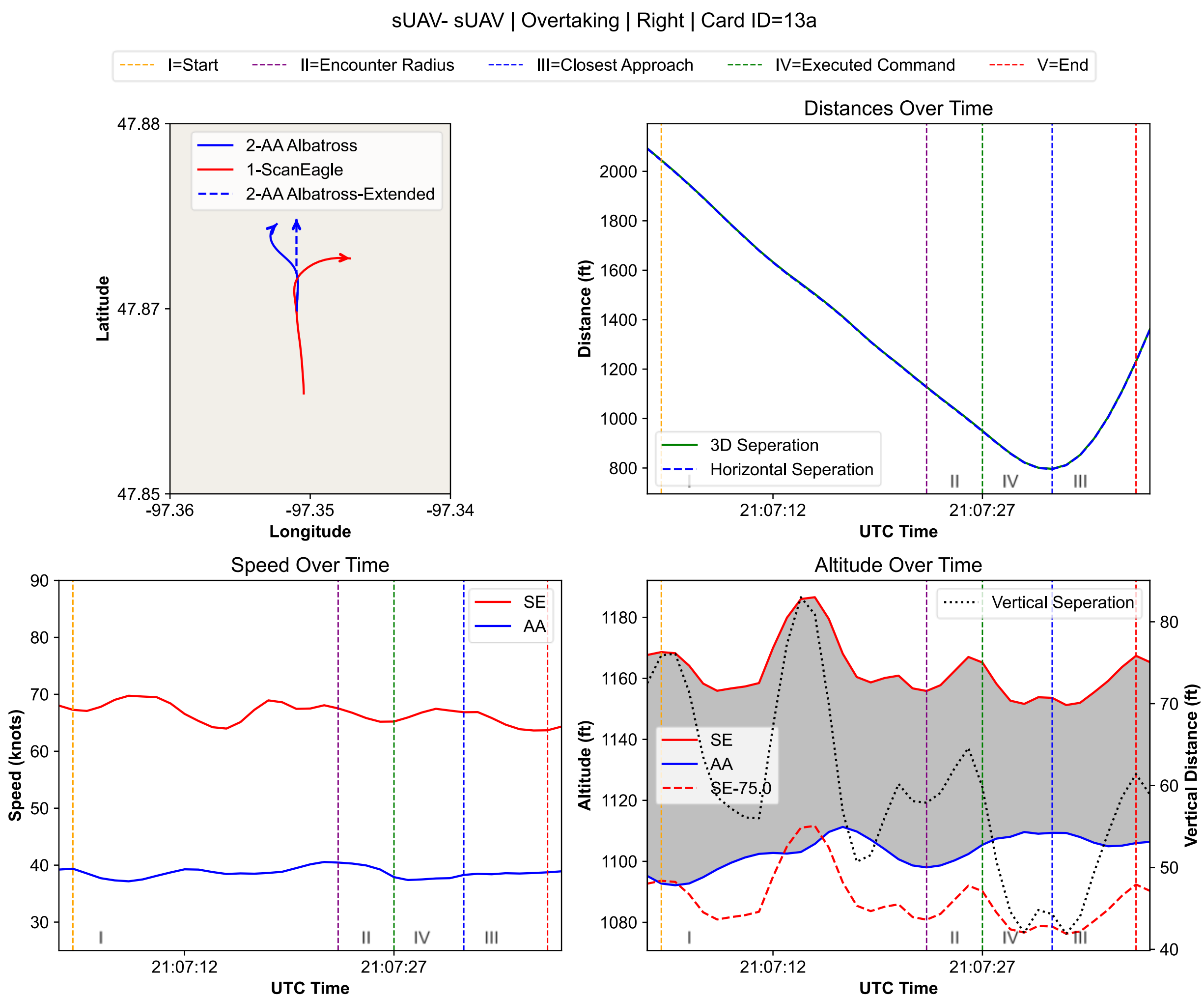
G.1 Round-1 : sUAS-sUAS



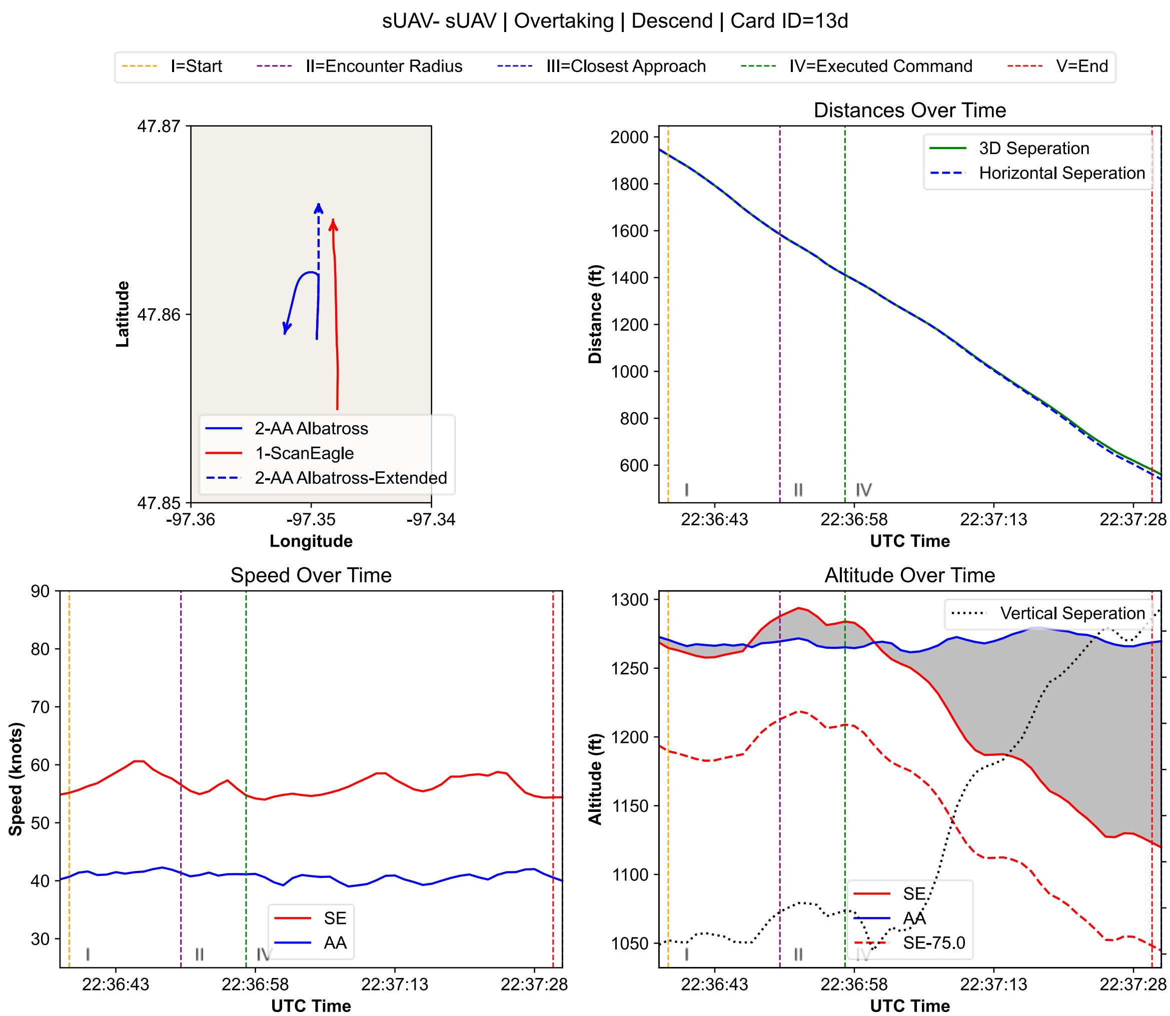


sUAV- sUAV | Head-On | Descend | Card ID=11e
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-AA Albatross
1-ScanEagle
Latitude
Longitude
47.86
47.85
47.84
-97.35
-97.35
-97.34
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
3500
3000
2500
2000
1500
1000
500
19:52:03
19:52:18
19:52:33
19:52:48
Speed Over Time
SE
AA
Speed (knots)
90
80
70
60
50
40
30
Altitude Over Time
Vertical Seperation
SE
AA
SE-75.0
Altitude (ft)
Vertical Distance (ft)
1300
1250
1200
1150
1100
1050
1000
300
275
250
225
200
175
150
125
I
II
III
IV

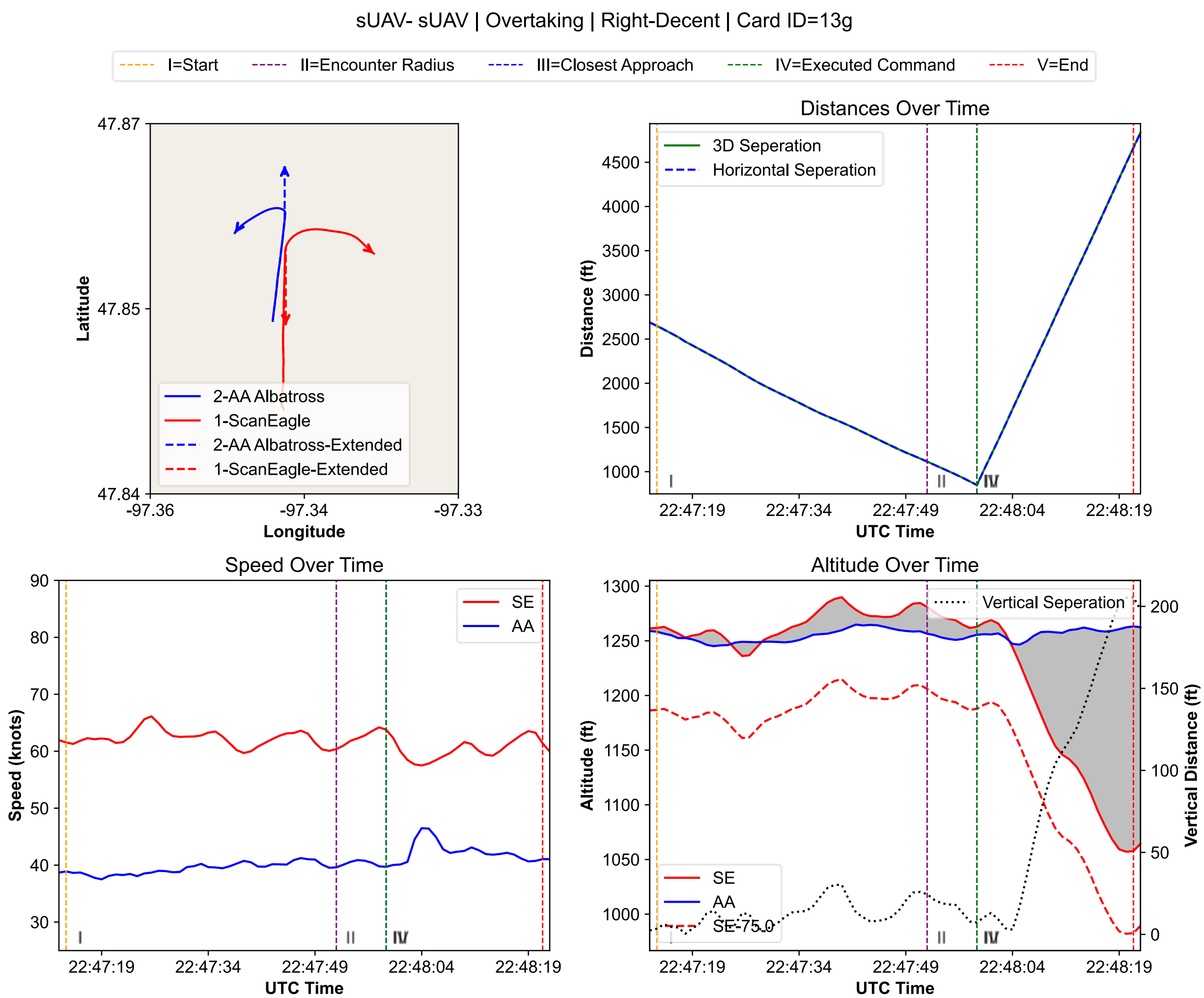

sUAV- sUAV | Head-On | Right-Decent | Card ID=11h
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-AA Albatross
1-ScanEagle
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
SE
AA
Speed (knots)
Altitude Over Time
Vertical Seperation
Altitude (ft)
Vertical Distance (ft)
SE-75.0



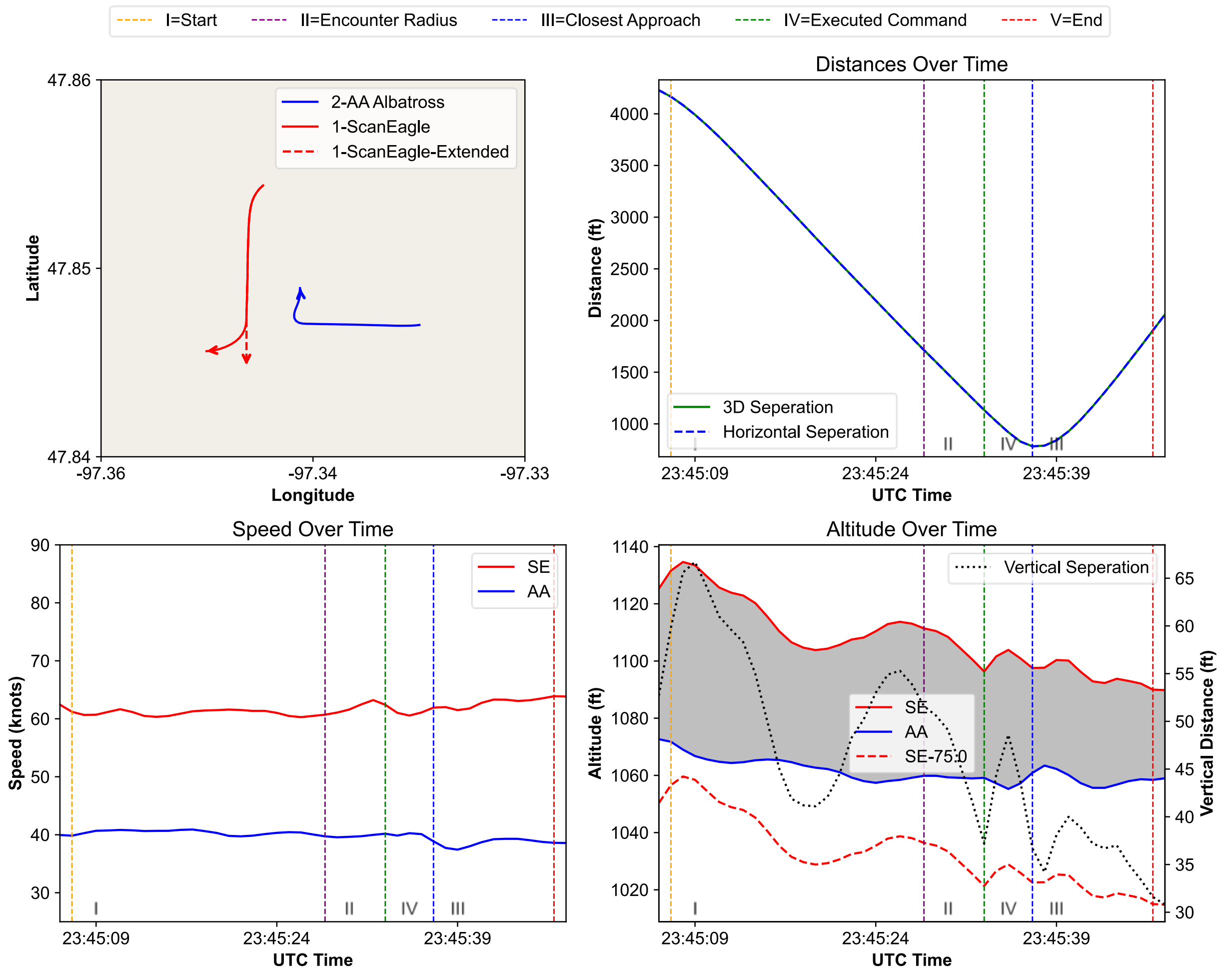
sUAV- sUAV | Overtaking | Right | Card ID=13a
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-AA Albatross
1-ScanEagle
2-AA Albatross-Extended
Latitude
Longitude
Distances Over Time
Distance (ft)
3D Seperation
Horizontal Seperation
UTC Time
Speed Over Time
Speed (knots)
SE
AA
Altitude Over Time
Altitude (ft)
SE-75.0
Vertical Seperation
Vertical Distance (ft)
21:07:12
21:07:27

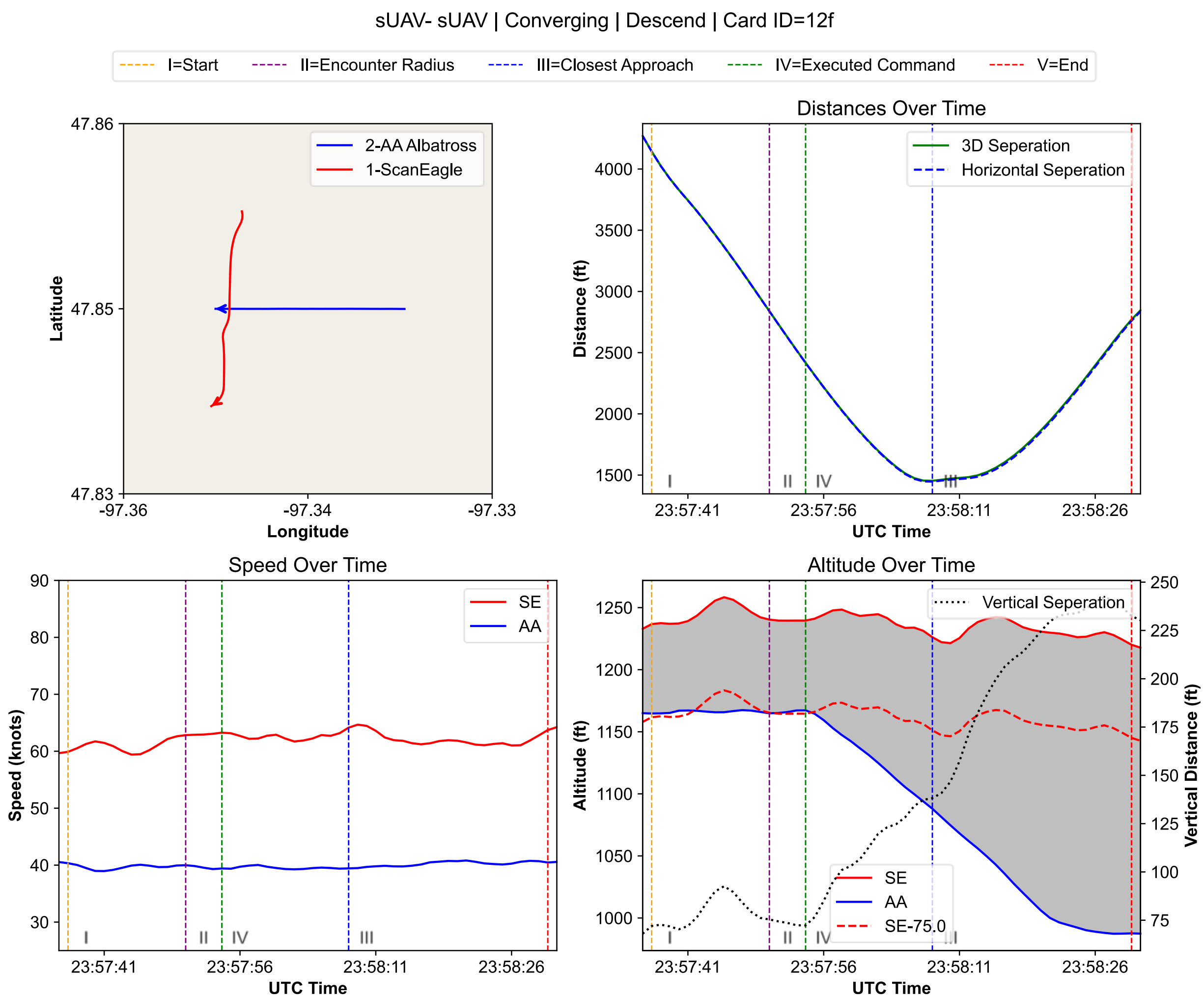


sUAV- sUAV | Overtaking | Descend | Card ID=13d
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
Latitude
Longitude
2-AA Albatross
1-ScanEagle
2-AA Albatross-Extended
Distances Over Time
Distance (ft)
3D Seperation
Horizontal Seperation
UTC Time
Speed Over Time
Speed (knots)
SE
AA
Altitude Over Time
Altitude (ft)
Vertical Distance (ft)
Vertical Seperation
SE-75.0

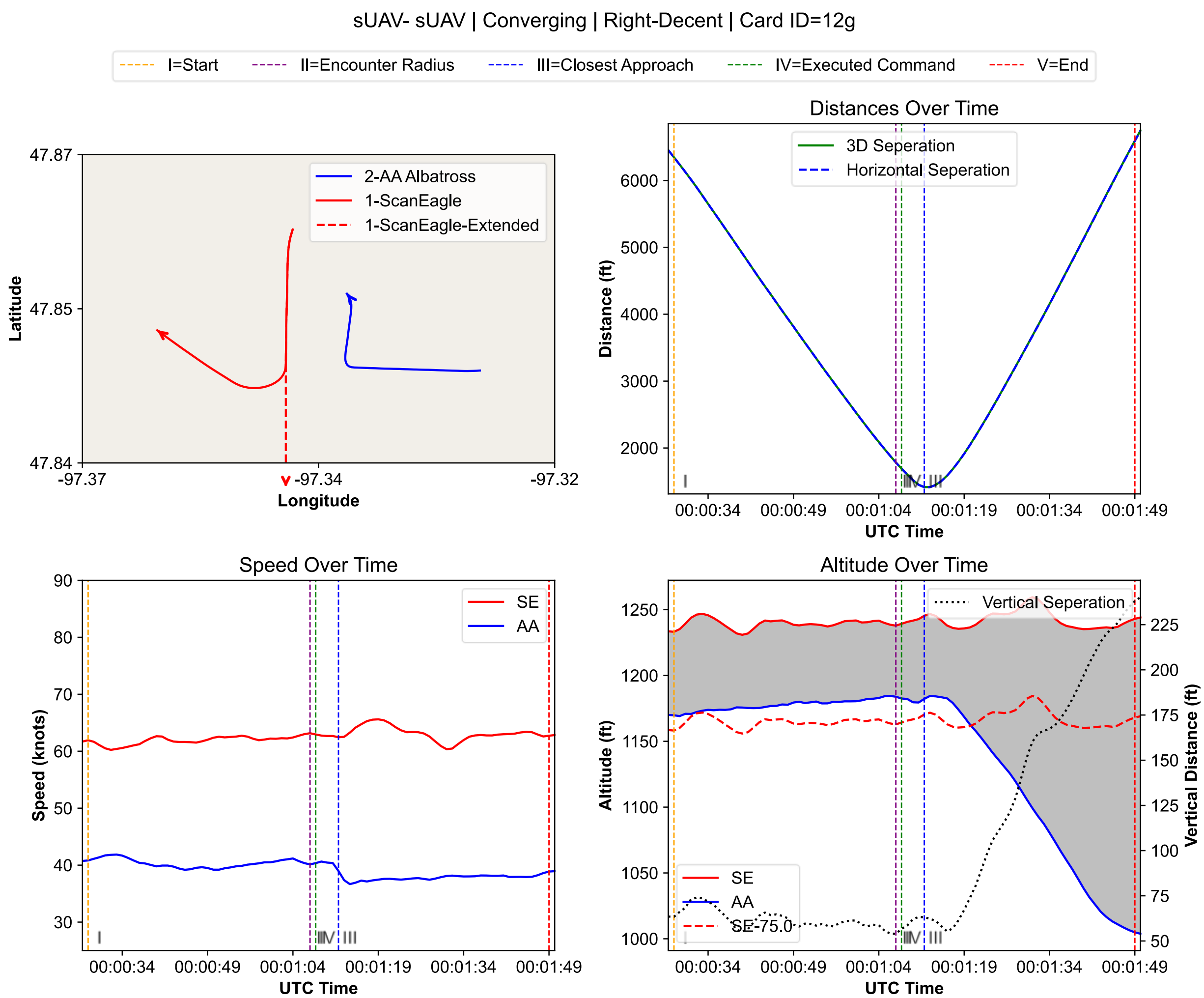

sUAV- sUAV | Overtaking | Right-Decent | Card ID=13g
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
Latitude
Longitude
2-AA Albatross
1-ScanEagle
2-AA Albatross-Extended
1-ScanEagle-Extended
Distances Over Time
Distance (ft)
UTC Time
3D Seperation
Horizontal Seperation
Speed Over Time
Speed (knots)
SE
AA
Altitude Over Time
Altitude (ft)
Vertical Distance (ft)
Vertical Seperation
SE-75.0

sUAV- sUAV | Converging | Right | Card ID=12c

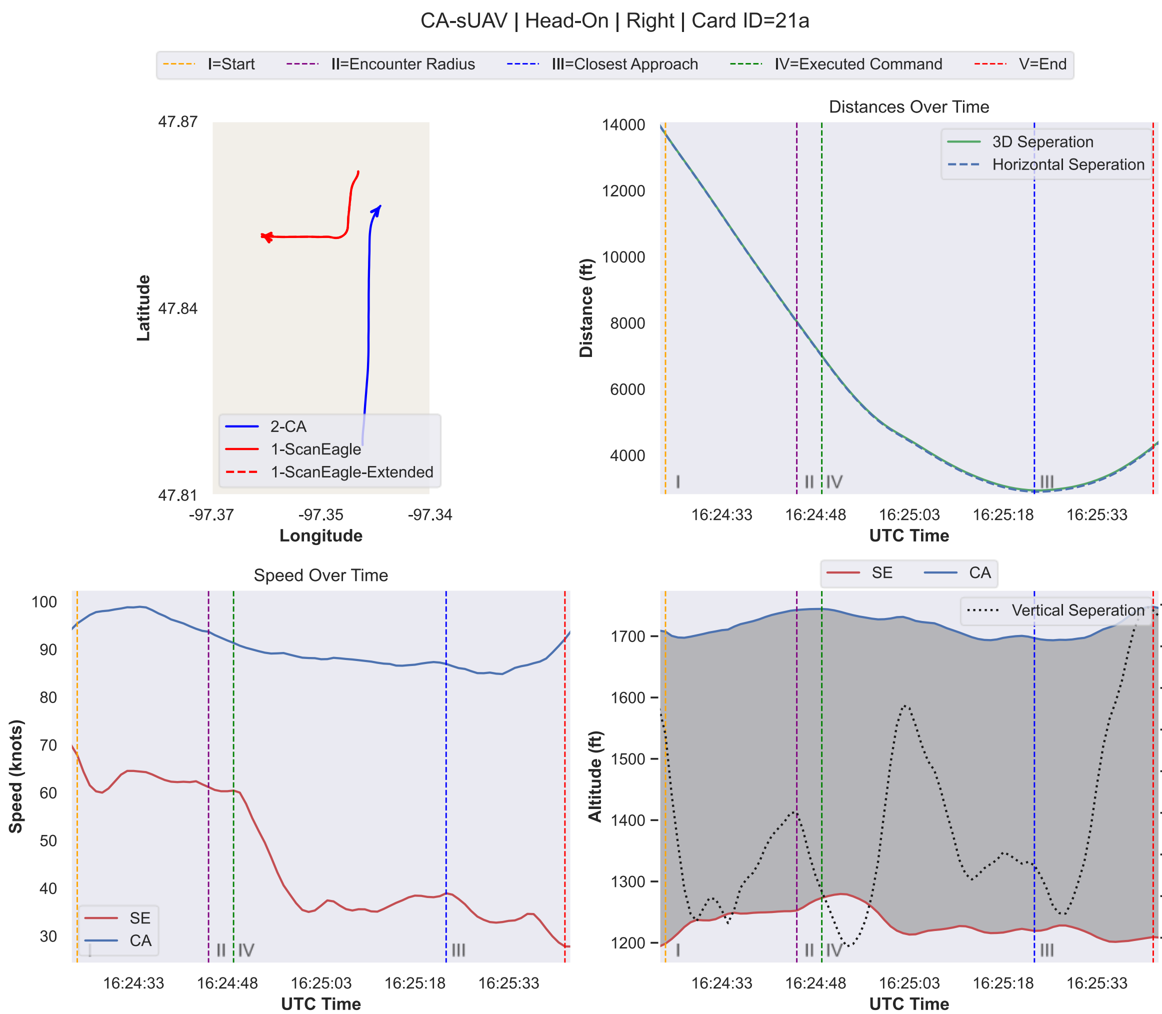


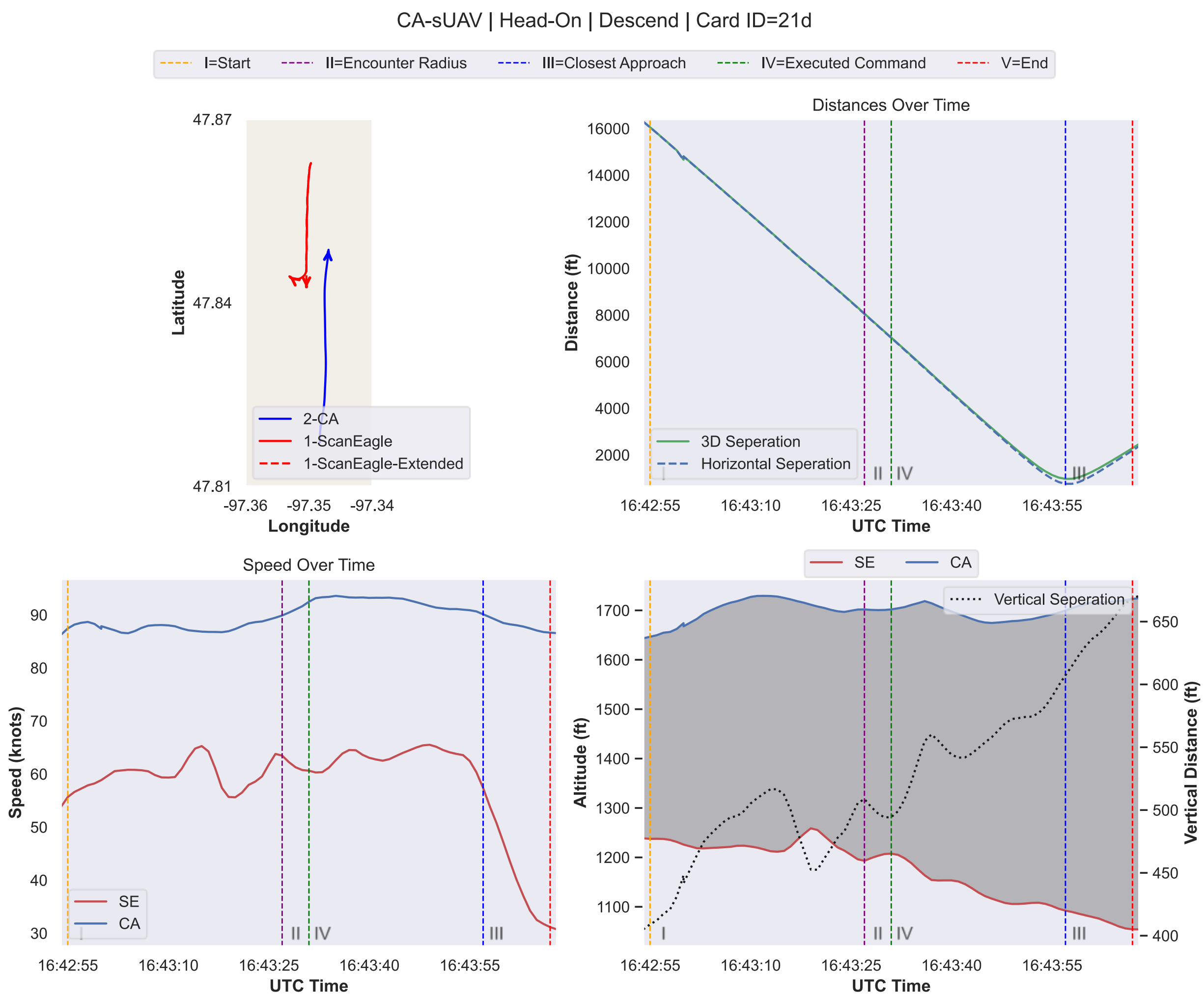


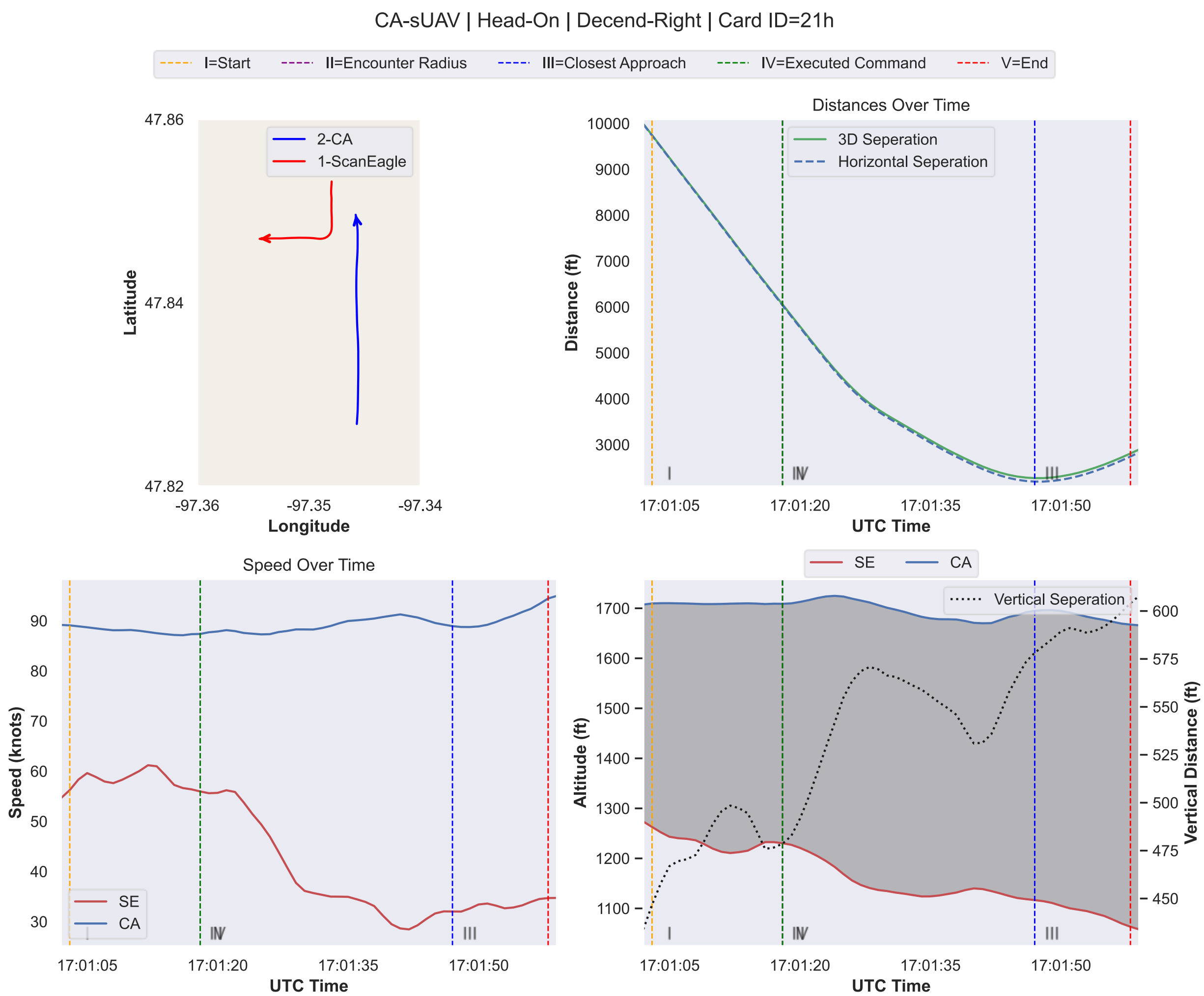
sUAV- sUAV | Converging | Descend | Card ID=12f
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-AA Albatross
1-ScanEagle
Latitude
Longitude
47.86
47.85
47.83
-97.36
-97.34
-97.33
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
4000
3500
3000
2500
2000
1500
UTC Time
23:57:41
23:57:56
23:58:11
23:58:26
Speed Over Time
SE
AA
Speed (knots)
90
80
70
60
50
40
30
Altitude Over Time
Vertical Seperation
SE-75.0
Altitude (ft)
Vertical Distance (ft)
1250
1200
1150
1100
1050
1000
250
225
200
175
150
125
100
75


sUAV- sUAV | Converging | Right-Decent | Card ID=12g
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-AA Albatross
1-ScanEagle
1-ScanEagle-Extended
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
SE
AA
Speed (knots)
Altitude Over Time
Vertical Seperation
SE-75.0
Altitude (ft)
Vertical Distance (ft)

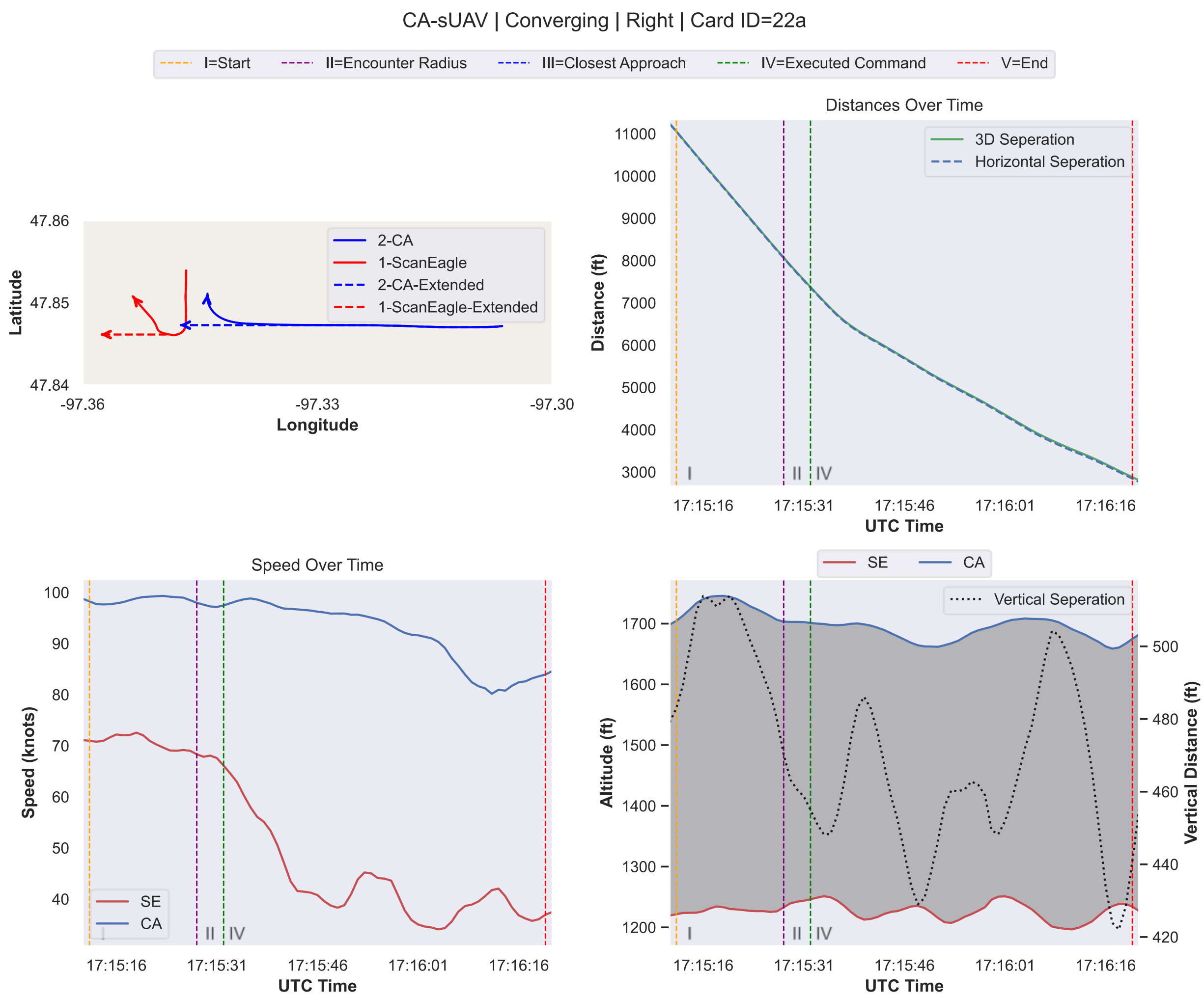
G.2. Round-1 : CA-UAS



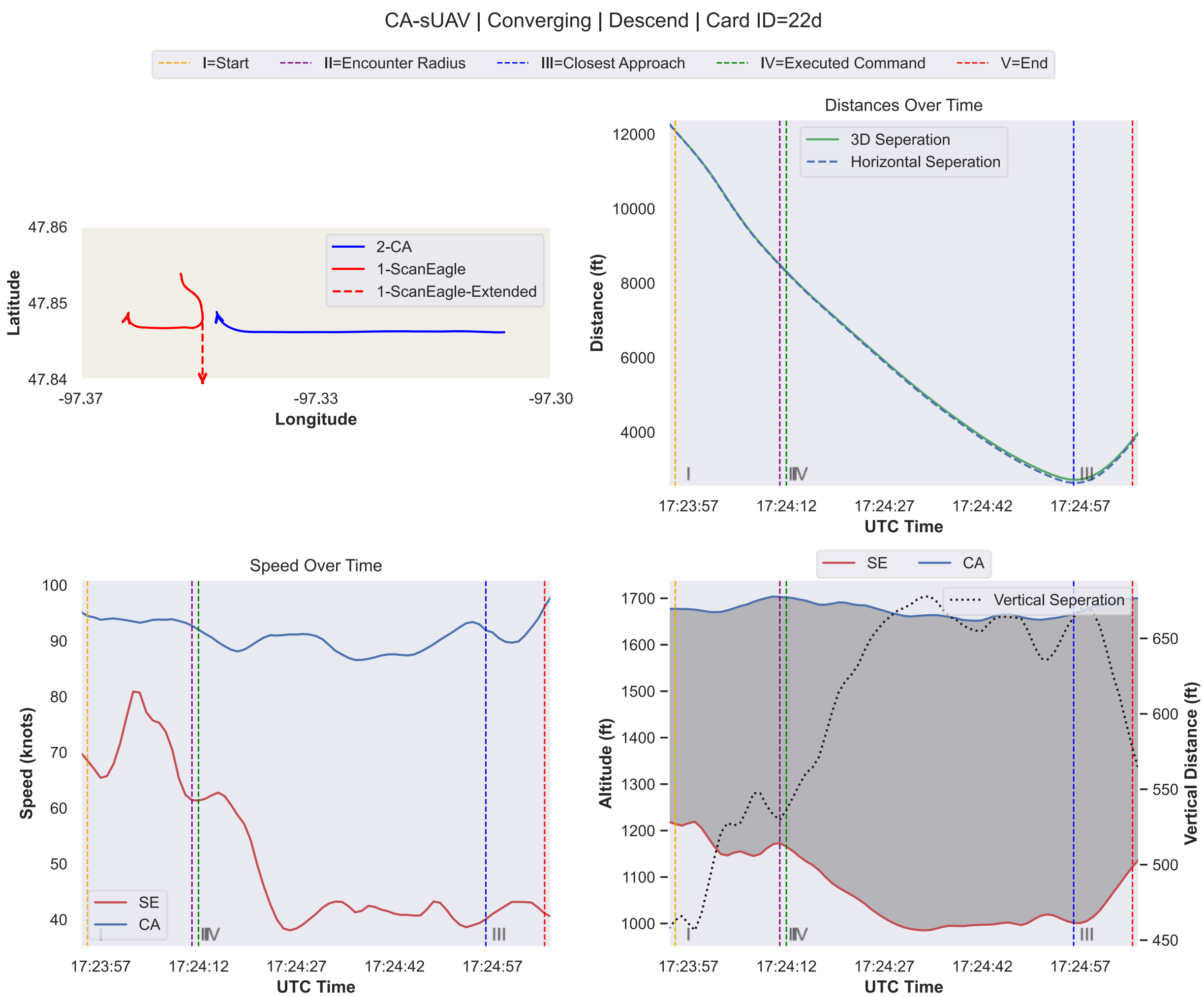

CA-sUAV | Head-On | Descend | Card ID=21d
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
Latitude
Longitude
2-CA
1-ScanEagle
1-ScanEagle-Extended
Distances Over Time
Distance (ft)
UTC Time
3D Seperation
Horizontal Seperation
Speed Over Time
Speed (knots)
SE
CA
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)



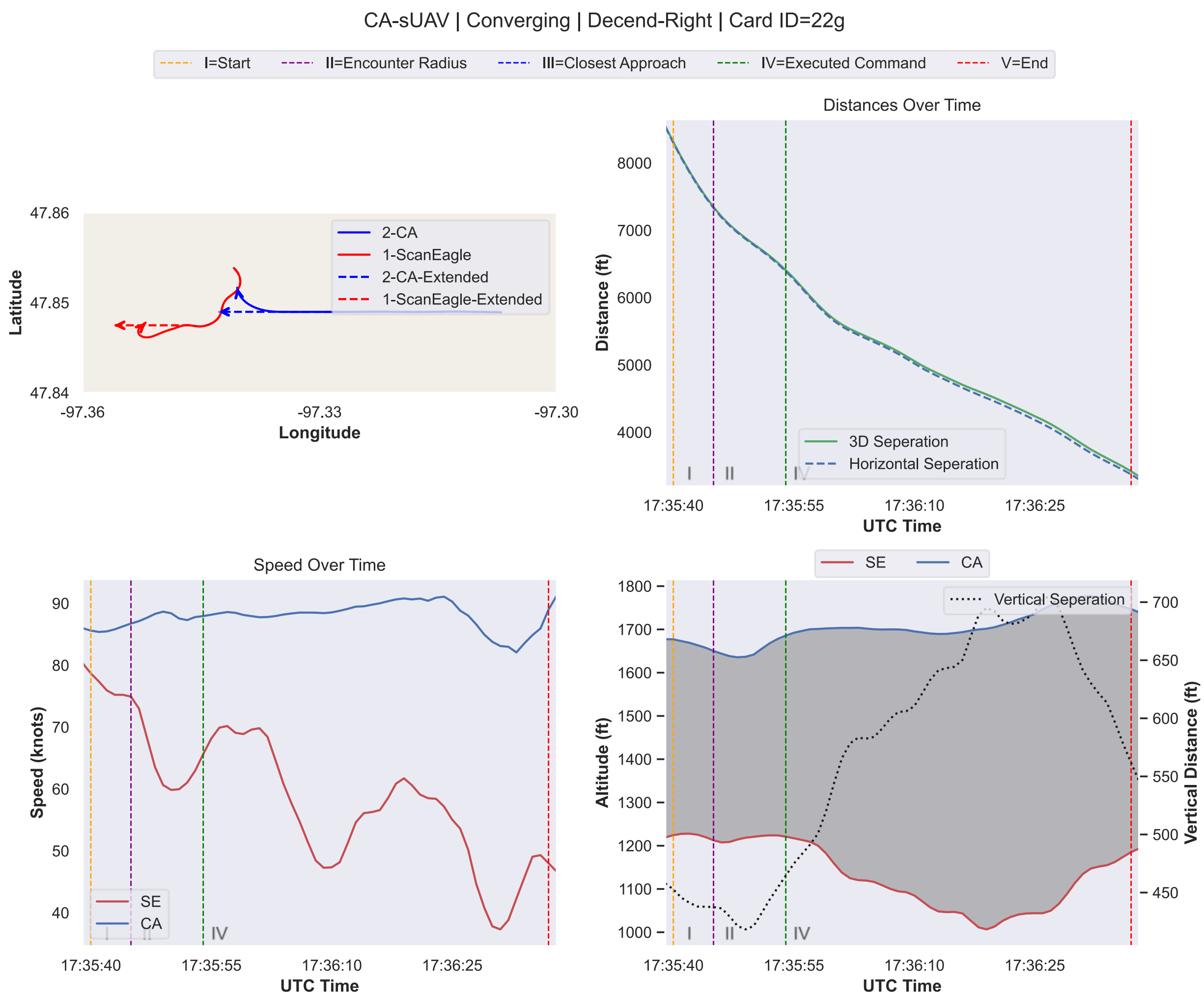
CA-sUAV | Head-On | Decend-Right | Card ID=21h
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-CA
1-ScanEagle
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
Speed (knots)
SE
CA
Vertical Seperation
Altitude (ft)
Vertical Distance (ft)

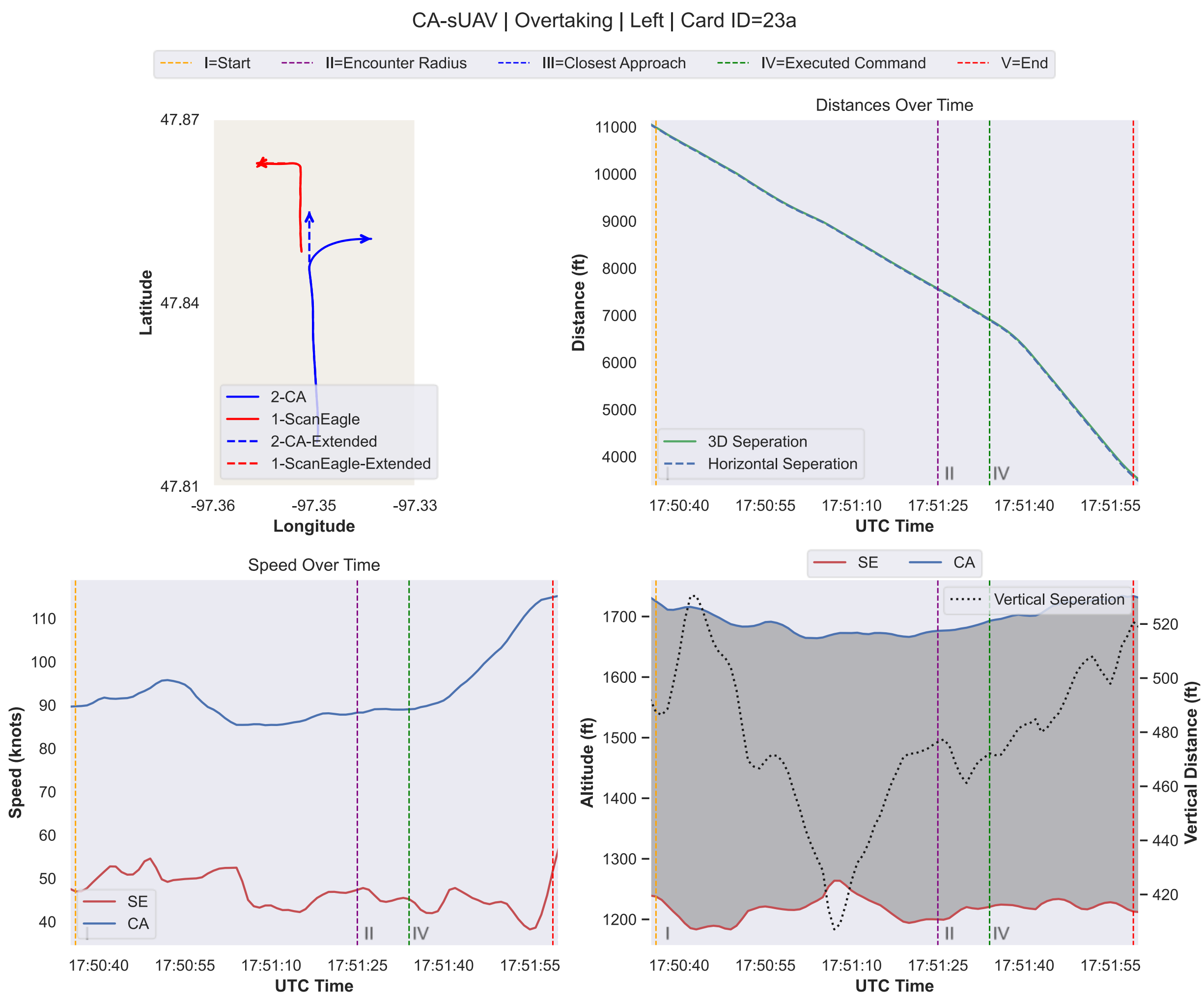


CA-sUAV | Converging | Right | Card ID=22a
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
Latitude
Longitude
2-CA
1-ScanEagle
2-CA-Extended
1-ScanEagle-Extended
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
Speed (knots)
SE
CA
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)

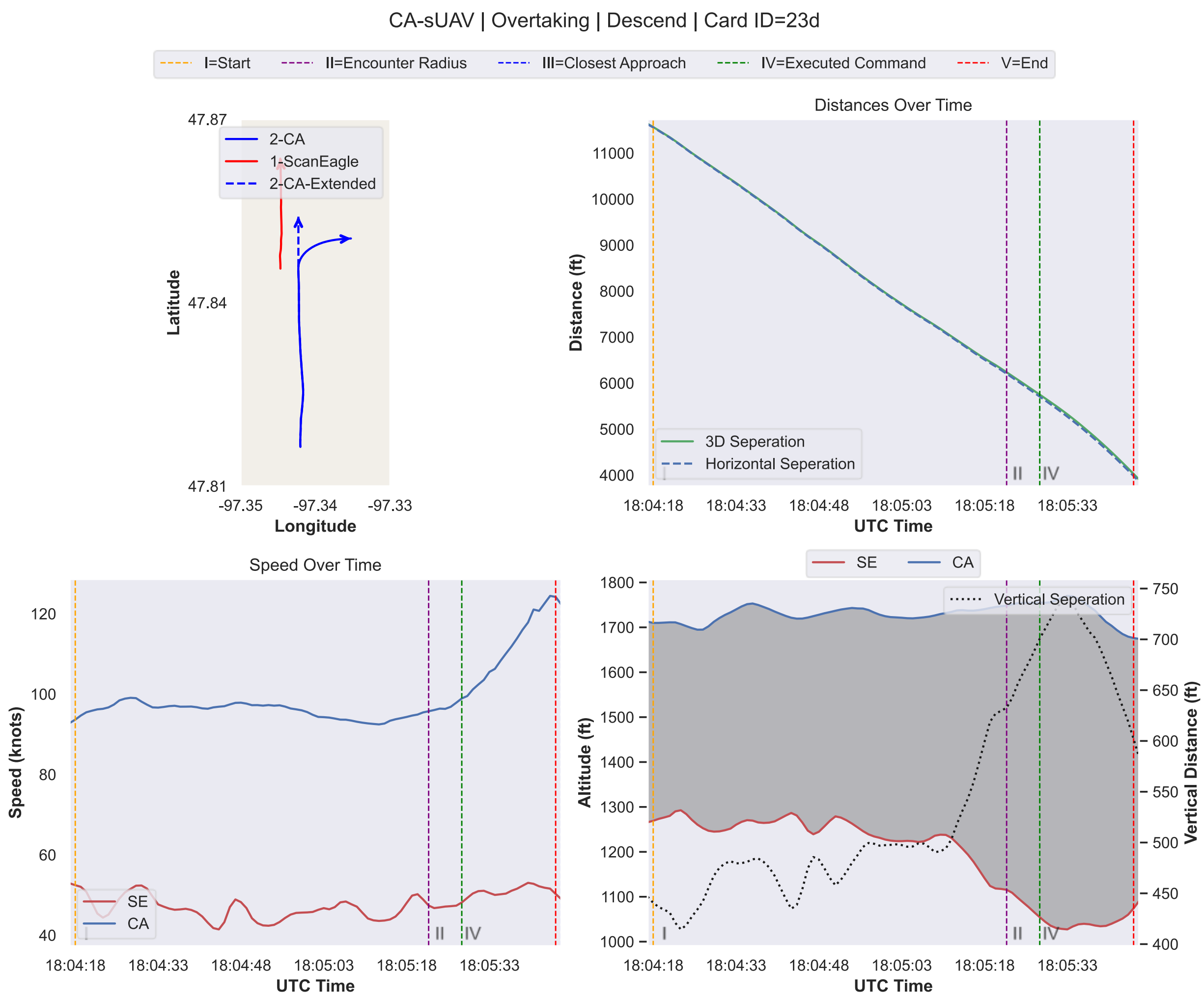


CA-sUAV | Converging | Descend | Card ID=22d
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-CA
1-ScanEagle
1-ScanEagle-Extended
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
Speed (knots)
SE
CA
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)

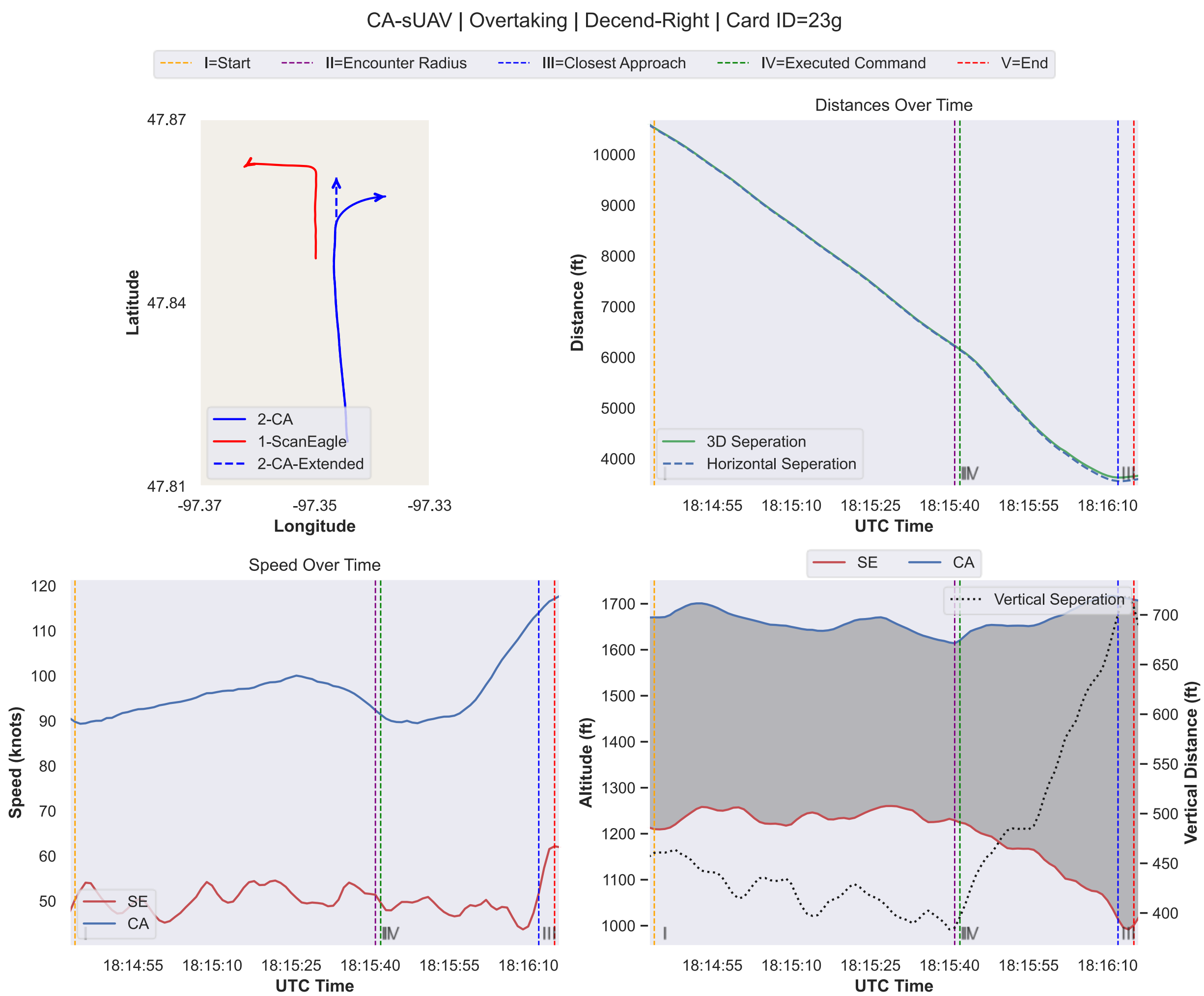

CA-sUAV | Converging | Decend-Right | Card ID=22g
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
Latitude
Longitude
2-CA
1-ScanEagle
2-CA-Extended
1-ScanEagle-Extended
Distances Over Time
Distance (ft)
3D Seperation
Horizontal Seperation
UTC Time
Speed Over Time
Speed (knots)
SE
CA
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)



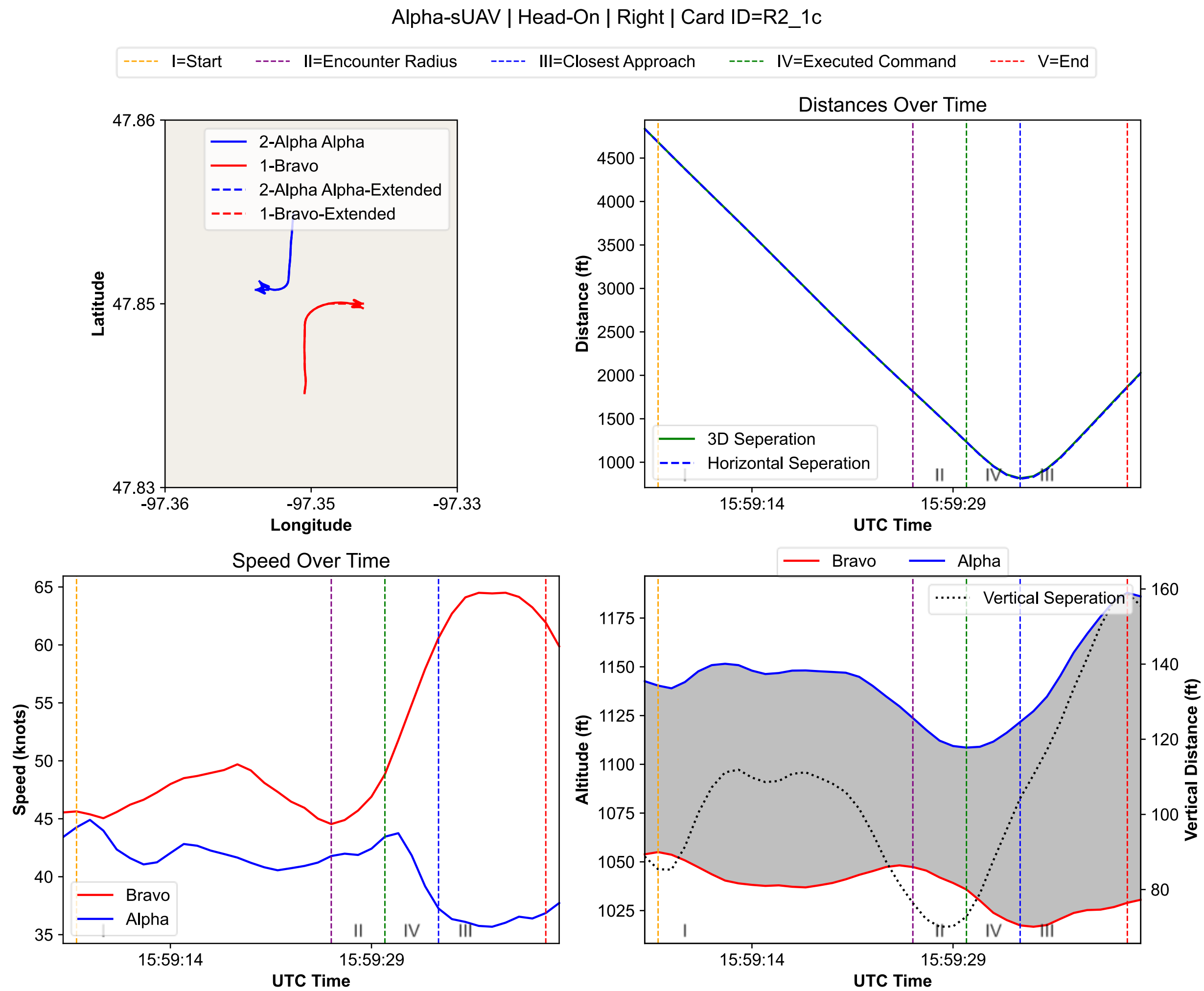
CA-sUAV | Overtaking | Left | Card ID=23a
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
Latitude
Longitude
2-CA
1-ScanEagle
2-CA-Extended
1-ScanEagle-Extended
Distances Over Time
Distance (ft)
3D Seperation
Horizontal Seperation
UTC Time
Speed Over Time
Speed (knots)
SE
CA
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)

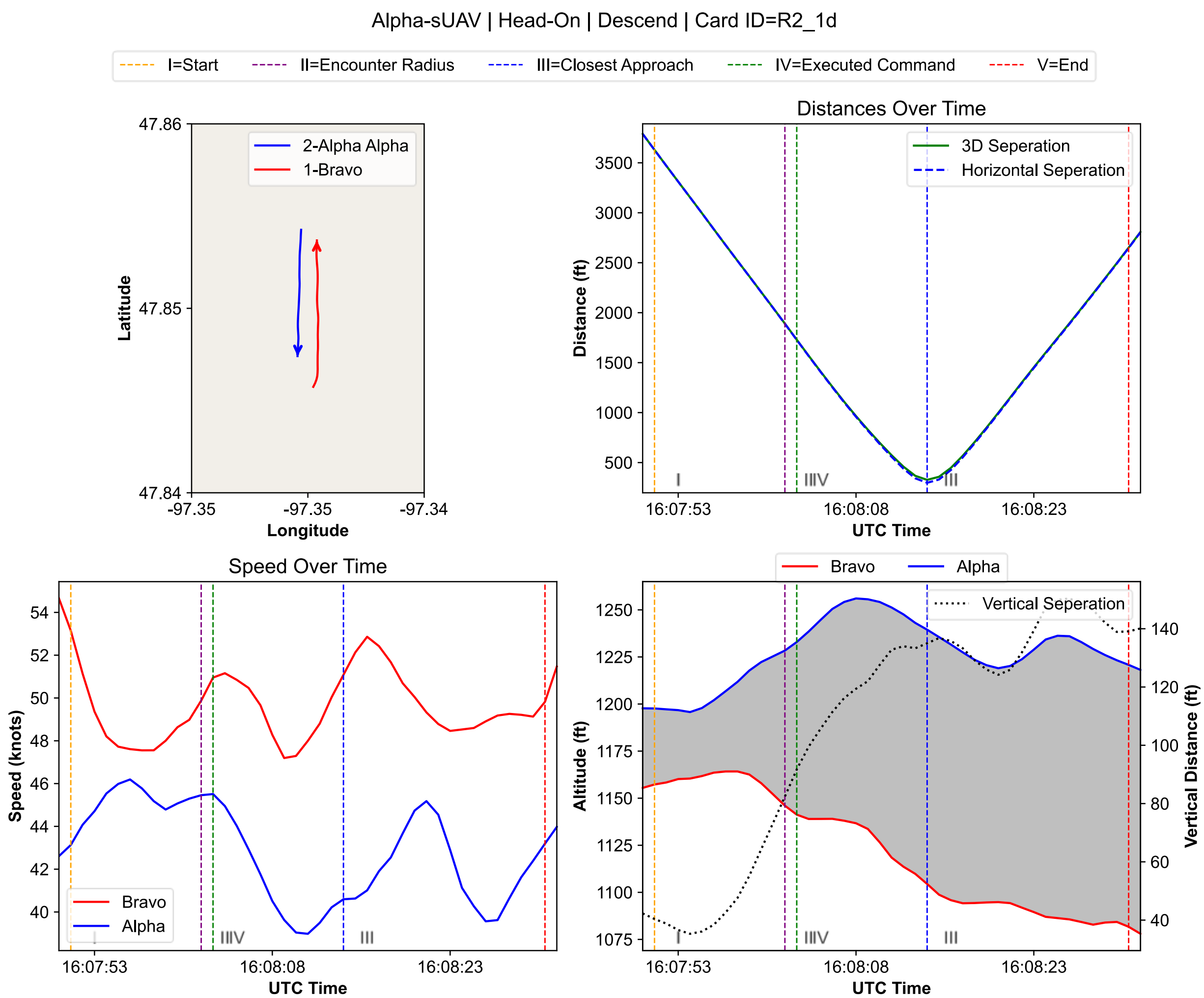


CA-sUAV | Overtaking | Descend | Card ID=23d
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-CA
1-ScanEagle
2-CA-Extended
Latitude
Longitude
47.87
47.84
47.81
-97.35
-97.34
-97.33
Distances Over Time
Distance (ft)
11000
10000
9000
8000
7000
6000
5000
4000
3D Seperation
Horizontal Seperation
18:04:18
18:04:33
18:04:48
18:05:03
18:05:18
18:05:33
UTC Time
Speed Over Time
Speed (knots)
120
100
80
60
40
SE
CA
Altitude (ft)
1800
1700
1600
1500
1400
1300
1200
1100
1000
Vertical Seperation
Vertical Distance (ft)
750
700
650
600
550
500
450
400

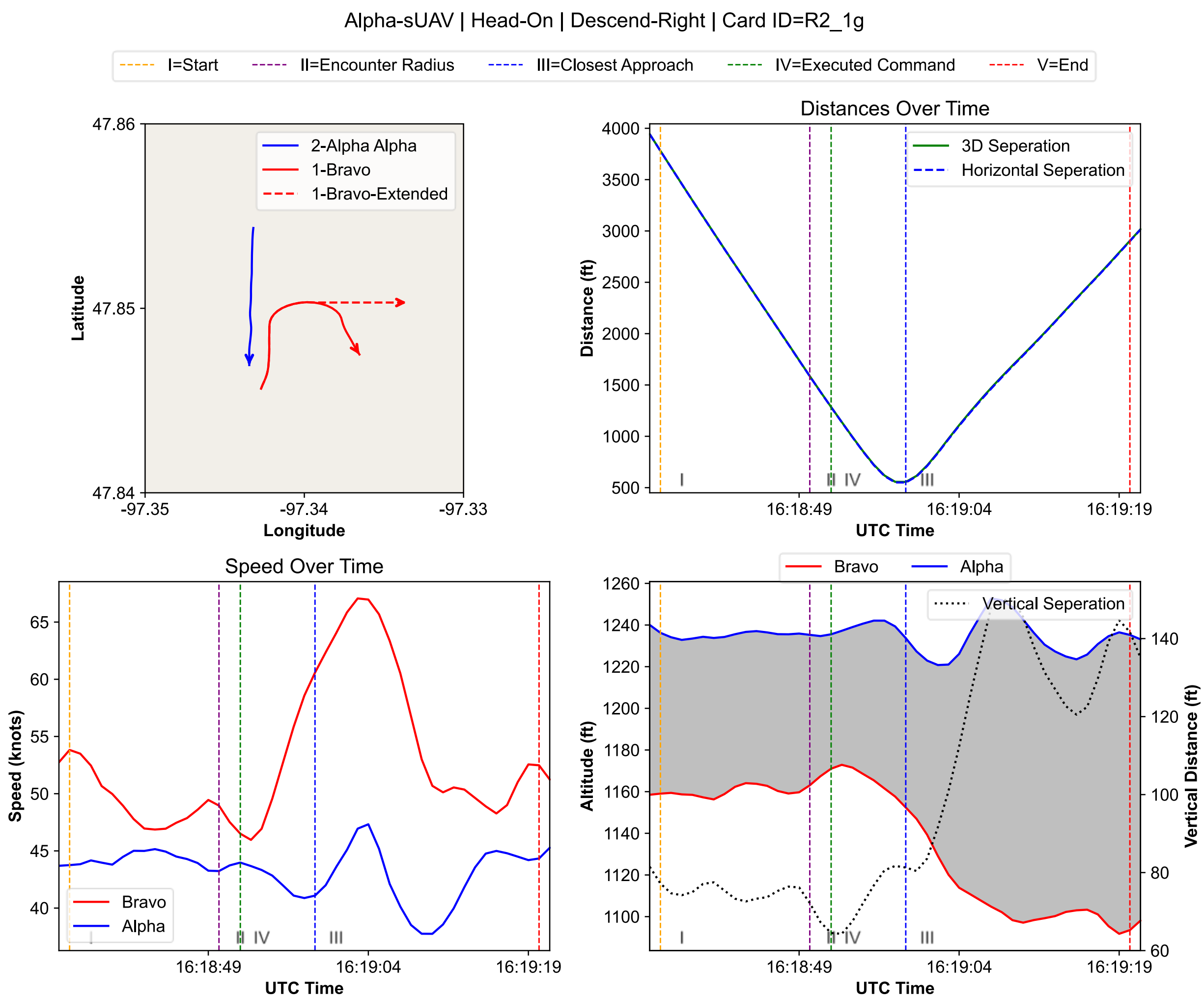

CA-sUAV | Overtaking | Decend-Right | Card ID=23g
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
Latitude
Longitude
2-CA
1-ScanEagle
2-CA-Extended
Distances Over Time
Distance (ft)
UTC Time
3D Seperation
Horizontal Seperation
Speed Over Time
Speed (knots)
SE
CA
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)

G.3 Round-2 : sUAS vs sUAS (RAC)

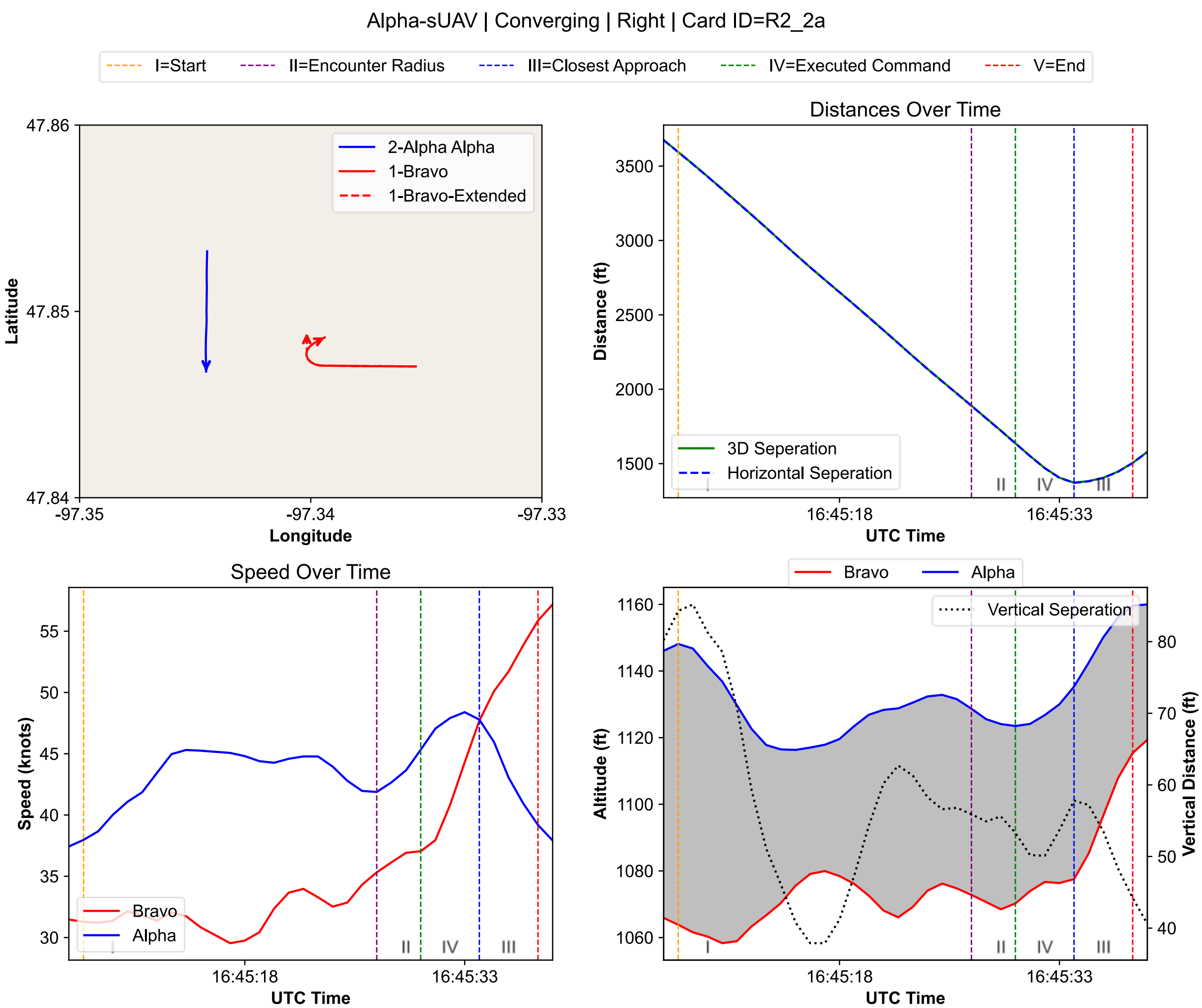




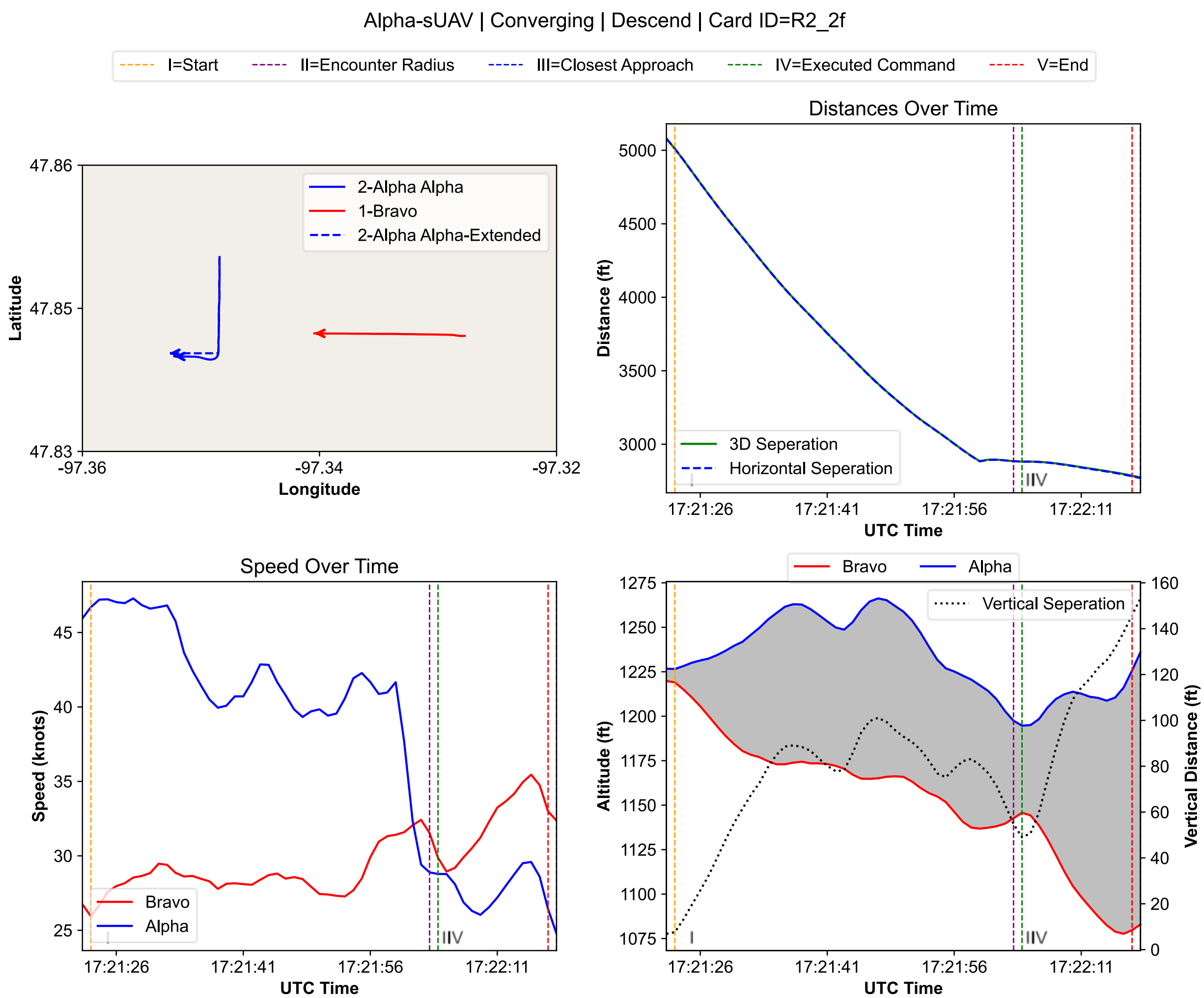
Alpha-sUAV | Head-On | Descend | Card ID=R2_1d
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-Alpha Alpha
1-Bravo
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
Speed (knots)
Bravo
Alpha
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)



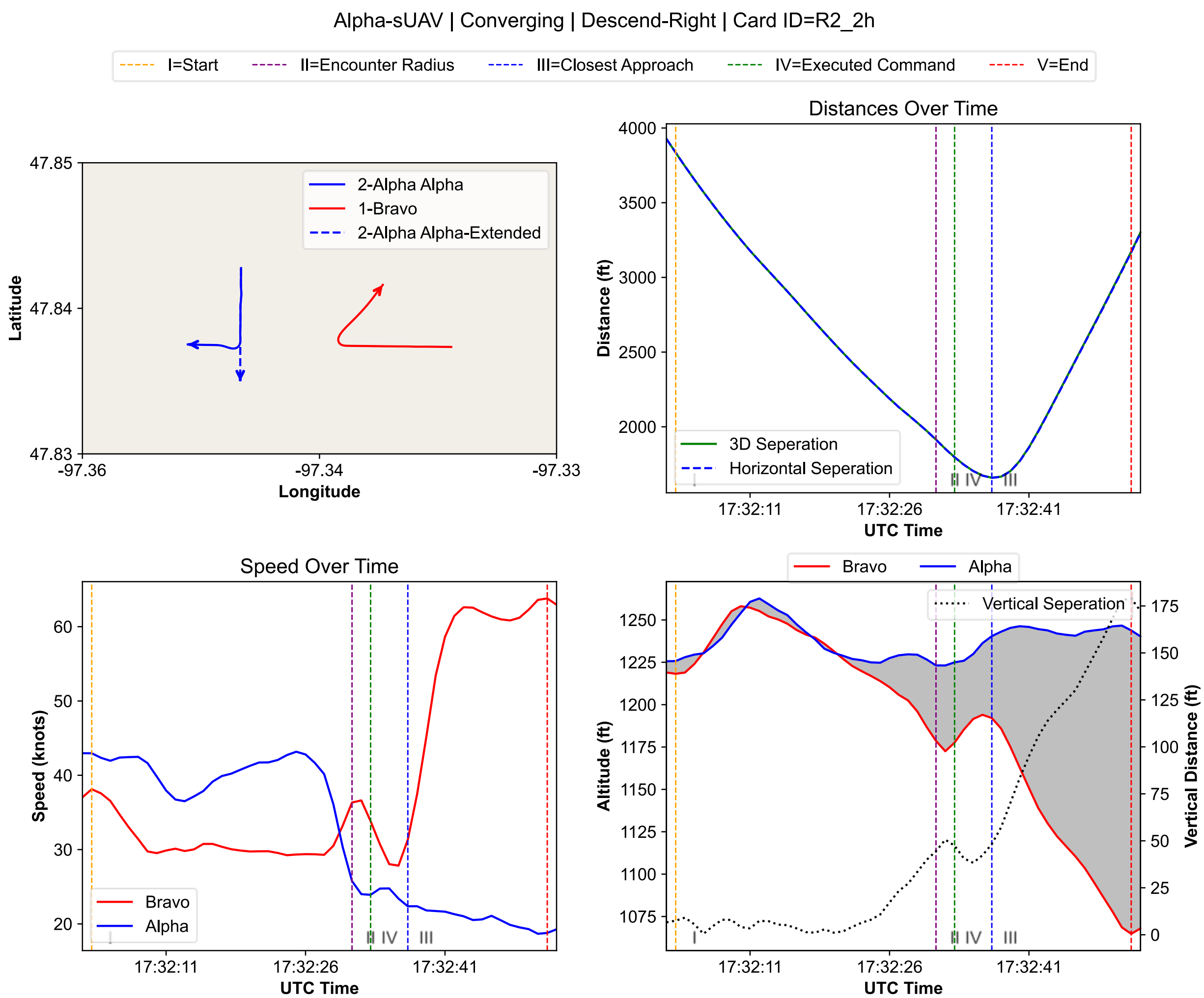
Alpha-sUAV | Head-On | Descend-Right | Card ID=R2_1g
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-Alpha Alpha
1-Bravo
1-Bravo-Extended
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
Speed (knots)
Bravo
Alpha
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)



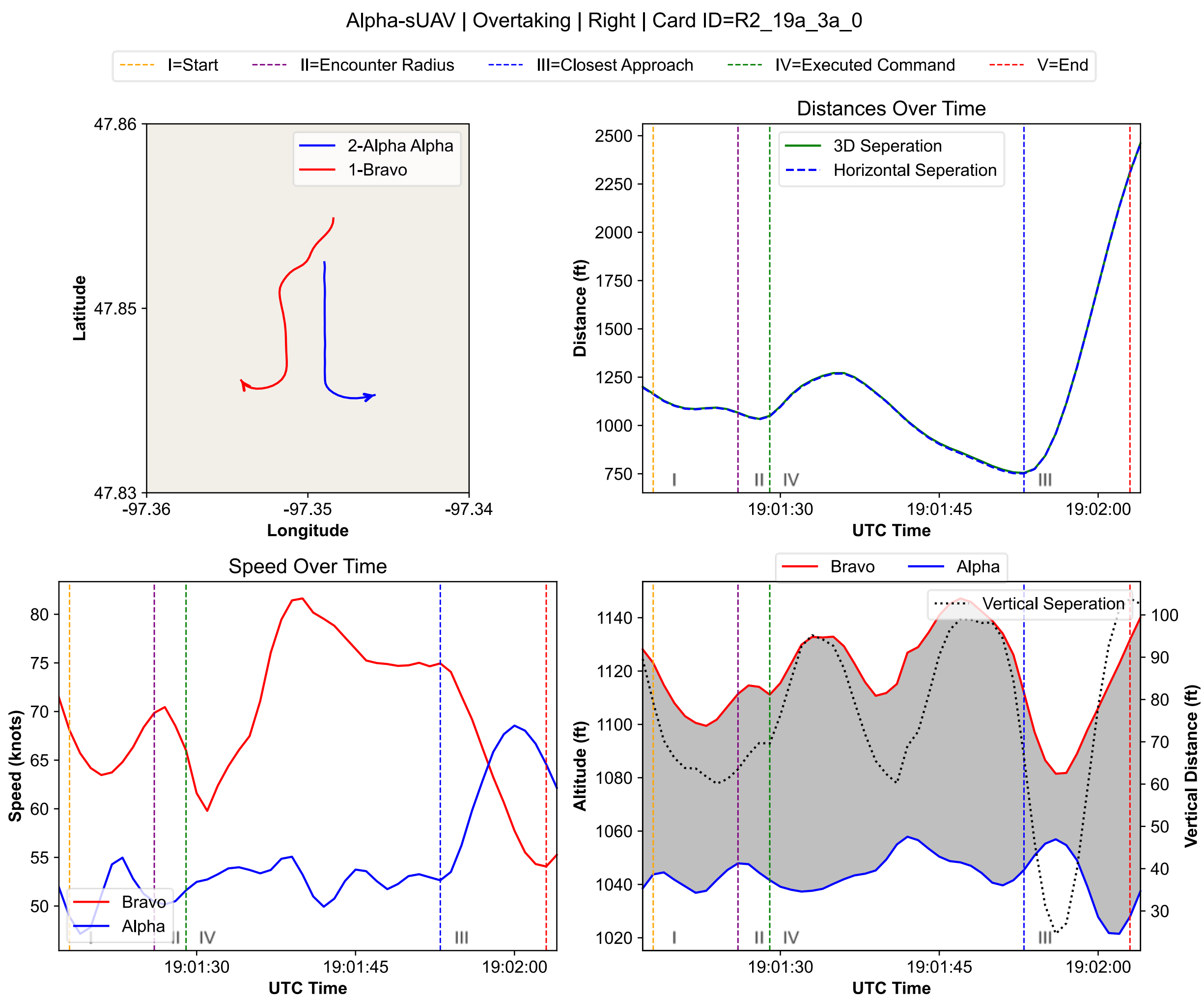
Alpha-sUAV | Converging | Right | Card ID=R2_2a
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-Alpha Alpha
1-Bravo
1-Bravo-Extended
Latitude
Longitude
47.86
47.85
47.84
-97.35
-97.34
-97.33
Distances Over Time
Distance (ft)
3D Seperation
Horizontal Seperation
3500
3000
2500
2000
1500
16:45:18
16:45:33
UTC Time
Speed Over Time
Speed (knots)
Bravo
Alpha
55
50
45
40
35
30
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)
1160
1140
1120
1100
1080
1060
80
70
60
50
40
I
II
IV
III



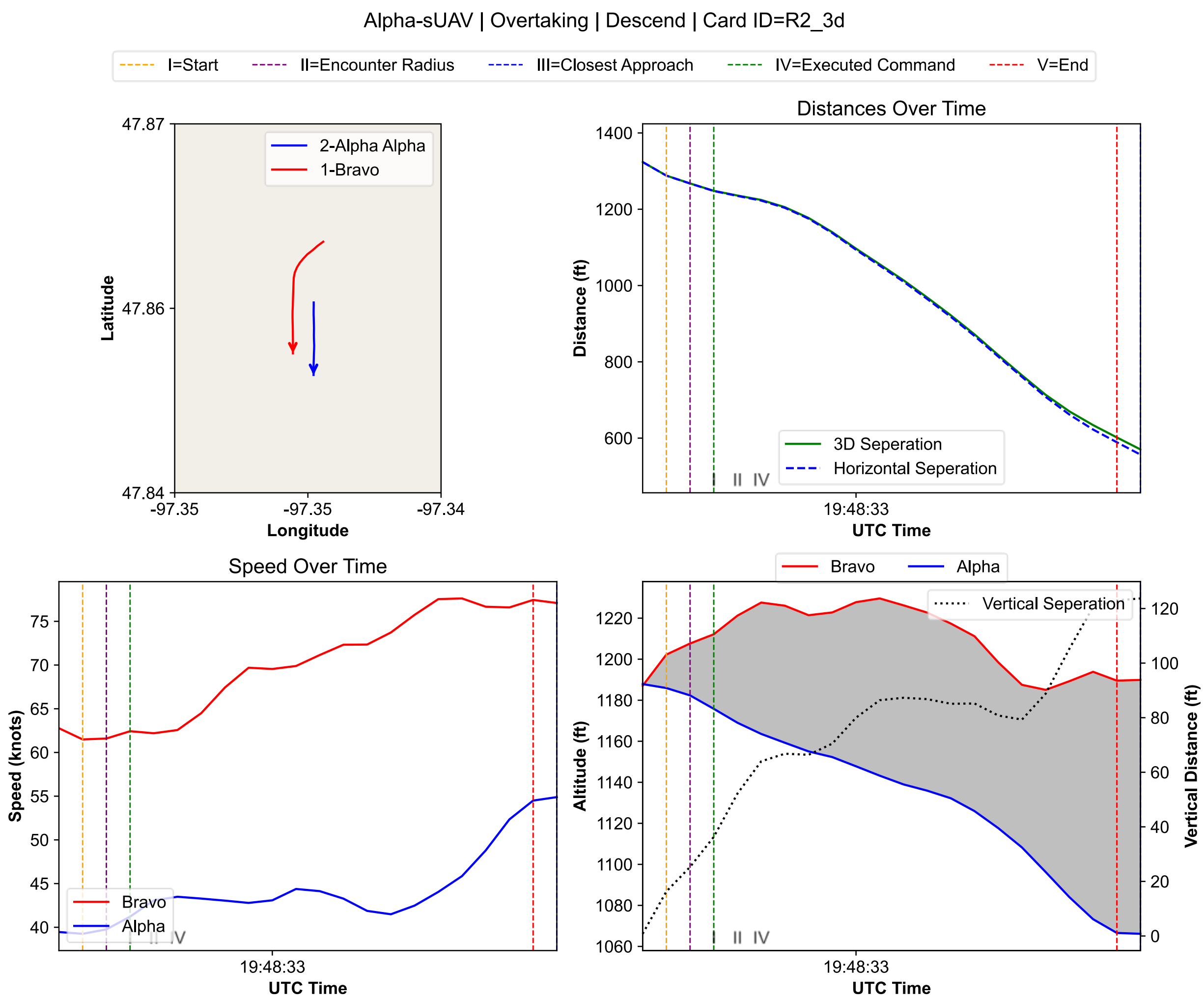
Alpha-sUAV | Converging | Descend | Card ID=R2_2f
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
Latitude
Longitude
2-Alpha Alpha
1-Bravo
2-Alpha Alpha-Extended
Distances Over Time
Distance (ft)
3D Seperation
Horizontal Seperation
UTC Time
Speed Over Time
Speed (knots)
Bravo
Alpha
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)



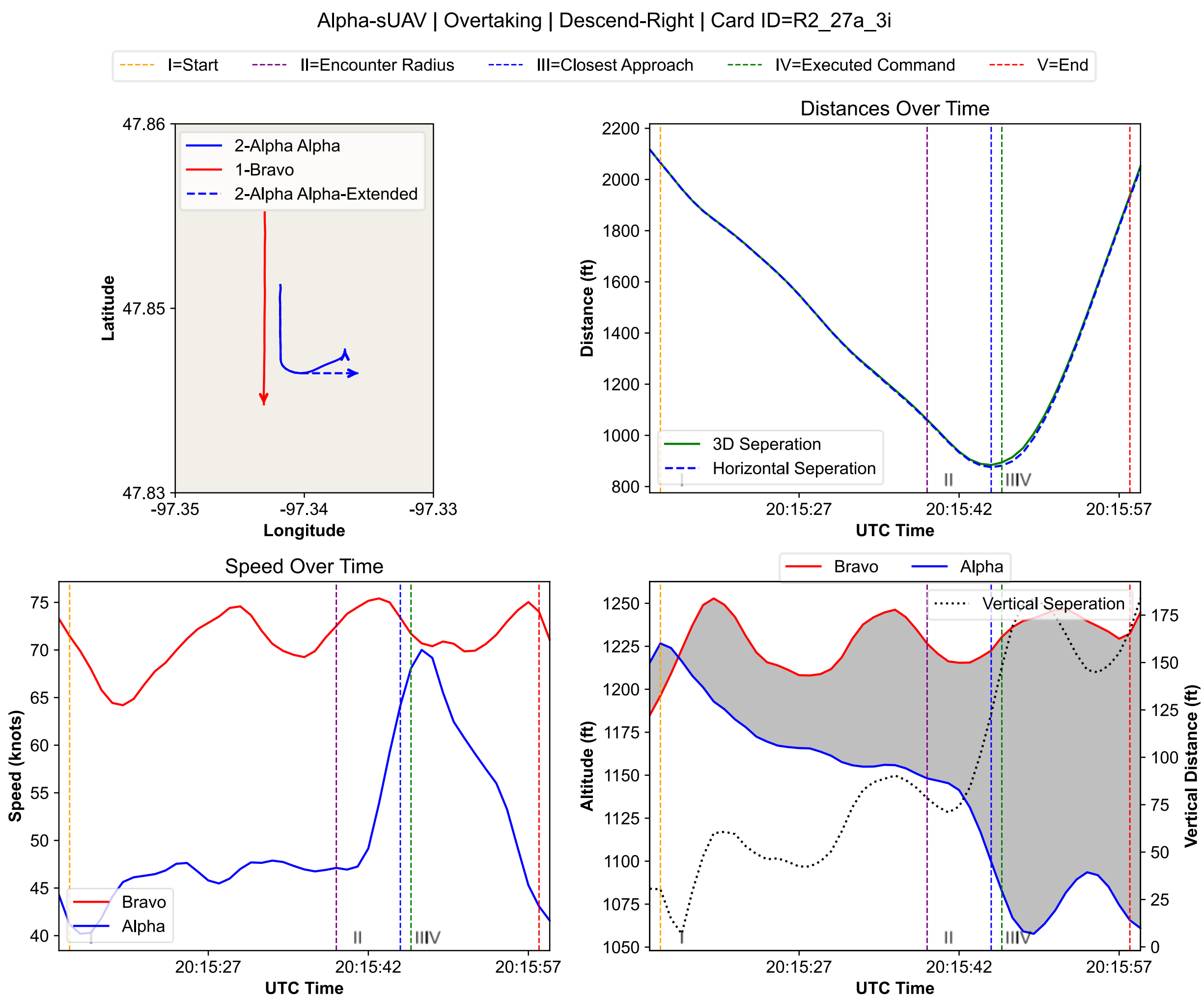
Alpha-sUAV | Converging | Descend-Right | Card ID=R2_2h
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-Alpha Alpha
1-Bravo
2-Alpha Alpha-Extended
Latitude
Longitude
47.85
47.84
47.83
-97.36
-97.34
-97.33
Distances Over Time
Distance (ft)
4000
3500
3000
2500
2000
3D Seperation
Horizontal Seperation
17:32:11
17:32:26
17:32:41
UTC Time
Speed Over Time
Speed (knots)
60
50
40
30
20
Bravo
Alpha
17:32:11
17:32:26
17:32:41
UTC Time
Bravo
Alpha
Vertical Seperation
Altitude (ft)
1250
1225
1200
1175
1150
1125
1100
1075
Vertical Distance (ft)
175
150
125
100
75
50
25
0
17:32:11
17:32:26
17:32:41
UTC Time

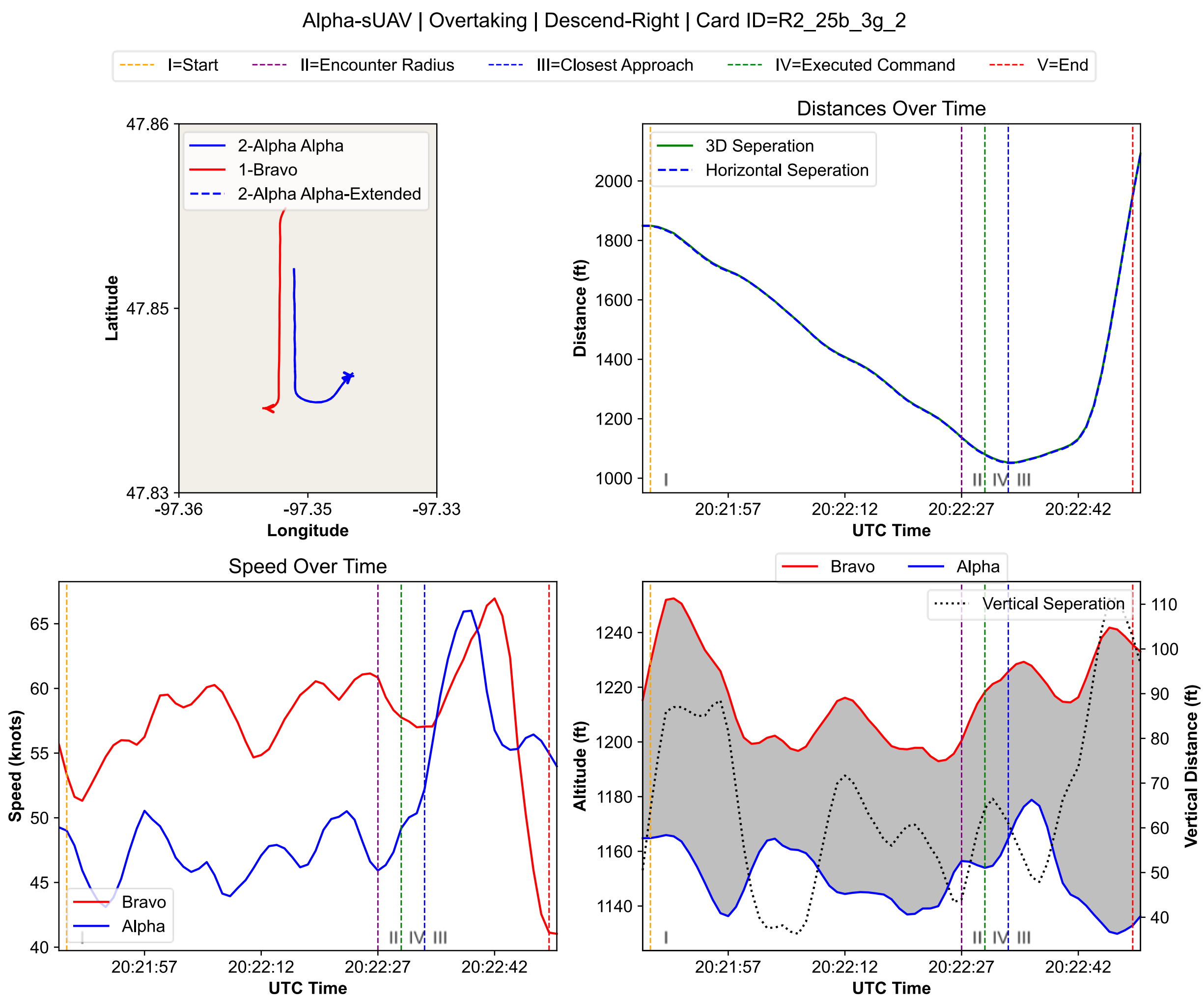


Alpha-sUAV | Overtaking | Right | Card ID=R2_19a_3a_0
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-Alpha Alpha
1-Bravo
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
Speed (knots)
Bravo
Alpha
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)



Alpha-sUAV | Overtaking | Descend | Card ID=R2_3d
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-Alpha Alpha
1-Bravo
Latitude
Longitude
47.87
47.86
47.84
-97.35
-97.35
-97.34
Distances Over Time
Distance (ft)
1400
1200
1000
800
600
3D Seperation
Horizontal Seperation
I II IV
19:48:33
UTC Time
Speed Over Time
Speed (knots)
75
70
65
60
55
50
45
40
Bravo
Alpha
19:48:33
UTC Time
Bravo
Alpha
Vertical Seperation
Altitude (ft)
Vertical Distance (ft)
1220
1200
1180
1160
1140
1120
1100
1080
1060
120
100
80
60
40
20
0
I II IV
19:48:33
UTC Time


Alpha-sUAV | Overtaking | Descend-Right | Card ID=R2_27a_3i
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-Alpha Alpha
1-Bravo
2-Alpha Alpha-Extended
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
Speed (knots)
Bravo
Alpha
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)


Alpha-sUAV | Overtaking | Descend-Right | Card ID=R2_25b_3g_2
I=Start
II=Encounter Radius
III=Closest Approach
IV=Executed Command
V=End
2-Alpha Alpha
1-Bravo
2-Alpha Alpha-Extended
Latitude
Longitude
Distances Over Time
3D Seperation
Horizontal Seperation
Distance (ft)
UTC Time
Speed Over Time
Speed (knots)
Bravo
Alpha
Altitude (ft)
Vertical Seperation
Vertical Distance (ft)

APPENDIX H – FINAL TASK 3 AND 4 RESULTS AND INTERPRETATIONS FROM KU

Foreword: At the time that the report, “Task 3 and 4 Draft/Preliminary Results and Interpretations” (31 July 2024) was submitted to ASSURE, the University of Kansas (KU) had not completed Task 4 flight testing. As such, the flight test findings and, most importantly, the comparison of simulation and flight test were not included. It was determined that, in lieu of submitting a comprehensive “Final Task 3 and 4 Results and Interpretations” report, only the KU sections of the Draft/Preliminary report be revised, and that they would be placed in this appendix to the Task 3 and 4 report.

H.1 UNIVERSITY OF KANSAS SIMULATIONS

The focus of simulations by KU is the simulation of ***autonomous*** Unmanned Aircraft System (UAS) flight control to avoid Right Of Way (ROW) violations with regards to other aircraft. Further, the simulations are intended to simulate avoidance maneuvers one might expect for UAS operated in missions during which the UAS would ***return to its mission*** following the successful avoidance of a crewed aircraft or another UAS. As such, the avoidance maneuvers simulated have the additional complication of needing to return to the mission. This has the important characteristic that the many computed trajectories of encounter maneuvers ***which return to mission flight lines*** in the General Interaction scenarios provide an estimate of the volume of airspace within which the UAS would be expected to need for normal operations interrupted by avoidance of a Right Of Way Violation (ROWV). Therefore, the ***required*** size of Reserved Airspace (RA) for flight corridor, can be ***derived***. Alternatively, given a ***proposed*** size of a Reserved Airspace, the probability of a Reserved Airspace Violation (RAV), P_{RAV}, can be computed. Regarding the analysis of the minimum size of a RA, the tendency to return to the UAS mission after an encounter might not result in the smallest estimate of the required size of RA. In particular, with the added constraint on the navigation and guidance algorithm to specifically avoid a RAV, the required size of a RA or the P_{RAV} for a given size of a RA could likely be reduced if the UAS turn rate is (autonomously) increased from a nominal rate to the rate needed to avoid exiting the RA.

H.1.1 Summary of Simulations Conducted

The KU simulation can be configured for a variety of scenarios and missions. For this investigation, these missions include the same General Interactions studied by the University of North Dakota (UND) and Embry Riddle Aeronautical Univerusty (ERAU) as well as two Reserved Airspace scenarios: flight in a corridor of fixed width and a grid surveying mission. In all scenarios the simulation consists of either a single smalle Unmanned Aircraft System (sUAS) or multiple sUAS flying in fixed formation encountering a crewed aircraft. These encounters are:

- at the same altitude,
- for a range of encounter angles,
- for three relative speeds, and

- designed such that a mid-air collision would occur if there were no avoidance maneuvering [Note: this may not be the worst-case scenario, as discussed later].

Based on the assumption that the crewed aircraft will not see the sUAS or the multiple sUAS in formation, in all cases the pilot of the crewed aircraft does not maneuver. As such, the sUAS will frequently be referred to as “ownship(s)” and the crewed aircraft as the “othership.” In all single sUAS cases, only horizontal maneuvers area used. For multiple sUAS avoidance maneuvers there are some vertical maneuvers as well.

As with all simulations conducted by the A54 team, *the main parameter of interest is the required detection distance for a sUAS detect and avoid system to avoid a Right Of Way Violation* over all encounter angles for a given relative speed. For encounters with a crewed aircraft, a right of way violation means not maintaining the required well-clear separation of 2,000 ft horizontally and 250 ft vertically. A secondary parameter of interest is the avoidance of a Near Mid-Air Collision (NMAC). In addition, the percentages of ROWV and NMAC are computed, which quantify the percentage of encounter angles at a given detection distance that result in a ROWV or NMAC. Beyond the quantitative calculations, observations of the simulation results will be used to determine if any new ROW rules should be considered.

In the flight in a corridor scenario, the sUAS or multiple sUAS are flying along the centerline of a reserved airspace corridor like what might happen when a sUAS is inspecting power lines over a long distance. The single sUAS or multiple sUAS are geographically constrained in a reserved corridor where it cannot exit the reserved airspace. Because of this restriction, the sUAS or multiple sUAS must avoid a crewed, non-cooperative aircraft while remaining inside of the reserved airspace. The recommendations and results for the moving corridor scenario are based upon the avoidance maneuvers in the General Interaction scenarios wherein the sUAS automatically returns--rather efficiently--to the intended course after the encounter. This then establishes the required width of the corridor, ensuring that the UAS does not exit the reserved corridor.

In the grid surveying scenario, the sUAS or multiple sUAS are flying in a surveying pattern to simulate a mission like agricultural spraying or ground mapping. While the sUAS or multiple sUAS are flying in this surveying pattern, an non-cooperative crewed aircraft enters the reserved airspace. The sUAS or multiple sUAS, upon detecting the crewed aircraft, maneuvers to avoid a ROW violation while remaining inside its reserved airspace. The grid surveying scenario is the only case where changes in altitude are simulated, and only for the case of the multiple sUAS in which the sUAS must avoid each other, which is accomplished with a small vertical separation.

In all simulations using the KU simulator, the crewed intruder aircraft is modeled as a Cessna 172. The heading and location at which the intruding aircraft will collide with the sUAS or multiple sUAS can be configured at the researcher’s discretion. The sUAS and multiple sUAS are modelled as SonicModell SkyHunters.

For Round 1 sUAS interactions with crewed aircraft, sUAS and a formation of two sUAS have been simulated. The studies of crewed aircraft and sUAS interactions by KU were not formally required by the Federal Aviation Administration (FAA); however, they were conducted to co-validate the analyses by UND and KU. The basis of the comparison is the comparison of KU’s autonomous sUAS simulations and UND’s simulations of piloted sUAS simulations with the crewed aircraft not following right of way rules. The key take-away of the comparisons is that for the "worst case" maneuvers, that is, when the detection distance is so small that a ROWV is just barely avoided, both KU and UND maneuvers require abrupt turns: for head-on encounters a 105^o turn to the right used for all UND encounters is essentially the same maneuver simulated by the autonomous simulations by KU wherein mostly 90^o turns are computed. The data generated by the simulations in Round 1 are, as by UND, in the form of graphs of three items vs the detection distance: the closest approach of the sUAS to traffic with ROW; the probability of a ROWV vs a crewed aircraft, that is approaching closer than 2,000 ft horizontally; and the probability of the UAS entering the NMAC volume of the crewed aircraft, that is, 500 ft horizontally. The KU simulations did not address Global Positioning System (GPS) uncertainty since this effect on ROW violations was carefully studied by UND.

H.1.1.1 Description of the Navigation and Guidance Algorithms

H.1.1.1.1 Avoidance Based on the Morphing Potential Field

The fundamental basis of the navigation and guidance algorithms explored by KU is the Morphing Potential Field (MPF) or artificial potential field navigation method. This is based on Khatib's research into obstacle avoidance in robotics [1], similar multi-agent approaches such as Reynolds' ground-breaking work on local flocking behaviors [2], Leonard and Fiorelli's work on coordinated control of groups [3]. In these approaches, a potential field is computed which creates a repelling influence on navigation and guidance by creating a "cost" to enter an undesired volume of airspace. In particular as in Equation 9.

$$\mathrm{pf} = \mathrm{A} \cdot \exp\left\{-\left(\frac{\left\|\vec{\mathrm{p}}^{\mathrm{obj}} - \vec{\mathrm{p}}^{\mathrm{o}}\right\|}{\sigma}\right)^2\right\} \qquad \text{Equation 9}$$

The numerator of the argument of the exponential is the distance norm between the object to be avoided and the avoiding aircraft. Figure 231 shows a plot of a stationary potential field and a *morphing* potential field, described below.

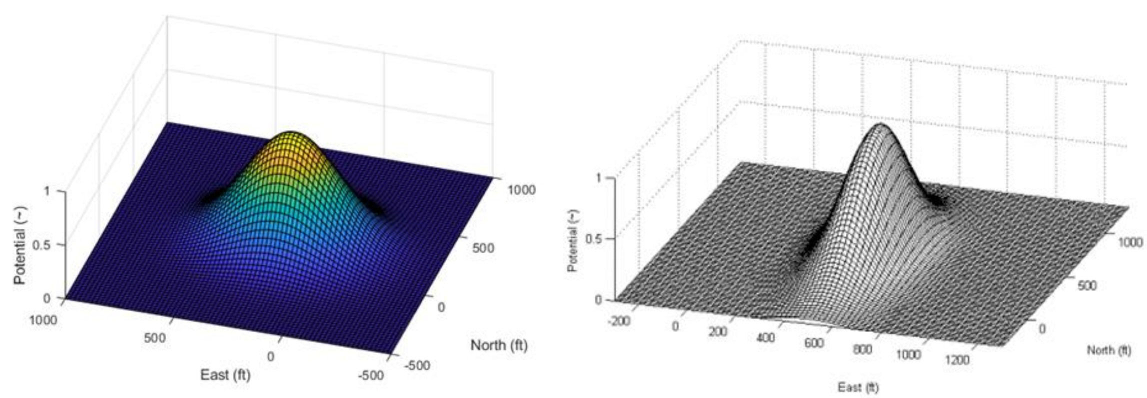


Figure 231 A stationary potential field, left, and a moving potential field, right.

Considering kinematic and physical constraints of aircraft flying at high speeds (e.g., minimum turning radii and limited deceleration capabilities), the aircraft must begin evasion of obstacles somewhat further in advance than would be necessary for slower moving vehicles (or a stationary object). Use of the generic potential formulation from Equation 9 in such an application is possible but would require significant enlargement in amplitude and/or choice of a larger avoidance radius. The resulting evasion path would be fairly inefficient, with respect to time off the desired trajectory, and lead to unnecessary avoidance maneuvers in aircraft passing an object at a safe distance with a nonconflicting heading, inhibiting operations with tight spatial constraints or in a congested urban area. To remedy these issues, a "morphing" factor Γ was integrated into the potential function, based on the angle of approach, magnitude of the relative velocity between aircraft, and kinematic aircraft constraints.

This extension of the potential field (visualized in Figure 231) "repels" the avoiding aircraft from entering airspace which might cause a right of way violation without the undesirable effects of amplitude or avoidance radius enlargement seen in the generic formulation. An additional reference shifting term **S** has also been included in the distance norm as a means of further shaping the potential to avoid unnecessary levels of cost beyond the avoided obstacle by shifting the potential function origin c away from the centroid of the object. The resultant formulation is deemed a morphing potential function [4]:

$$mpf = \exp\left\{-\Gamma\left(\frac{\|\vec{p}^{obj} - \vec{p}^{o} - \vec{S}\|}{\sigma}\right)^2\right\} \qquad \text{Equation 10}$$

Figure 232 shows the geometric meanings of the terms in parenthesis in Equation 10.

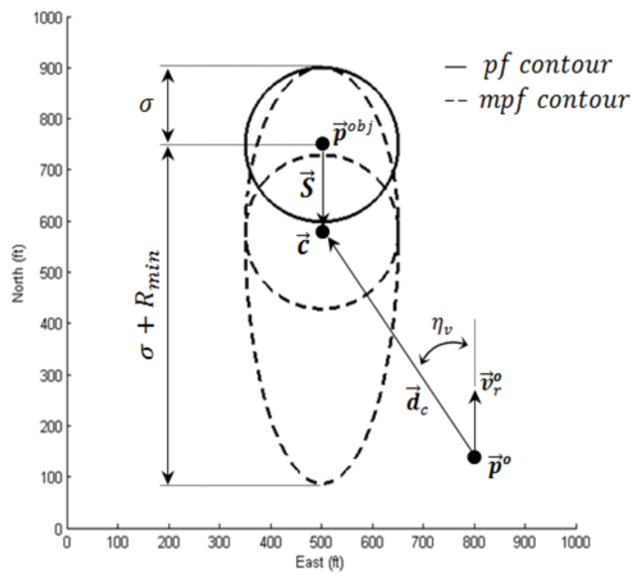


Figure 232. Morphing Potential Field Geometry.

H.1.1.1.2 Avoidance Based on Loiter Maneuvers

Another approach used in this research is a modification of the MPF algorithm, utilizing the relative distance and detection range as inputs to the avoidance logic. In this simplified version, the minimum required detection range is a function of the relative velocity of two aircraft. This maneuver is described further in Section H.1.1.2.1.3 Avoidance Using the Loiter Maneuver.

H.1.1.2 General Interactions

H.1.1.2.1 Single sUAS vs. Crewed Aircraft Not Following ROW Rules

Simulations were conducted for general interactions between a single sUAS vs a crewed aircraft which does not deviate from its intended path, that is, it does not obey right of way rules—because the assumption is that the pilot cannot see the sUAS. This limitation only affects the "substantially-head-on" encounters, which KU has interpreted as –15º to +15º from head on (Encounter angles of 165º to 195º).

H.1.1.2.1.1 Results for MPF Avoidance

The simulations were conducted for numerous heading angles to essentially cover all possible head-on- converging and overtaking-converging encounters. Figure 233 shows the definition of the heading angle between the sUAS and the crewed aircraft. Each aircraft heading angle was defined with respect to a global system, and the sUAS heading was always set to be at 0 degrees in the simulations.

Note that for all encounters, the sUAS is flying at a constant 45 ft/s, but the crewed aircraft speed ranged from 145 ft/s to 170 ft/s to 195 ft/s to see the effect of varying the relative speeds. Also, note that the morphing potential field navigation and guidance and algorithm is used for most encounters. Modifications to this algorithm are on-going, including a modification to consider non-constant speeds for the sUAS, which is expected to, for instance dramatically decrease the distance a sUAS must deviate from course to avoid traffic. This is further discussed in the section on flight in a corridor.

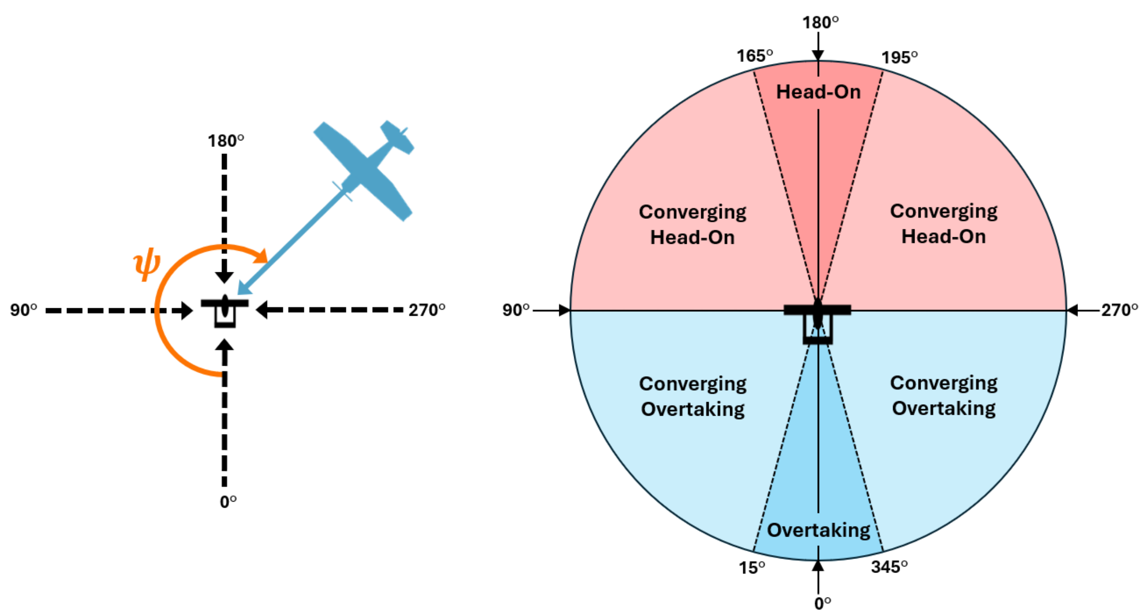


Figure 233. Non-cooperative/"Othership" Aircraft Heading Angle Definition.

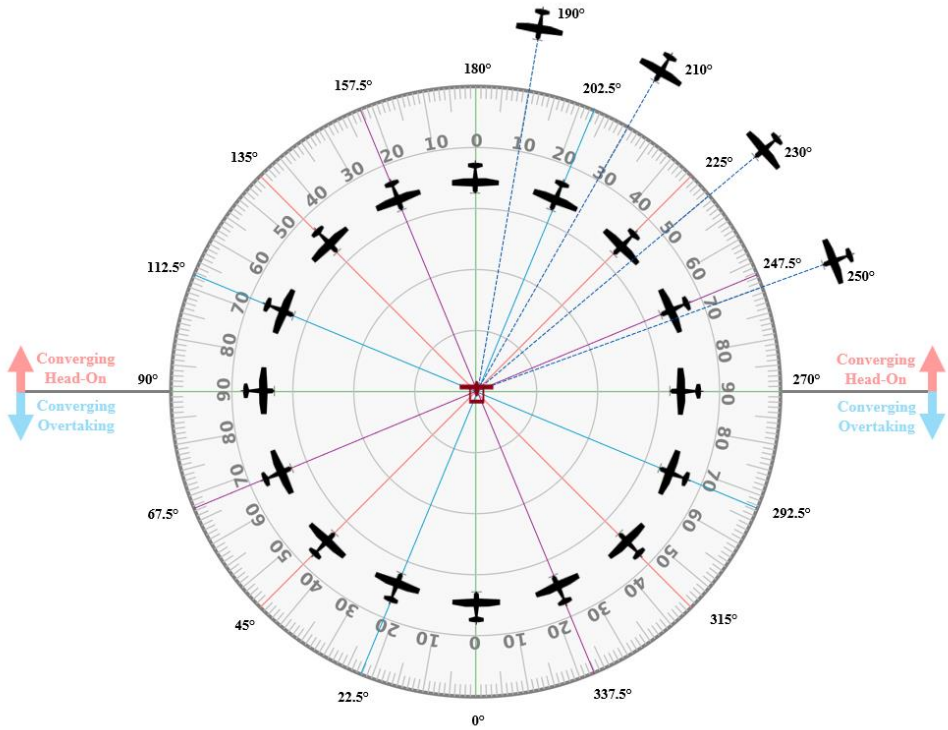


Figure 234. Non-cooperative/”Othership” Aircraft Heading Angle Definition.

To highlight the performance of the morphing potential field, the following figures highlight three scenarios when:

4) The detection range is large, causing the sUAS to successfully avoid the non-cooperative aircraft (Figure 235).
5) The detection range is an intermediate value, which still allows the sUAS to avoid the non-cooperative aircraft but performs a slightly more evasive maneuver (Figure 236).
6) The detection range is too low, causing a ROW violation between the sUAS and the non-cooperative aircraft along with a severe avoidance maneuver Figure 237).

In all three figures, the purple dots show the position of the “navigation points” used by the guidance algorithm. As shown, placement of these points on the left side of the crewed aircraft causes the guidance (avoidance) algorithm to favor passing to the left of the crewed aircraft. This aspect of the algorithm is particularly useful for the case of the crewed aircraft overtaking the sUAS: if the crewed aircraft pilot happens to see the sUAS and therefore turns right, the sUAS is more likely to turn left, thereby avoiding a potential ROWV or mid-air collision.

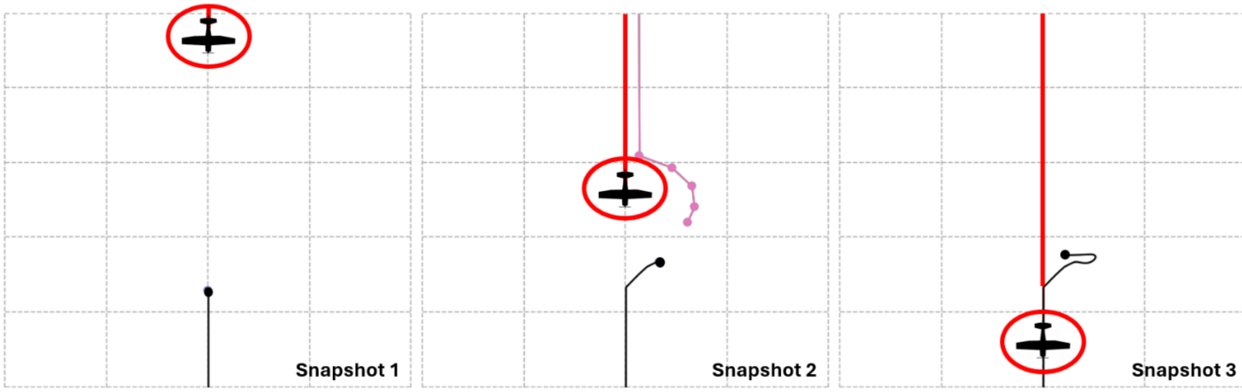


Figure 235. Large Detection Range with Successful Avoidance.

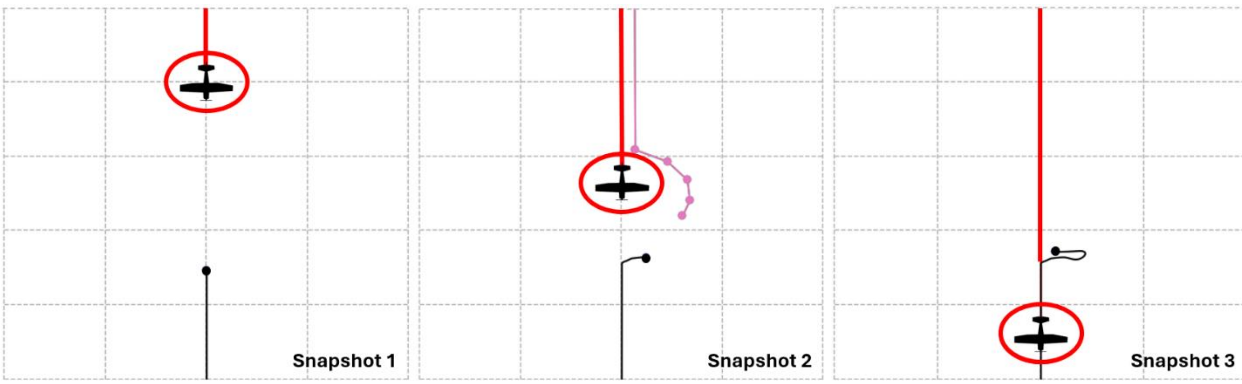


Figure 236. Intermediate Detection Range with Successful Avoidance.

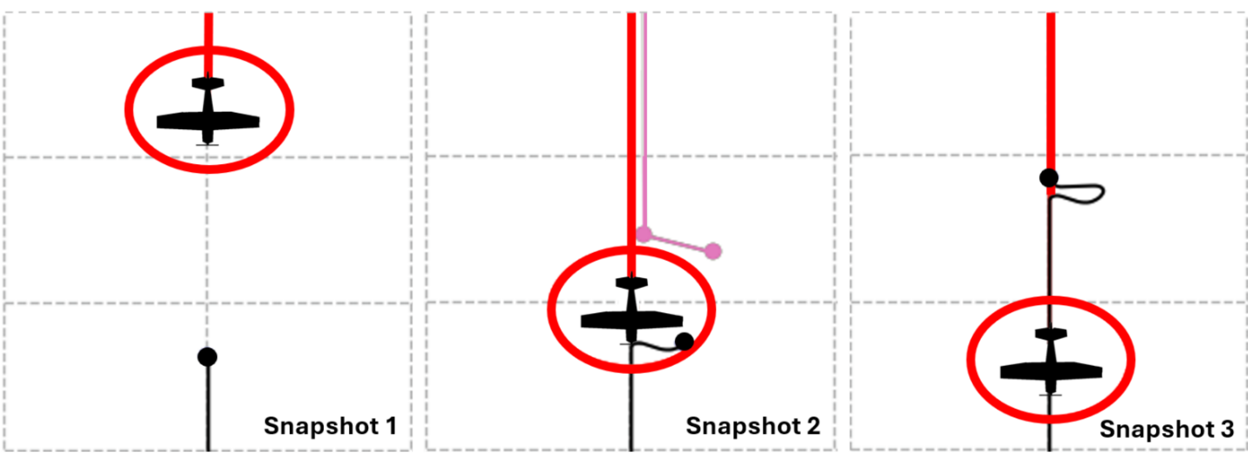


Figure 237. Low Detection Range with ROW Violation.

The following graphs highlight the results of the single sUAS vs. Crewed encounters. The graphs are a combination of three plots. One is the detection distance vs the minimum distance between the aircraft during the simulation. The other is the detection distance vs the percentage right-of-way violations (P_{ROWV}) and percentage of near midair collisions (P_{NMAC}). Any simulation case with a minimum distance of 2,000 ft or lower is considered a ROW violation, and any with a distance less than 500 ft is considered an NMAC.

The red region shows the percentage of simulations where the sUAS and the Cessna 172 nearly collided midair at the corresponding detection distance. The yellow region shows the percentage of simulations where the sUAS and the Cessna 172 violated the right of way requirement at the corresponding detection distance. The light green region shows simulations where the sUAS successfully began avoiding NMAC and ROW violations with the simulated crewed aircraft at certain heading angles. The darker green region shows simulations where the sUAS successfully avoided NMAC and ROW violations with the simulated crewed aircraft at all heading angles. Note that the demarcation between red, yellow, and green regions are based on detection distances used for the simulations, however required detection distances may be based on interpolation between the discrete detection distances. For instance, for the overtaking at the 0-degree heading case, the minimum detection distance to avoid NMAC is 4,800 ft.

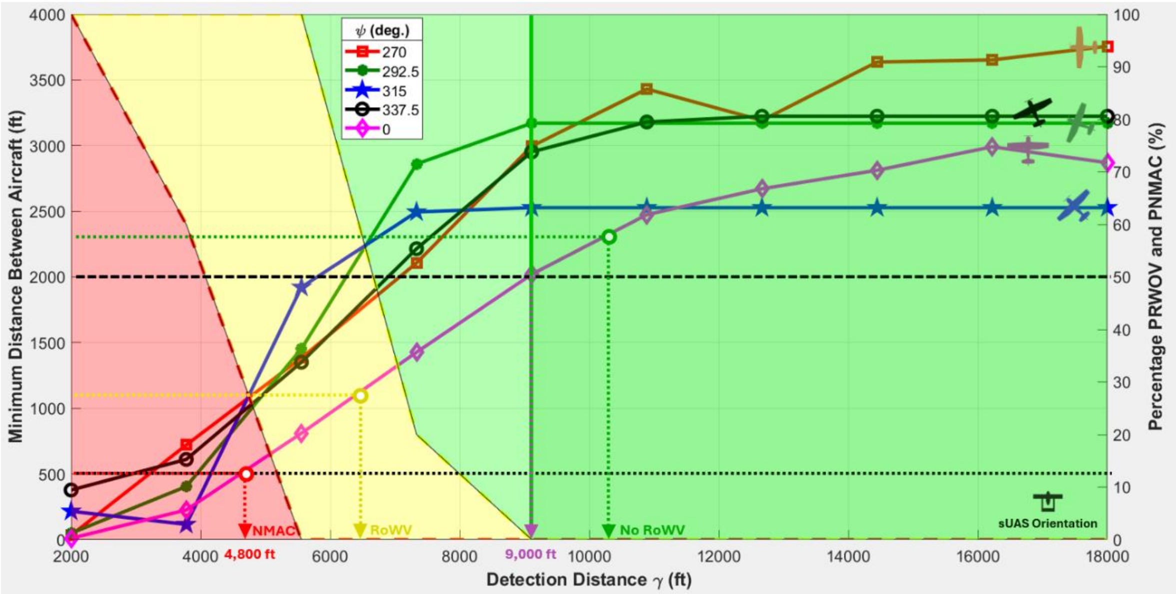


Figure 238. General Interactions 145 ft/s Crewed Aircraft Overtaking Single sUAS Flying at 45 ft/s Annotated for Clarity.

As an example of the type of results generated, Figure 239 shows the results of an non-cooperative aircraft flying at 170 ft/s overtaking a single sUAS with collision angles between 0 and 90 degrees. For there to be no ROW violations, the minimum detection distance was computed to be approximately 9,800 ft.

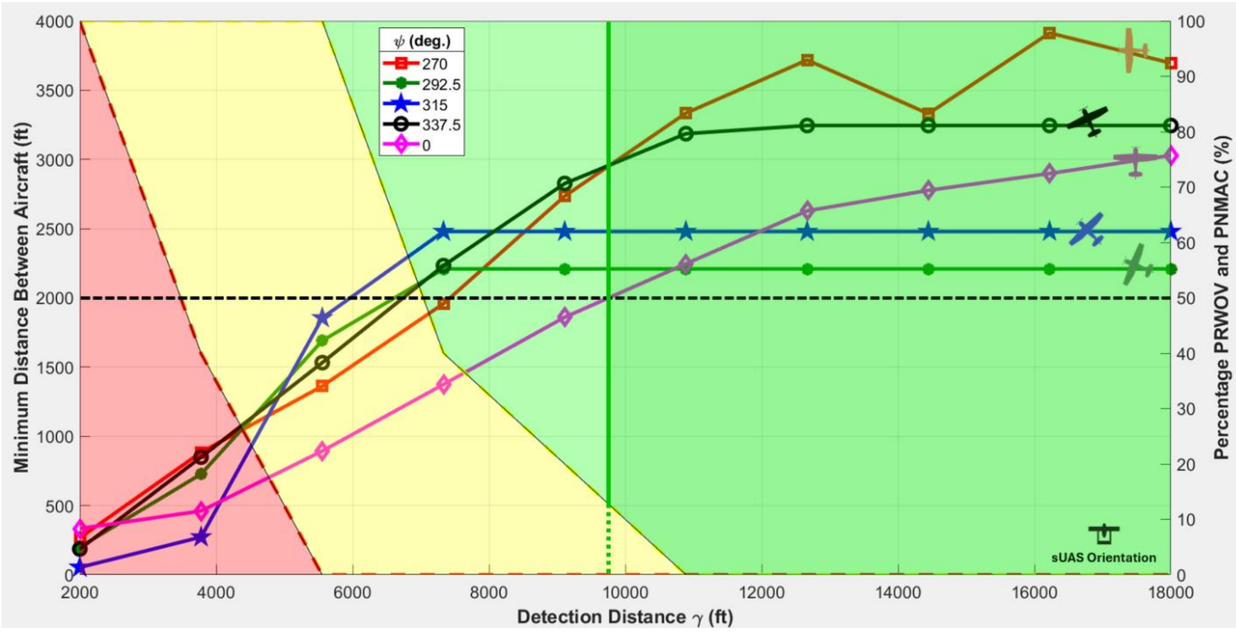


Figure 239. General Interactions 170 ft/s Crewed Aircraft Overtaking Single sUAS Flying at 45 ft/s.

Figure 240 shows the results of an non-cooperative aircraft flying towards a single sUAS for collision angles between 180 and 270 degrees, once again with the Cessna flying at 170 ft/s. Similar to the data from the overtaking-converging cases, the minimum detection distance must be at least 10,200 ft for the sUAS to avoid ROW violations. Note that the 270-degree encounter angle for both the overtaking-converging and head-on-converging case are identical. This is so the results can be compared more directly.

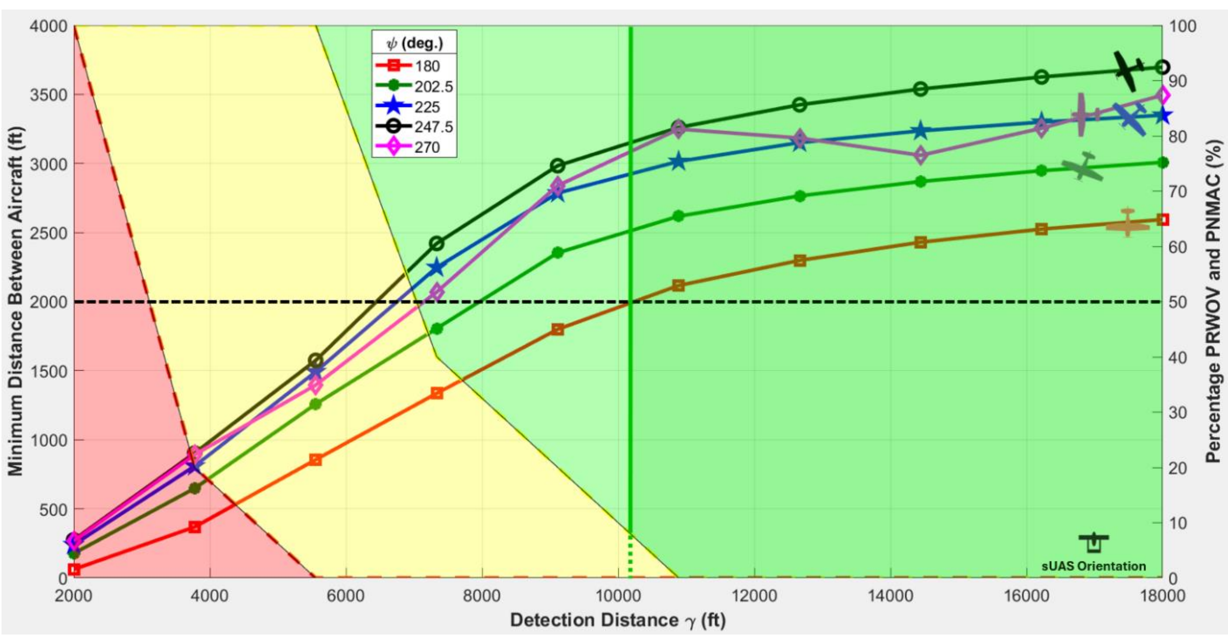


Figure 240. General Interactions 170 ft/s Crewed Aircraft Head-On with Single sUAS Flying at 45 ft/s.

Considering now the simulations with a higher, 195 ft/s, speed of the Cessna, for the head-on converging angles there are a greater number of overall ROW violations, while NMACs remain at the same percentage likelihood. At this higher closing speed, the required detection distance for a worst-case scenario is higher, at 11,100 ft. Figure 241 can compared directly with Figure 240 to see the differences caused by the different closing speeds. All graphs for the head-on-converging and overtaking-converging scenarios can be found in Appendix I.

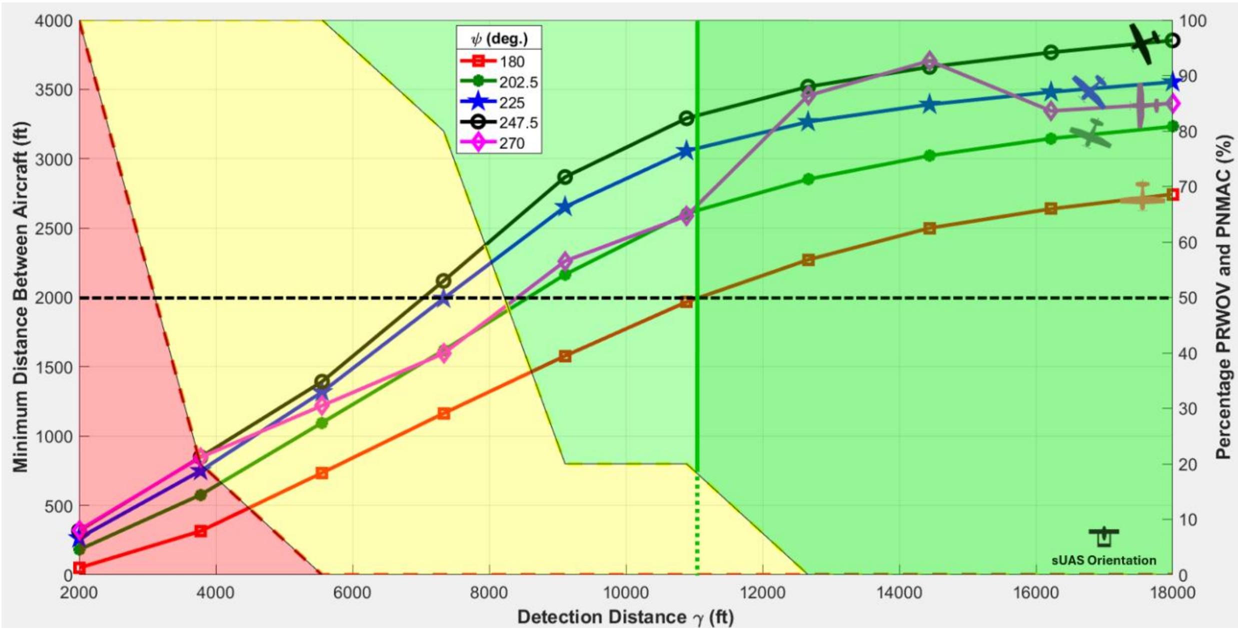


Figure 241. General Interactions 195 ft/s Crewed Aircraft Head-On Converging with Single sUAS Flying at 45 ft/s.

Table 134. Minimum Detection Distances for MPF Simulated Avoidance Maneuvers for sUAS vs Crewed Aircraft.

Highest Relative Velocity (ft/s)	Detection Distance (ft)	
	Head-On Converging	**Overtaking Converging**
190	9,100	9,100
215	10,200	9,800
240	11,100	10,800

As can be inferred from Table 134, the minimum required detection distances for MPF simulated avoidance maneuvers for the sUAS are lower for a slower incoming crewed aircraft and higher for a faster incoming crewed aircraft. Additionally, the Head-On converging scenarios pose a greater risk for collisions and thus on average require greater detection distances for the same crewed aircraft speed as compared to the Overtaking converging scenarios.

H.1.1.2.1.2 Roll and Yaw Rates During Simulated Encounters

Based on all the General Interactions studied, the highest yaw and roll rates required for a successful avoidance maneuver are given in Table 135. Roll rates greater than 45 degrees/s and yaw rates at or above 20 degrees/s were considered undesirable. These values approach the threshold for being considered undesirable but are still within the maneuvering capabilities of the SkyHunter UAS.

Table 135. Worst Case Roll and Yaw and Roll Rates for General Interaction Simulations.

Velocity, $\boldsymbol{V_{C172}}$ (ft/s)	Roll Rate, $\dot{\boldsymbol{\phi}}$ (deg/s)	Yaw Rate, $\dot{\boldsymbol{\psi}}$ (deg/s)	Proximity (ft)	Detection Distance, DD (ft)	Heading, $\boldsymbol{\psi_{sUAS}}$ (deg)
145	41	18	3,040	18,000	0
145	24	19	2,530	7,300	45
170	43	19	3,030	18,000	90
195	32	16	3,060	10,800	135
195	28	20	2,750	9,100	67

There are only a few cases where an sUAS has a higher than recommended roll rate. Yaw Rates above 20 degrees/s and Roll Rates above 45 degrees/s are highlighted in yellow as possible points of concern for the integrity of the sUAS. These cases represent situations where the detection distance was very low, causing a drastic change in sUAS attitude due to attempting an avoidance maneuver. This is due to the morphing potential field, as the strength of the potential field increases with proximity. Detection of the non-cooperative aircraft at the last second causes the sUAS to experience a very strong potential field which leads to severe avoidance maneuvers and undesirable attitude rates.

A graphical example of the worst sUAS attitude rates found can be seen in Figure 242 and Figure 243. They show the roll rates and yaw rates experienced by a single sUAS while attempting to prevent a ROW violation at different heading angles. The direct relationship between low detection distances and undesirable attitude rates can be clearly inferred, as the sUAS makes sudden movements with little time to prevent violations. It can also be seen that most of the attitude rates lie in the acceptable range with no rates approaching adverse levels.

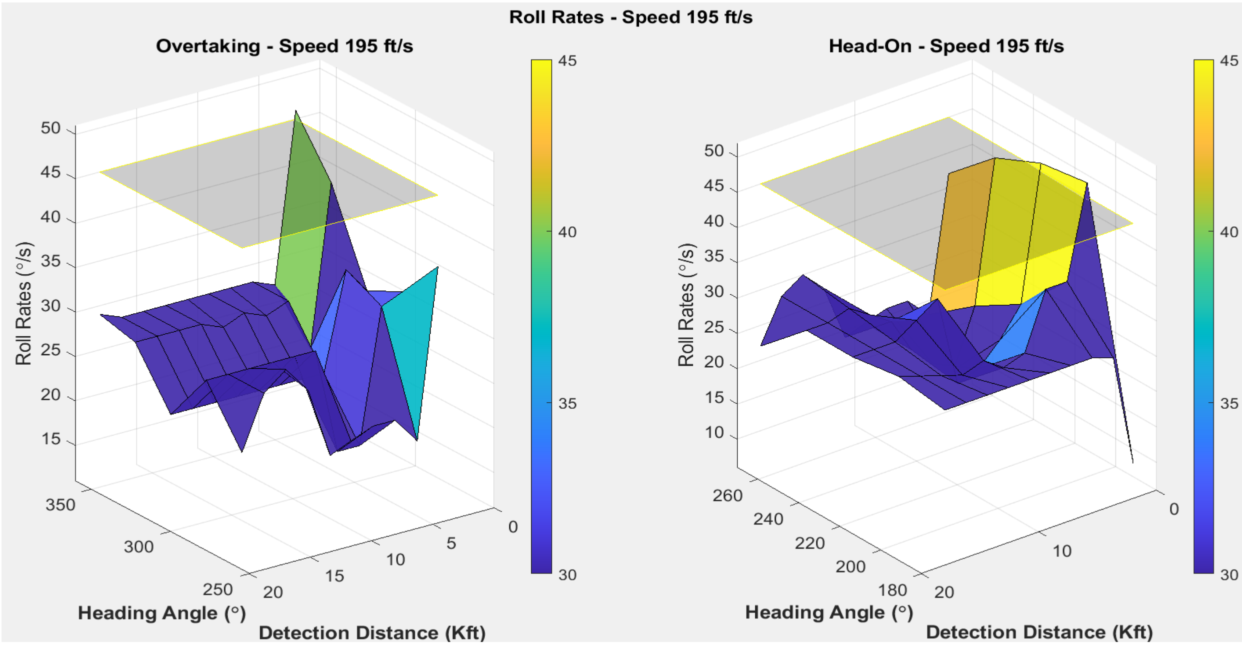


Figure 242. Maximum Attained Roll Rates of 195 ft/s Crewed Aircraft Head-On Converging with Single sUAS Flying at 45 ft/s.

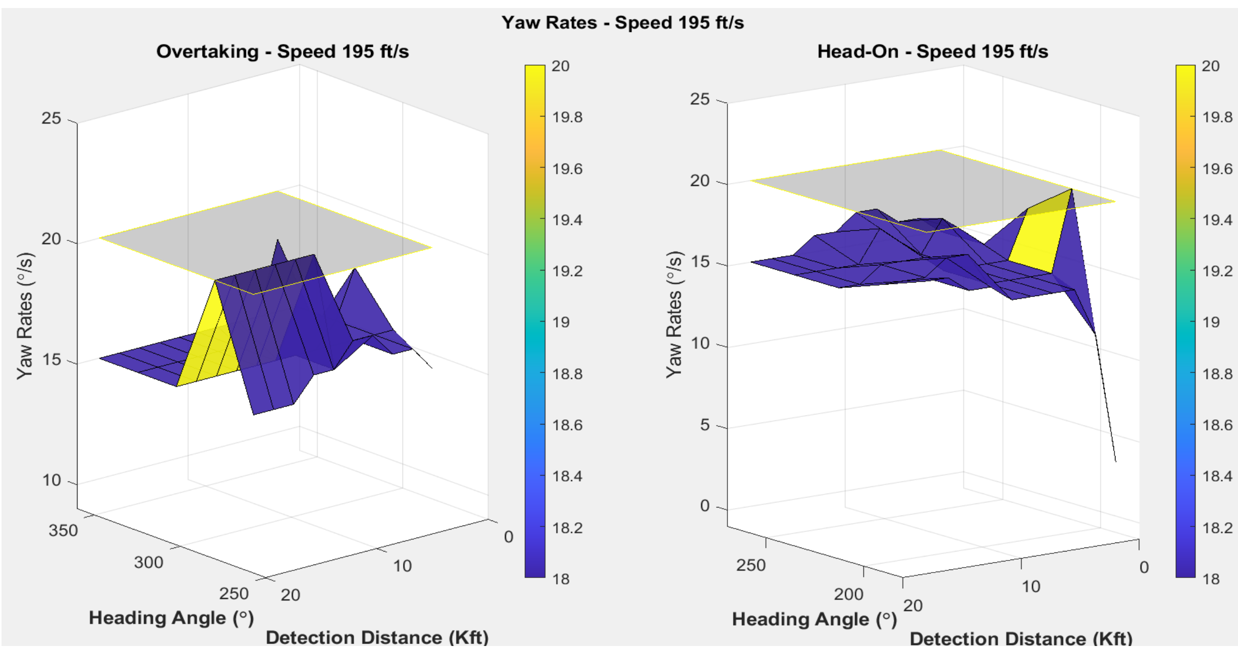


Figure 243. Maximum Attained Yaw Rates of 195 ft/s Crewed Aircraft Head-On Converging with Single sUAS Flying at 45 ft/s.

H.1.1.2.1.3 Avoidance Using the Loiter Maneuver

An alternative to using the MPF avoidance concept is to, for encounters converging from one side or the other, simply have the sUAS or sUAS formation *loiter* to wait for the crewed aircraft to pass by. Based on a comparison of the avoidance performance of the MPF algorithm and the loiter algorithm, it has been found that conditional use of one or the other would reduce the minimum required detection distance. However, whereas the MPF algorithm works in all cases, the loiter algorithm does not work in a wide range of head-on and overtaking cases because ROW violations would occur in these cases.

Once the non-cooperative Cessna is detected by the sUAS, the sUAS loiters about its current position until the distance between the non-cooperative crewed aircraft and the sUAS increases. An example of a successful loiter is shown in Figure 244.

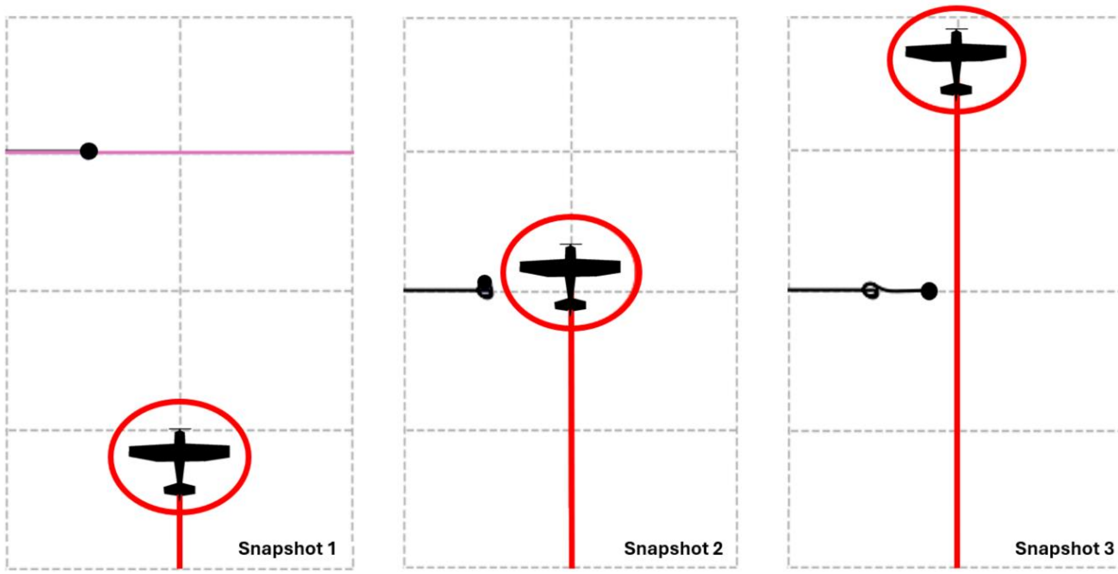


Figure 244. Successful Loiter Maneuver.

This loiter maneuver has the same deviation from the sUAS path no matter the non-cooperative aircraft speed, as the sUAS enters the loiter as soon as the crewed aircraft is detected. The figure below highlights two loiter maneuvers at the same detection distance and incoming crewed aircraft angle, with a 145 ft/s Cessna shown on the left and a 195 ft/s Cessna on the right.

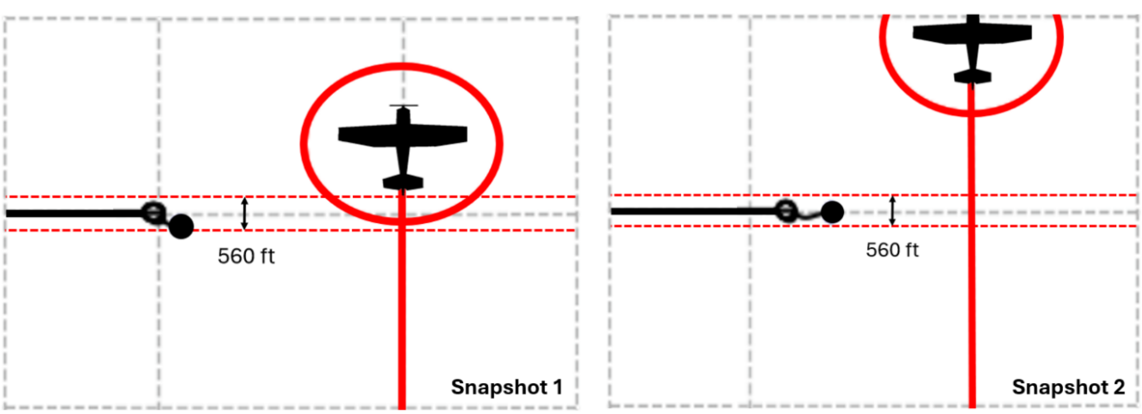


Figure 245. Maneuver Width at Varying Cessna Speeds.

The diameter of the loiter circle is roughly 560 ft, and this is typically the maximum the aircraft diverges from its flight path. In some cases, due to the nonlinearity of the aircraft encounter, the sUAS will make a wide turn to make it back on its flight path. This is due to the location that the sUAS exits the loiter circle from, and some examples are provided below. On the right the loiter maneuver with a preferable exit from the loiter circle, and on the left is a loiter maneuver with a non-preferable exit. In this case, the non-preferable exit creates a 990 ft divergence from the sUAS flight path.

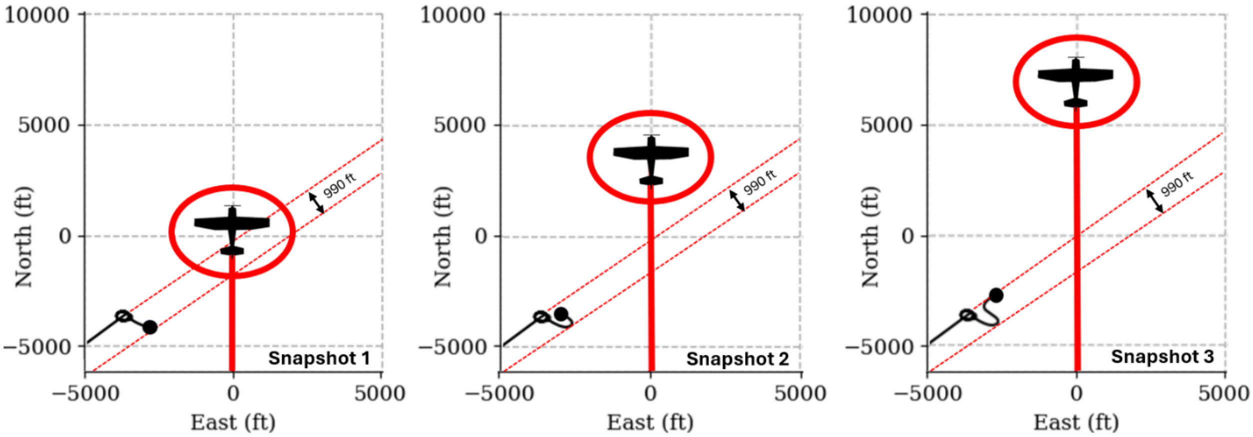


Figure 246. Loiter Encounter When sUAS Departs Loiter in an Aspect that Requires a Lateral Maneuver to Return to its Intended Path.

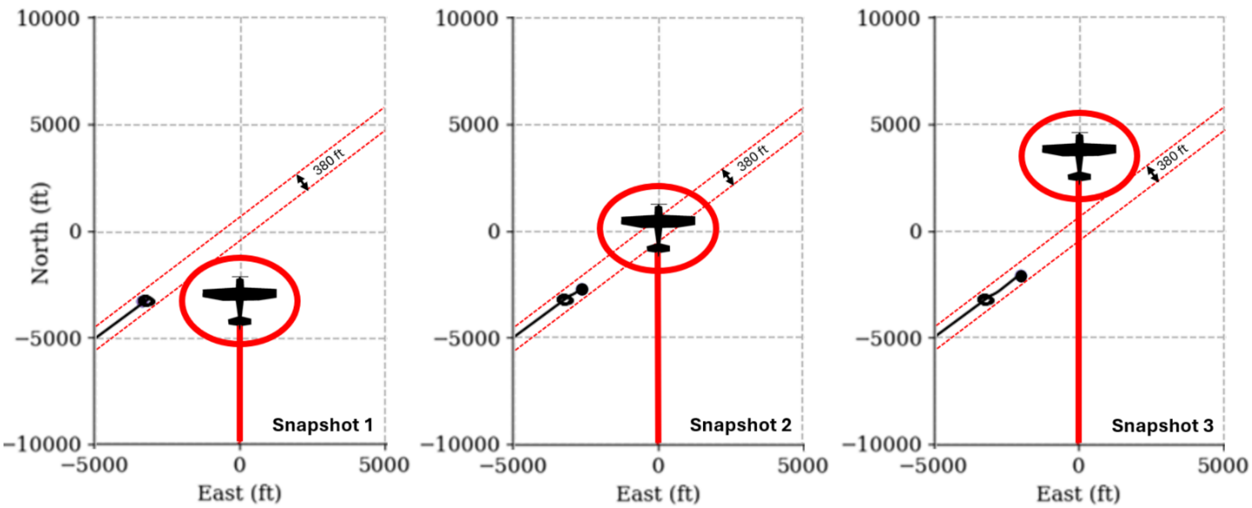


Figure 247. Loiter Encounter When sUAS Departs Loiter in a Favorable Aspect that Does Not Require a Lateral Maneuver to Return to its Intended Path.

This new loiter maneuver was studied to compare the alterative collision avoidance logic with MPF logic. When implementing this logic, it was known that it would not be successful for substantially head-on and overtaking crewed aircraft Encounters. Table 136 shows the minimum required detection distance for a range of encounter angles for the loiter maneuver.

Table 136. Minimum Required Detection Distances for Loiter Maneuvers for a single sUAS.

Maximum Relative Velocity (ft/s)	Substantially Head-On (135° to 225°)	Converging from Right (225° to 315°)	Substantially Overtaking (315° to 45°)	Overtaking from Left (45° to 135°)

190	Fails	13,200	Fails	9,200
215	Fails	12,200	Fails	8,700
240	Fails	13,800	Fails	9,900

H.1.1.2.1.4 Comparison of MPF and Loiter Avoidance Strategies

As can be seen in Table 137, the minimum required detection distance values are lower using a loiter maneuver than a MPF logic only for a certain section of overtaking heading angles. The loiter maneuver fails for heading angles that are substantially head-on and substantially overtaking. Additionally, it produces a higher minimum required detection distance value for all head-on converging heading angles, as compared to the distance values calculated using the MPF logic. This is because when the loiter maneuver gets initiated, the sUAS stops and loiters directly in the path of the incoming crewed aircraft. One solution to this problem would be to have the sUAS travel a certain perpendicular distance to the incoming crewed aircraft's flight path before loitering, so it does not loiter in the path of the incoming aircraft and successfully avoids it. This would increase the range of heading angles for which the loiter maneuver would work. However, such a maneuver was not simulated and analyzed by the University of Kansas. The sections of heading angles for which the loiter maneuver works better than the MPF logic can be seen in Figure 248.

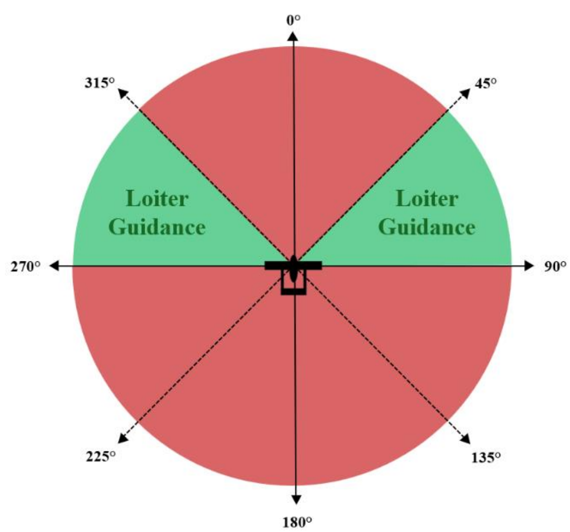


Figure 248. Heading Angles Where Loiter Guidance Works Better than Morphing Potential Field Guidance.

Comparing Table 136 and Table 137, it can be seen while the MPF avoidances always work, the loiter guidance produces a lower detection distance requirement for heading angles between 45 and 90 and 270 and 315.

If the autopilot uses the computed relative heading angle, which is possible once an othership has been detected nearby, the autopilot can then select the best avoidance algorithm. For such a case, Table 137 gives the minimum detection distances for the combined MPF/Loiter avoidance algorithms.

Table 137. Minimum Detection Distances for Combined MPF/Loiter Avoidance Algorithms.

Maximum Relative Velocity (ft/s)	Head-on Converging (MPF) (180º to 270º) (ft)	Substantially Overtaking (MPF) (315º to 0º) (ft)	Overtaking from Left (Loiter) (270º to 315º) (ft)
190	9,100	9,100	9,200
215	10,200	9,800	8,700
240	11,100	10,800	9,900

H.1.1.2.2 Multiple sUAS vs Crewed Aircraft

For the General Interaction encounters between multiple sUAS and crewed aircraft, the same head-on- converging, and overtaking-converging cases were investigated. Two sUAS in formation flight—a potential remote-sensing or mapping formation—were considered in these simulations. The two sUAS are laterally separated by 500 ft and maintain the same altitude over the full simulation. Lateral separation is considered to be the more challenging scenario to ensure separation. Aircraft separated *in trail* would be easier to ensure separation from other traffic. When experiencing the morphing potential field, there are some cases in which the sUAS are predicted to collide with each other to avoid the crewed aircraft. These cases occur rarely, only when a low detection distance causes a severe avoidance maneuver. A possible solution is to modify the simulation to command the sUAS to different altitudes either when appropriate or as soon as the crewed aircraft is detected. However, the determination of minimum detection distance to avoid a ROWV is not affected by not separating the sUAS vertically. Such a separation maneuver is an “easily-implemented” operation, in that the sensors required are either GPS or LIDAR, or both. With these “proximity sensors”, the multiple sUAS can be commanded to maneuver to avoid each other vertically.

To highlight the performance of the morphing potential field with multiple sUAS, Figure 249 shows a successful avoidance maneuver with the Cessna flying at 170 ft/s with a large detection range.

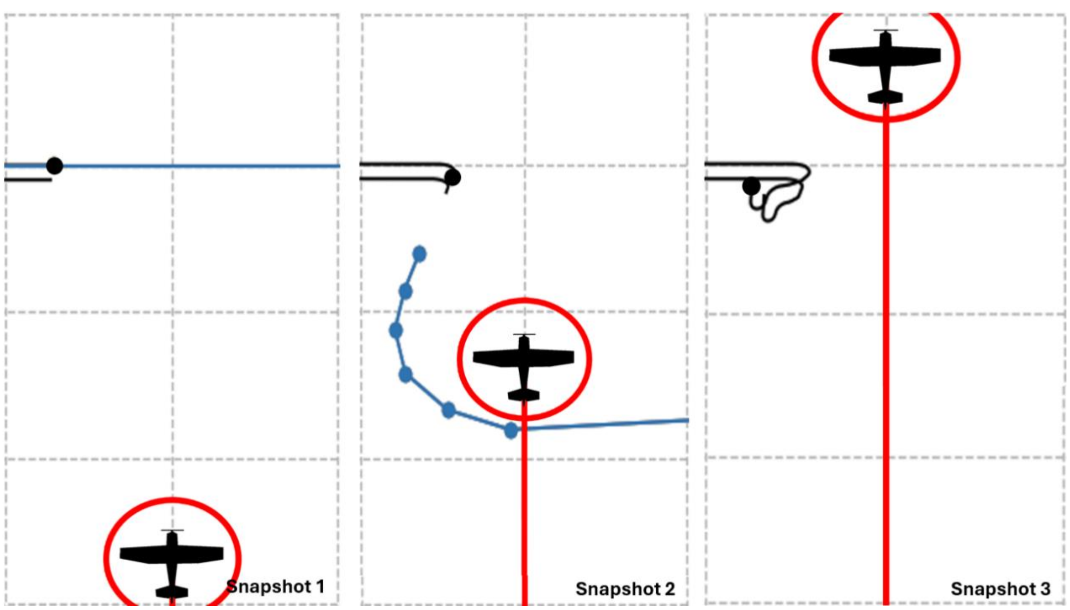


Figure 249. Two sUAS Flying in Formation with Successful Maneuver.

For the General Interaction, multiple sUAS vs Crewed aircraft scenario, the data shows that a 10,600 ft detection distance for the multiple sUAS would mitigate the probability of NMACs and ROW violations. NMACs appear more likely to occur in the overtaking-converging configuration at lower detection distances while ROW violations appear more likely to occur in the head-on converging configuration at lower detection distances.

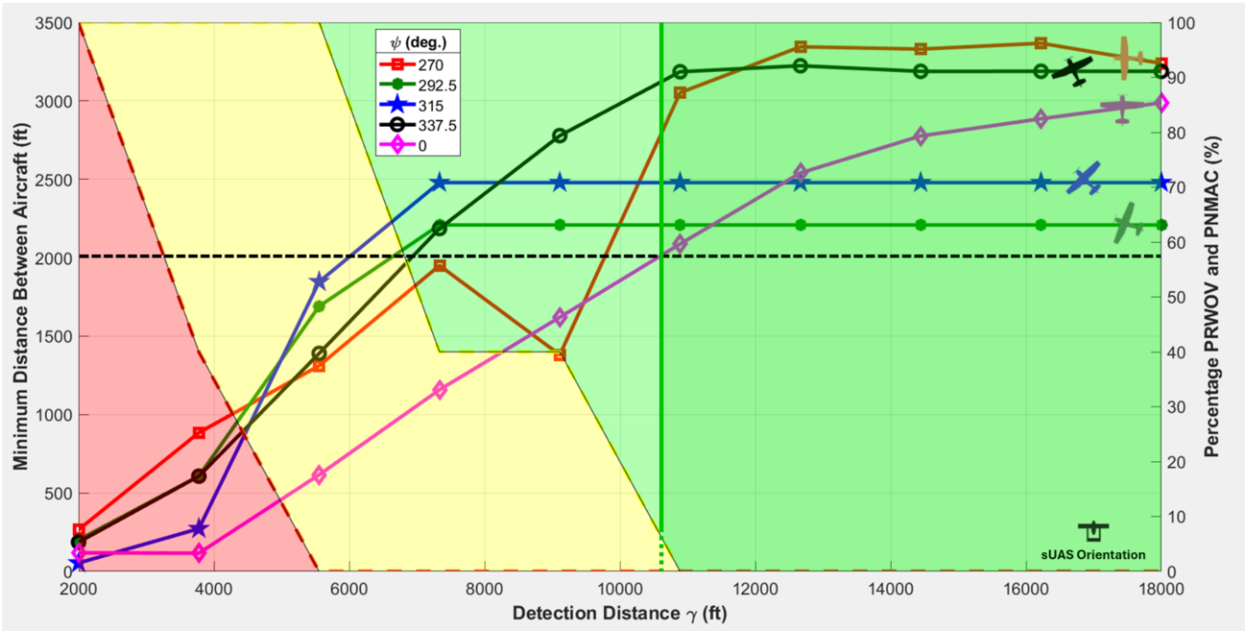


Figure 250. General Interactions 170ft/s Crewed Aircraft Overtaking Multiple sUAS Flying at 45 ft/s.

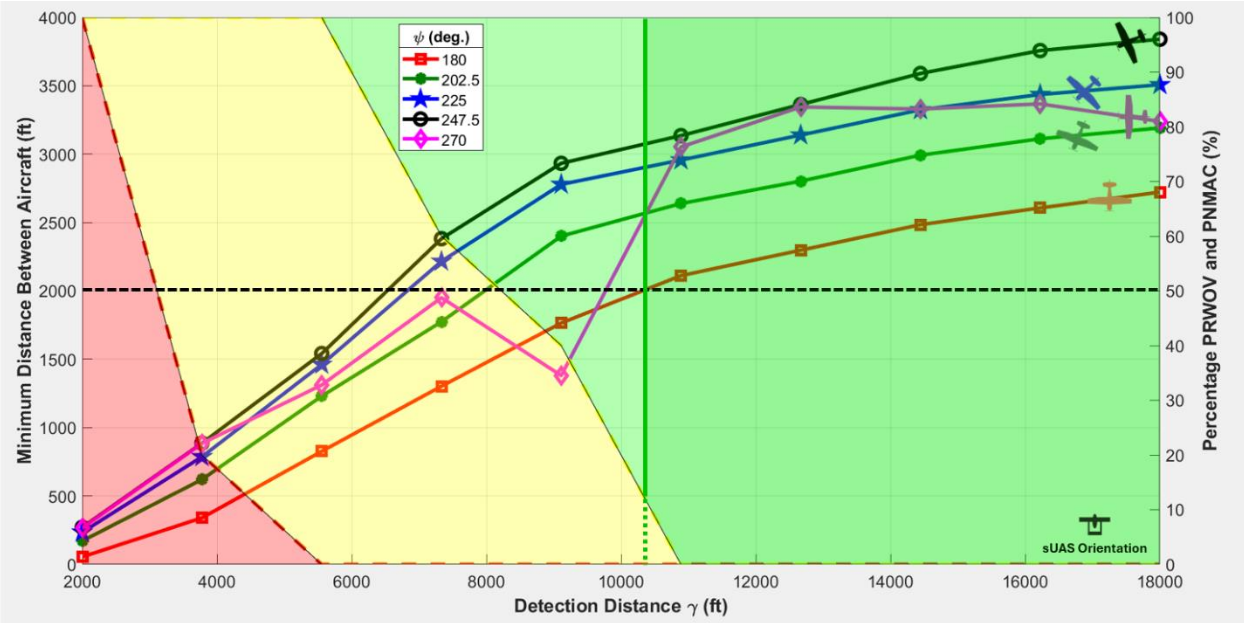


Figure 251. General Interactions 170 ft/s Crewed Aircraft Head-On Converging with Multiple sUAS Flying at 45 ft/s.

In both above figures, a sudden drop in minimum distance between aircraft occurs during head-on and overtaking scenarios between the 8,000 and 10,000 ft detection distance. This is due to a nonlinearity caused by using the morphing potential field guidance. When comparing results for different closing speeds of the non-cooperative aircraft, many results align closely with those for the single sUAS. For instance, for lower closing speeds there are less ROW violations even with multiple sUAS, but the minimum required detection distance is around 10,600 ft. However, at higher closing speeds with the non-cooperative aircraft approaching the multiple sUAS head-on and overtaking, the worst-case scenario requires a larger detection distance of around 11,200 ft. An example of the higher closing speed at the overtaking angles is highlighted in Figure 252.

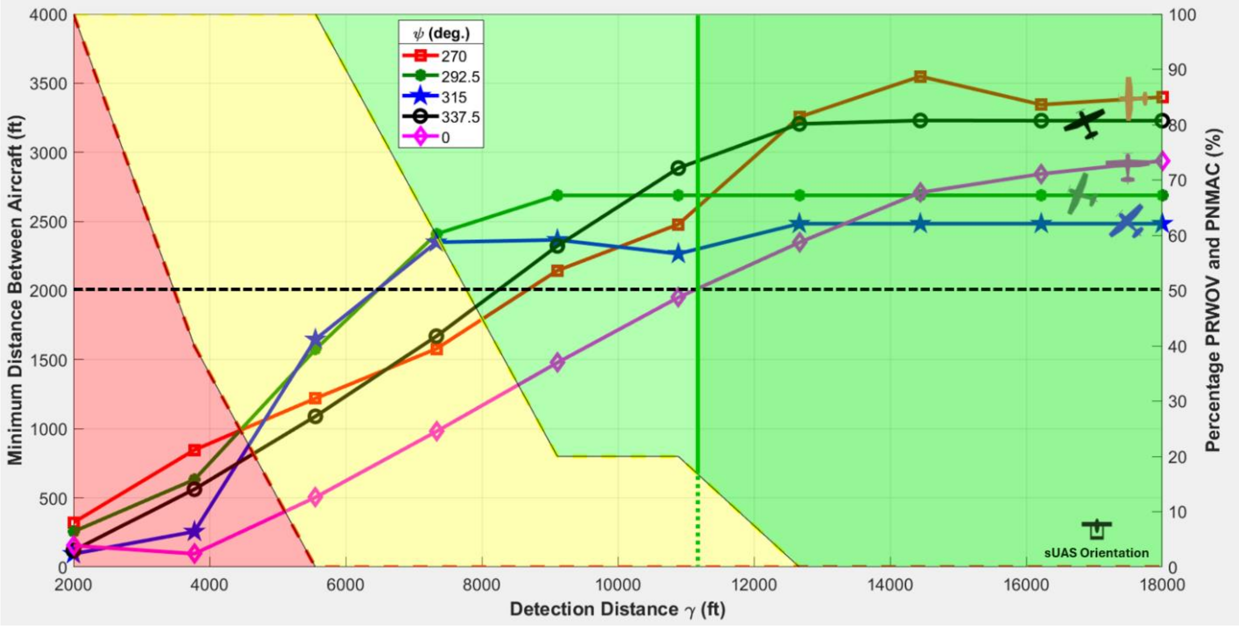


Figure 252. General Interactions 195 ft/s Crewed Aircraft Overtaking Multiple sUAS Flying at 45 ft/s.

From Table 138, the minimum required detection distances for MPF simulated avoidance maneuvers for the multiple sUAS are lower for a slower incoming crewed aircraft, and higher for a faster incoming crewed aircraft. Additionally, the Head-On converging scenarios pose a greater risk for collisions and thus on average require greater detection distances for the same crewed aircraft speed as compared to the Overtaking converging scenarios. The trends seen with multiple sUAS are similar to the trends seen with a single sUAS.

Table 138. Minimum Detection Distances for MPF Simulated Avoidance Maneuvers for Multiple sUAS vs Crewed.

Highest relative velocity (ft/s)	Detection Distance (ft)	
	Head-on Converging	**Overtaking Converging**
190	9,200	9,100
215	10,300	10,100
240	11,200	11,100

H.1.1.2.2.1 Roll and Yaw Rates During Simulated Encounters

Table 139 displays the highest roll and yaw rates experienced by either sUAS. Note that some of the roll and yaw rates are slightly above the undesirable threshold, likely due to the added nonlinearity of multiple sUAS flight. These undesirable rates are only experienced briefly during avoidance maneuvers. Furthermore, loss of control from undesirable rates mainly occurs when the direction of roll/yaw changes (oscillatory behavior). In the case of these simulations, however, the undesirable rates remain exclusively positive or exclusively negative until they return to 0, signifying a successful maneuver and no loss of control.

Table 139. Worst Case Roll and Yaw and Roll Rates for General Interaction Simulations.

Velocity, $\boldsymbol{V_{C172}}$ (ft/s)	Roll Rate, $\dot{\boldsymbol{\phi}}$ (deg/s)	Yaw Rate, $\dot{\boldsymbol{\psi}}$ (deg/s)	Proximity (ft)	Detection Distance, DD (ft)	Heading, $\boldsymbol{\psi_{sUAS}}$ (deg)
145	48	21	2,950	9,100	22
170	25	21	2,210	7,300	67
170	43	19	2,990	18,000	0
195	47	24	2,140	9,100	90

All the simulations were analyzed, and it was found that the yaw and roll rates for the sUAS are well within safe ranges while the sUAS or multiple sUAS is evading the crewed aircraft. There are only a few cases where an sUAS in the multiple sUAS formation has a higher than recommended roll rate. Yaw rates above 20 degrees/s and roll rates above 45 degrees/s are highlighted in yellow as possible points of concern for the integrity of the sUAS. Again, these cases represent situations where the detection distance was very low, causing a drastic change in sUAS attitude due to attempting an avoidance maneuver.

A graphical example of the worst sUAS attitude rates found can be seen in Figure 253 and Figure 254. They show the roll rates and yaw rates experienced by multiple sUAS while attempting to prevent a ROW violation at different heading angles. The direct relationship between low detection distances and undesirable attitude rates can again be clearly inferred, as the sUAS makes sudden movements with little time to prevent violations. It can also be seen that most of the attitude rates lie in the acceptable range with no rates approaching adverse levels.

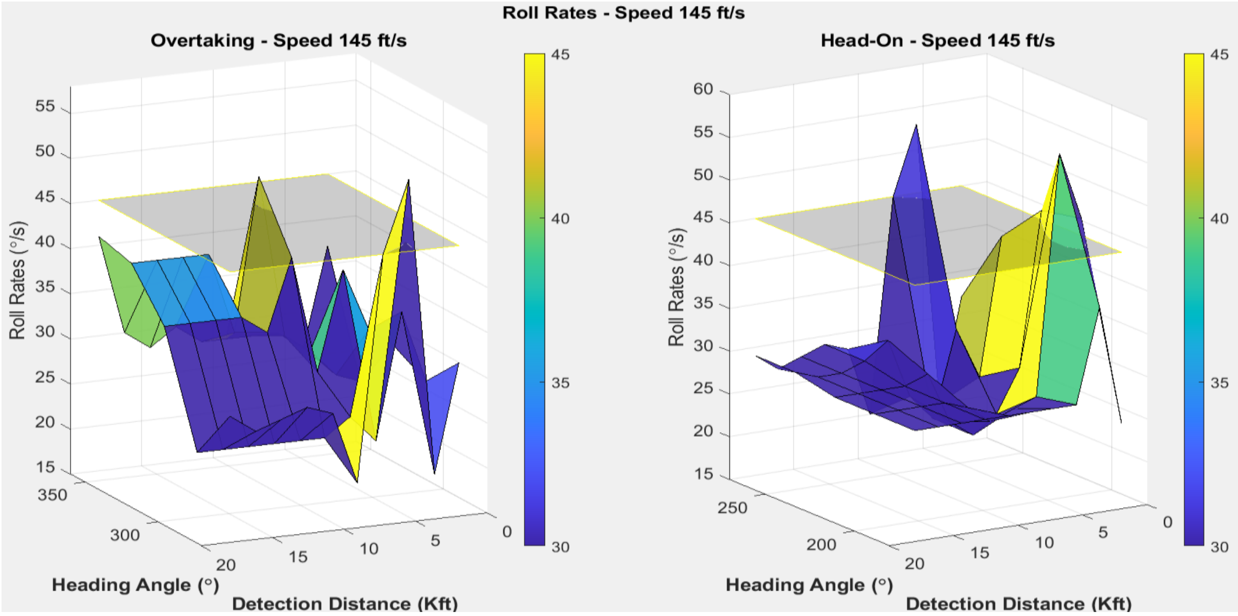


Figure 253. Maximum Attained Roll Rates of 145 ft/s Crewed Aircraft Head-On Converging with Multiple sUAS Flying at 45 ft/s.

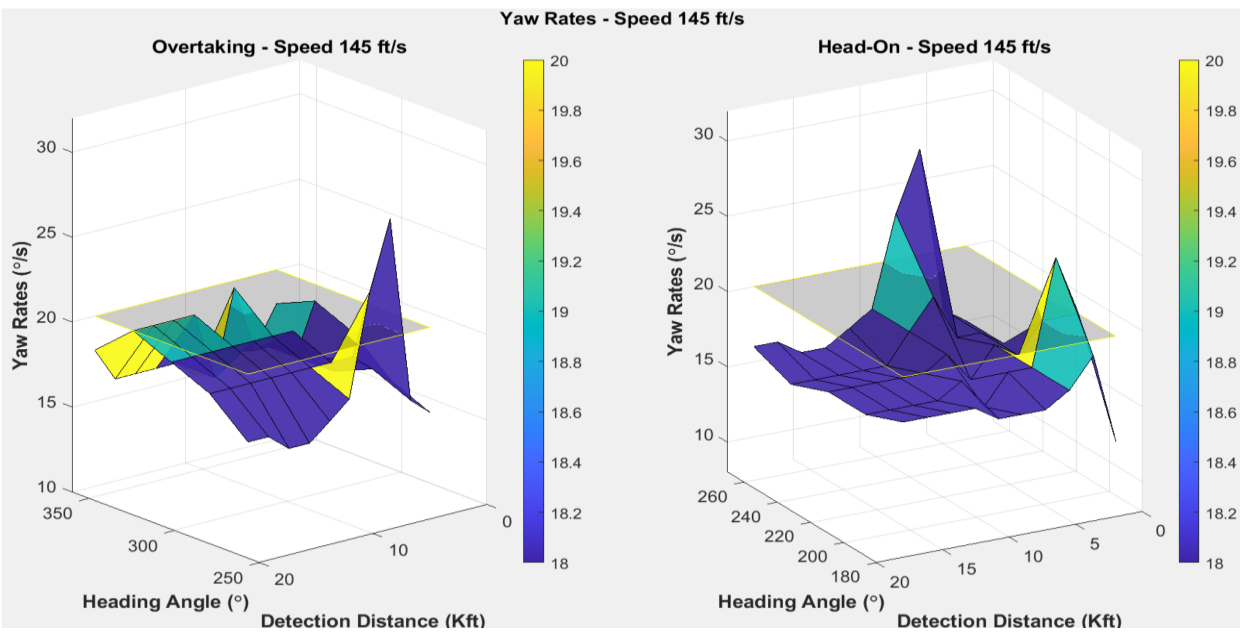


Figure 254. Maximum Attained Yaw Rates of 145 ft/s Crewed Aircraft Head-On Converging with Multiple sUAS Flying at 45 ft/s.

H.1.1.2.3 Observations on General Interaction Simulations

When observing the effect of different closing speeds for head-on and overtaking encounters, a few trends were noticed.

- For both single and multiple sUAS, a lower closing speed resulted in less ROW violations overall
- At intermediate crewed aircraft speeds, the multiple sUAS resulted in a higher number of ROW violations than the single sUAS.
- At higher crewed aircraft speeds against a single sUAS, head-on encounter angles required a higher detection distance to perform a worst-case ROWV avoidance maneuver.
- For multiple sUAS, both head-on and overtaking encounter angles require a higher detection distance to perform a successful avoidance maneuver; thus, a multiple sUAS is more susceptible to ROW violations, especially higher crewed aircraft speeds.

After investigating the General Interaction encounter scenarios, the following observations have been made:

- For all encounter angles for an non-cooperative aircraft at a relatively low speed (145 ft/s), both single and multiple sUAS must be able to detect the non-cooperative aircraft at 9,200 ft in a worst-case encounter.
- For all encounter angles for an non-cooperative aircraft at an intermediate speed (170 ft/s), both single and multiple sUAS detection distance must be 10,300 ft.
- For all encounter angles for an non-cooperative aircraft at higher speed (195 ft/s), single and multiple sUAS require a larger detection distance to perform successful avoidance maneuvers, at 11,200 ft.

Table 140. Required Detection Distance Based on Highest Relative Velocity.

Highest Relative Velocity (ft/s)	Required Detection Distance Single sUAS (ft)	Required Detection Distance Multiple sUAS (ft)
190	9,100	9,200
215	10,200	10,300
240	11,100	11,200

Figure 255 shows a graphical representation of the required minimum detection distances listed in Table 140.

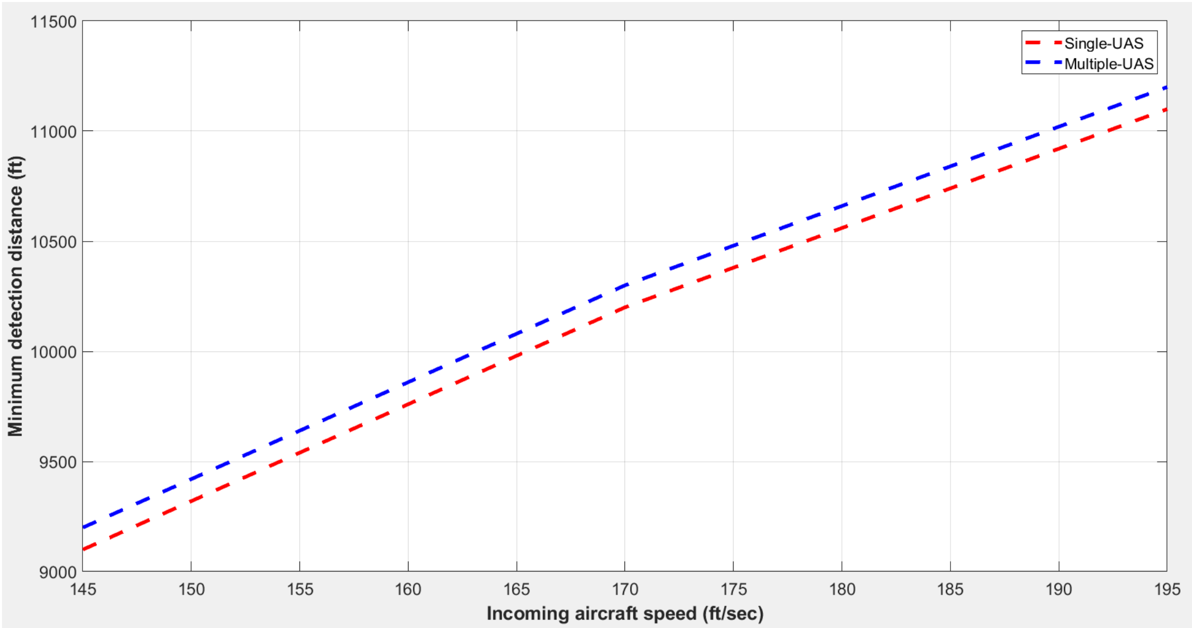


Figure 255. Required Minimum Detection Distance Based on Incoming Aircraft Speed.

Over the range of incoming aircraft speeds simulated for by the University of Kansas Flight Research Team, there appears to be fairly linear relationship between the minimum detection distance required to prevent a ROW violation and incoming crewed aircraft speed. To determine the required detection distance for combinations of sUAS and non-cooperative aircraft speed not simulated here, it would be desirable to have a non-dimensional equation. However, the y-intercept of the relationship could change dramatically if more incoming aircraft speeds were simulated that were higher or lower than the speeds that have been tested for. Additionally, a higher discretization in the incoming aircraft speeds could introduce non-linearities that do not display themselves currently. Note that considering a linear relationship with the given data set would produce an overly conservative approximation.

H.1.1.2.4 Recommendations Affecting Right of Way Rules

- When a sUAS encounters a crewed aircraft from a head-on-converging heading angle, the sUAS should make an avoidance maneuver by banking to its right to avoid the incoming aircraft. Thus, even if the crewed aircraft pilot makes a last-minute observation of the sUAS and makes a right turn to avoid it, the sUAS and the aircraft will completely avoid each other.
- When a sUAS encounters a crewed aircraft from an overtaking-converging heading angle, if the crewed aircraft turns to the right, there is some value in allowing the sUAS to turn to the left; this would prevent a situation where the sUAS and the crewed aircraft turn into each other creating a ROWV or even an NMAC. However, if the sUAS turns right, the avoidance algorithm may require a more aggressive turn to prevent a ROWV if the dynamics of the sUAS allows it.

H.1.1.3 Reserved Airspace Simulations for Flight in a Corridor

In the flight in a corridor scenario, the sUAS or multiple sUAS is flying along the center of a reserved airspace corridor. This reserved airspace corridor is representative of an observation mission for rail or power lines over a long distance. The single sUAS or multiple sUAS is geographically constrained by the reservation such that it cannot exit the reserved airspace. Because of this restriction, the sUAS or multiple sUAS must avoid the crewed intruder while remaining inside of the reserved airspace. The recommendations and results for the flight in a corridor scenario are based upon the simulated avoidance maneuvers in the General Interactions scenario, which cover the full range of encounter angles for a sUAS flying along a straight line.

H.1.1.3.1 sUAS Encounters with a Crewed Aircraft in a Corridor

As shown in Figure 256, the sUAS flies along the center line of the corridor. The crewed aircraft will then enter the corridor for head-on-converging, and overtaking-converging scenarios, prompting the sUAS to perform an avoidance maneuver--without leaving the corridor. Due to the similarities with General Interaction simulations, it was decided to *derive* the required corridor width from the maximum deviation of an sUAS from its intended path (over all encounter angles), that is, distance *b* in the figure below. The required minimum width of a corridor, *W*, would then be twice the distance *b*. As noted earlier, since the autonomous sUAS is programmed to return to its desired flight path after an encounter, if the corridor is sufficiently wide, there will be no ROWV. The required width of the corridor then is a function of the same parameters of the General Interactions study, that is, relative velocity, encounter angle and the detection distance. This would guarantee the sUAS does not leave the corridor even for the most challenging encounters if traffic detection occurs at a distance greater than or equal to the minimum required detection distance.

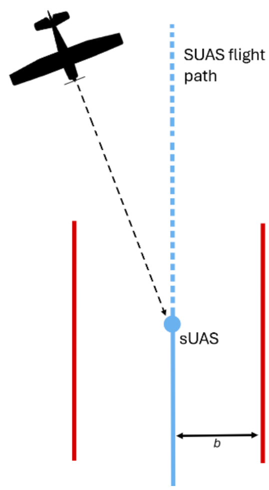


Figure 256. sUAS Encounter with a Crewed Aircraft While Flying in a Reserved Airspace Corridor.

H.1.1.3.1.1 MPF Maneuvers for sUAS Encounters with a Crewed Aircraft in a Corridor

From inspection of the General Interaction trajectories, it is clearly seen that, in general, as the detection distance gets larger, so does the divergence from the original sUAS flight path. As such, the data for head-on-converging and overtaking-converging encounter angles, all non-cooperative aircraft speeds, and both single and multiple sUAS, were used to find the largest deviation from the intended flight path in the avoidance maneuver.

As an example, in Figure 257on the left, for an sUAS encountering a crewed aircraft traveling at 145 ft/s at a 270-degree heading, the largest divergence from the straight-line path of the single sUAS is roughly 4,500 ft. Based on this information, the safest corridor width would be twice this, or 9,000 ft. On the right, for the same encounter angle, but with a Cessna traveling at 195 ft/s, the maneuver from the original flight path is only 3,210 ft, meaning a narrower corridor is needed.

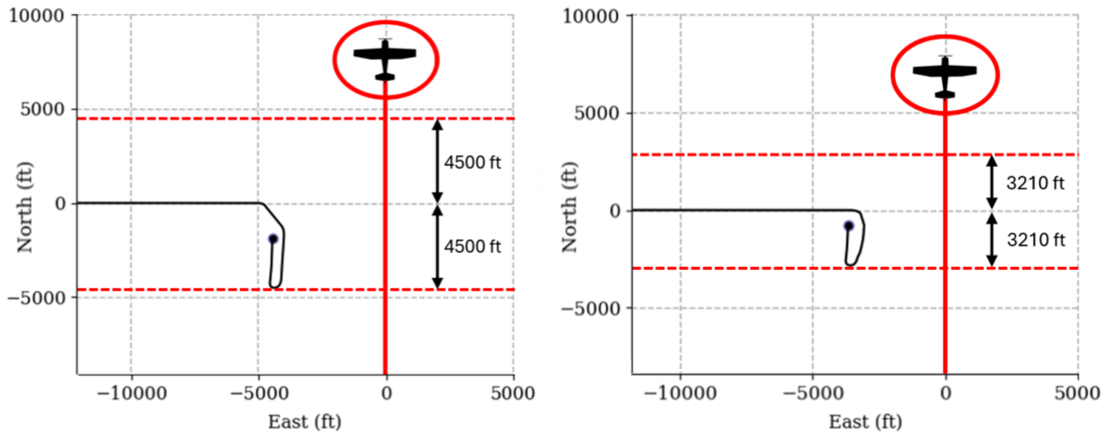


Figure 257. Single sUAS Flying at 45 ft/s Required Corridor Width for 270º Encounter with Crewed Aircraft Flying at 145 ft/s (L) and 170 ft/s (R).

Table 141. Minimum Corridor Width Required Based on Avoidance Algorithm.

Heading Angles	Incoming Aircraft Speed (ft/s)	Minimum corridor width using MPF (ft)
Head-On Converging	145	9,000
	170	7,200
	195	6,800
Overtaking Converging	145	9,000
	170	7,200
	195	6,400

Table 141 summarizes the minimum corridor width required depending on incoming aircraft heading angle as well as speed, to prevent a right of way violation using a MPF algorithm.

H.1.1.3.1.2 Loiter Maneuvers for sUAS Encounters with a Crewed Aircraft in a Corridor

As noted in Section H.1.1.2.1.3 Avoidance Using the Loiter Maneuver, an alternative to using the MPF avoidance concept is to, for encounters converging from one side or the other, simply have the sUAS or sUAS formation ***loiter*** to wait for the crewed aircraft to pass by.

This maneuver has the same deviation from the sUAS path no matter the non-cooperative aircraft speed. The diameter of the loiter circle is roughly 560 ft, making the total corridor width required 1,120 ft and this is typically the maximum the aircraft diverges from its flight path. Thus, this would be the typical corridor width for most heading angles that would use this maneuver. In some cases, due to the nonlinearity of the aircraft encounter, the sUAS will make a wide turn to make it back on its flight path. In such a case, the non-preferable exit creates a maximum of a 990 ft divergence from the original sUAS flight path, resulting in a maximum corridor width requirement of 1,980 ft.

Figure 258 highlights the maximum corridor widths required to successfully avoid a ROWV. The case on the left displays the maximum corridor width required in an overtaking scenario, while the case on the right displays the maximum corridor width required in a head-on-converging scenario.

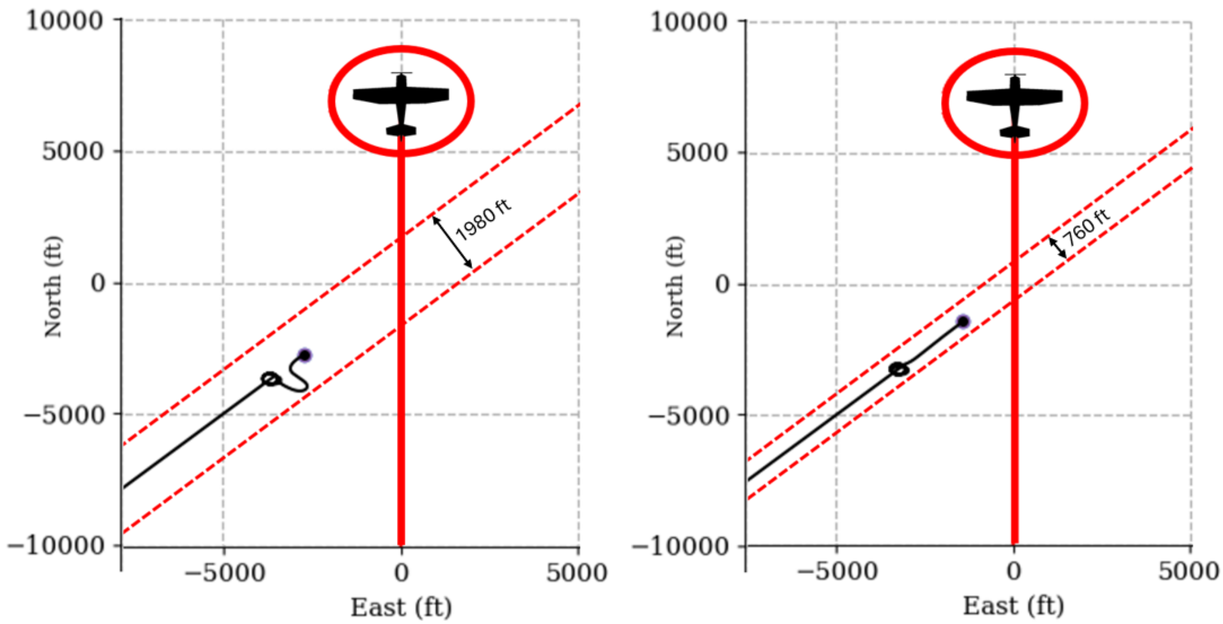


Figure 258. Maximum Corridor Widths for Overtaking Converging (L) and Head on Converging (R) Scenarios.

However, as was also discussed in Section H.1.1.2.1.3 Avoidance Using the Loiter Maneuver, the loiter maneuver fails for heading angles that are substantially head-on and substantially overtaking. Additionally, it performs worse than the MPF logic for heading angles between 315 degrees and 270 degrees. Thus, the loiter guidance should only be used for heading angles between 315 degrees and 0 degrees.

The maneuver widths for a full set of encounters when the loiter maneuver works is highlighted in Figure 259.

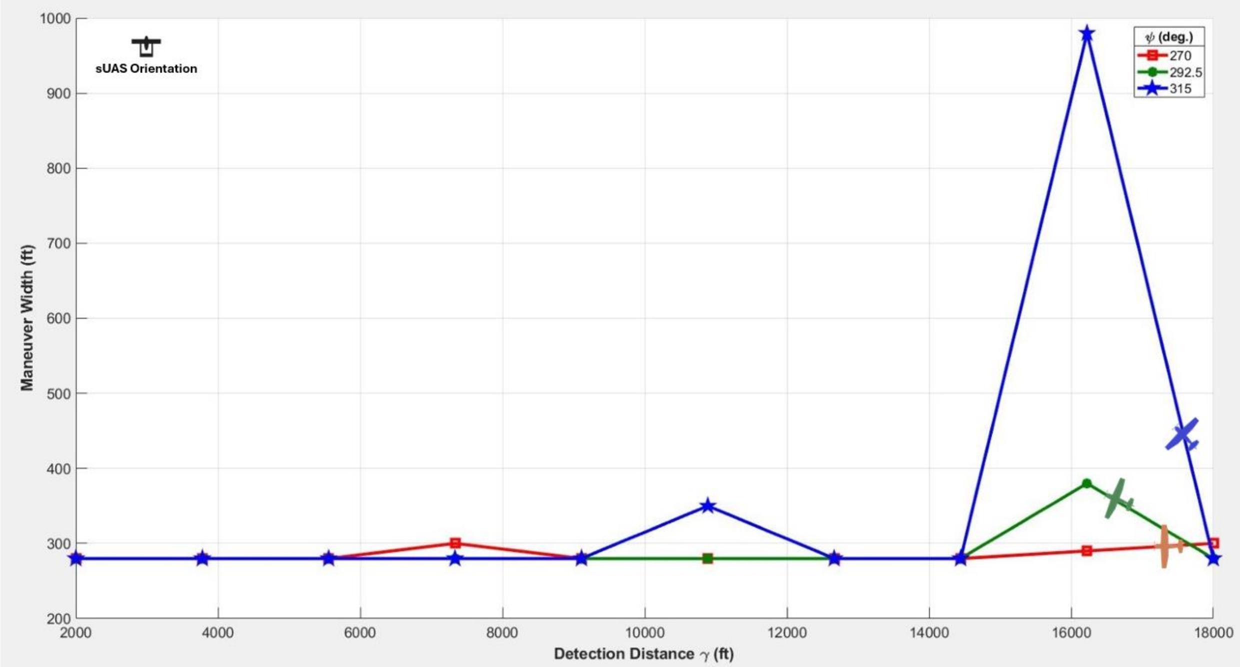


Figure 259. Maneuver Width for 170 ft/s Crewed Aircraft Overtaking Single sUAS Flying at 45 ft/s when Loiter Works.

As evident by the data, the loiter maneuver is not used at all for heading angles between 180^o to 270^o and 315^o to 0^o. However, for non-cooperative aircraft heading angles from roughly 270^o to 315^o, the loiter maneuver is successful at lower detection distances than the morphing potential field and minimizes the corridor width. Even with a non-desirable exit from the loiter circle, the corridor width is very small compared to the previous results shown by the morphing potential field. The worst case loiter maneuver creates a divergence from the flight path of 990 ft, resulting in a corridor width of 1,980 ft. This is less than the bare minimum required to include the 'buffer' of 2,000 ft, so for the loiter maneuver the corridor should be 4,000 ft to include the buffer on either side. One possible takeaway from this is to have a more complex guidance which incorporates the benefits of both the loiter maneuver and the morphing potential field.

Table 142. Minimum Corridor Width Required Based on Heading and Closing Speed Using Loiter Algorithm.

Heading Angle	Incoming Aircraft Speed (ft/s)	Minimum Corridor Width Using Loiter (ft)	Recommended Corridor Width Using Loiter with Buffer (ft)
Overtaking (270^o to 315^o)	145	1,340	4,000
	170	1,980	4,000
	195	1,760	4,000

Table 142 summarizes the minimum corridor width required depending on incoming aircraft heading angle as well as speed, to prevent a right of way violation using a Loiter algorithm.

As stated in Section H.1.1.2.1.3 Avoidance Using the Loiter Maneuver, if the autopilot uses the computed relative heading angle, it can then select the best avoidance algorithm requiring the lowest corridor width. For such a case, Table 143 gives the minimum corridor widths for the combined MPF/Loiter avoidance algorithms.

Table 143. Minimum Corridor Widths Required for Combined MPF/Loiter Avoidance Algorithms.

Incoming Aircraft Velocity (ft/s)	Head-On Converging (MPF) (180° to 270°) (ft)	Substantially Overtaking (MPF) (315° to 0°) (ft)	Overtaking from Left (Loiter) (270° to 315°) (ft)
145	10,300	9,000	4,000
170	7,200	7,200	4,000
190	6,800	6,400	4,000

To increase the range of heading angles for which the loiter maneuver would work, the sUAS would have to travel a certain perpendicular distance to the incoming crewed aircraft's flight path before loitering, so it does not loiter in the path of the incoming aircraft and successfully avoids it. However, this perpendicular movement before loitering would result in a higher corridor width requirement than the widths found in Table 143. Such a maneuver was not simulated and analyzed by KU.

H.1.1.3.2 Multiple sUAS Encounters with a Crewed Aircraft in a Corridor

When investigating the maneuver divergence or 'width' from the preplanned flight path of multiple sUAS, the maximum still occurred at a detection distance of 18,000 ft for a relatively slow (145 ft/s) non-cooperative Cessna at a heading angle of 270 degrees. However, the maneuver width was much larger, nearly 5,200 ft, due to multiple sUAS. Even if the lateral separation of 500 ft between the sUAS is subtracted from the maneuver width, it would still be a larger divergence. This is evidence that a larger corridor is needed when flying with multiple sUAS. The multiple sUAS encounter with the largest maneuver width is highlighted in Figure 260.

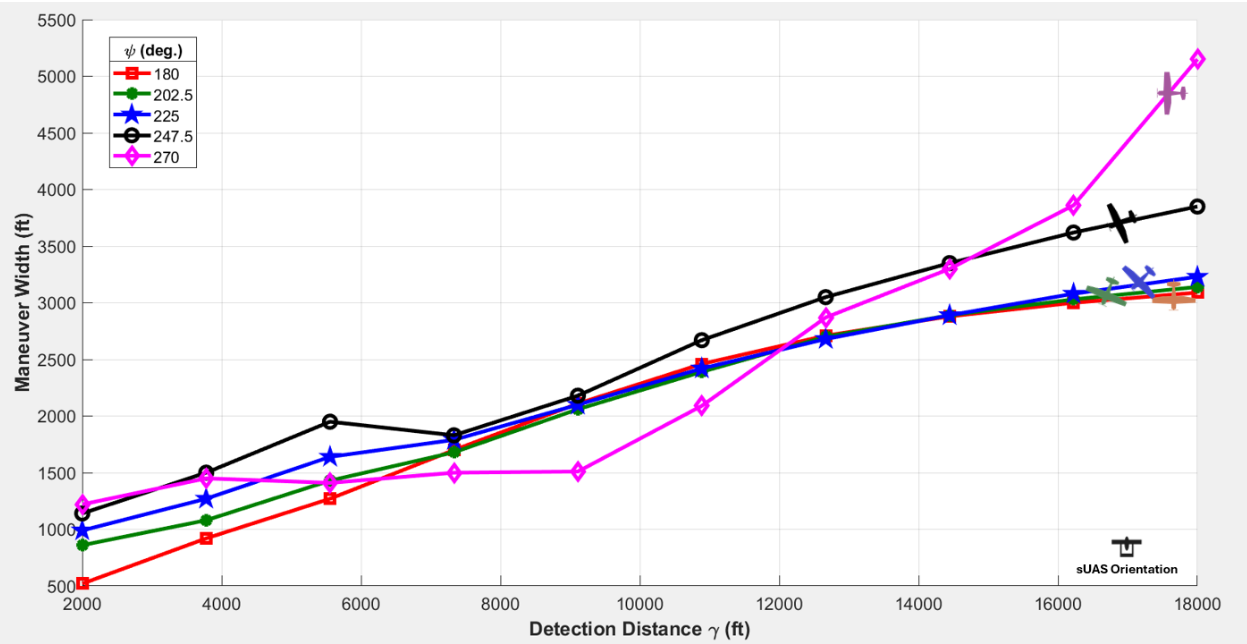


Figure 260. Maneuver Width of Multiple sUAS Flying at 45 ft/s with 145 ft/s Crewed Aircraft.

For the intermediate (170 ft/s) and fast (195 ft/s) non-cooperative Cessna speeds, the maximum maneuver width is only slightly larger than the single sUAS, with widths slightly over 3,600 ft. For the intermediate and fast speeds, the maximum maneuvers width occurs at heading angles of 270 degrees and 247.5 degrees respectively. Once again, leveraging the data from the general encounters between multiple sUAS and the non-cooperative Cessna shows that at lower detection distances, smaller maneuver widths will still result in successful avoidance maneuvers. However, if the corridor width is based on these, for a larger detection distance the sUAS would leave the prescribed corridor. The remaining data for the maneuver width of the multiple sUAS is in Appendix I.

H.1.1.3.3 Observations on Reseerved Airspace Simulations for Flight in a Corridor

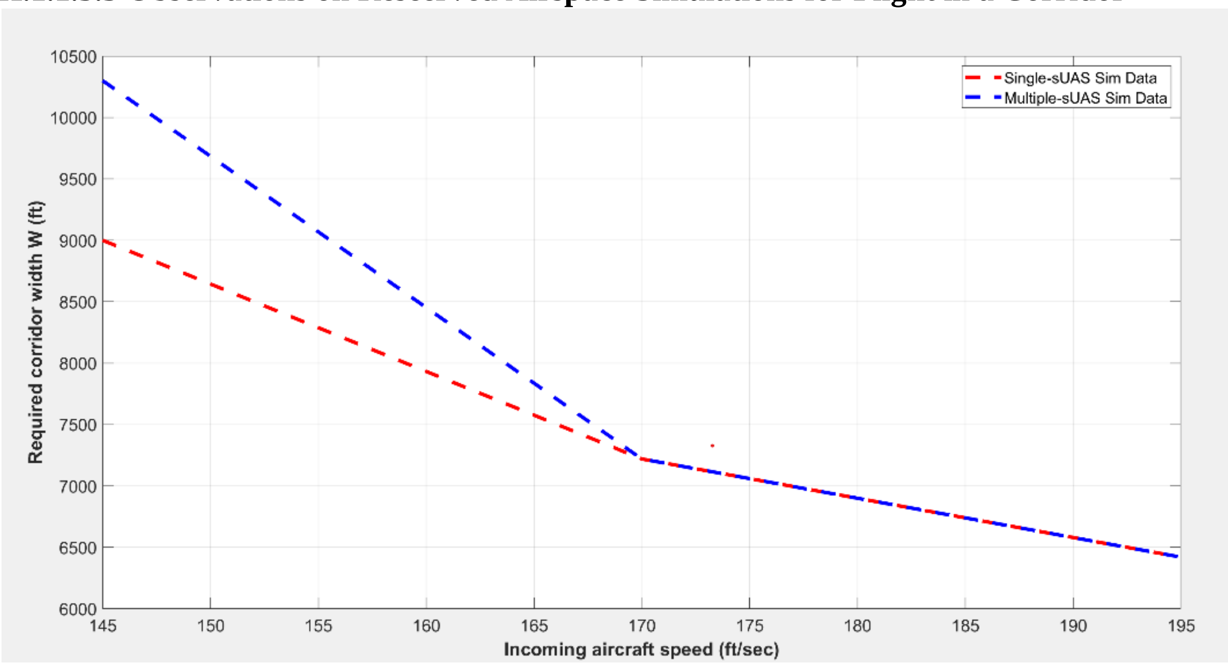


Figure 261. Required Corridor Width for sUAS Flying at 45 ft/s Encountering Crewed Aircraft.

Figure 261 shows the largest corridor widths required at each aircraft closing speed for single and multiple sUAS, if only the MPF guidance is used. The maneuvering width widely changes as a function of relative velocity, relative approach angle, and relative position of the incoming crewed aircraft with respect to the UAS which is directly a function of detection range. As shown in Figure 259 and Figure 260, the maneuver width changes over a broad range of values which indicates its high sensitivity to initial conditions, approach velocity and the properties mentioned above. It can be concluded that in many cases (not all cases), when the relative speed is higher, the intruder aircraft leaves the area of encounter faster, which eventually reduces the potential for violating the minimum ROW rules. This can be seen when the relative approach angle between the sUAS and Cessna 172 in the encounters (shown in Appendix I) are kept constant at 270 degrees. The faster the incoming Cessna 172 flies, the sooner it is outside of the minimum required ROW distance which means the sUAS needs a smaller maneuver width.

When examining the maneuver widths for single and multiple sUAS, a few conclusions can be drawn. First, the morphing potential field algorithm has successful avoidance for the full range of head-on and overtaking encounter angles. However, the morphing potential field is a costly algorithm, and can often drive the sUAS to make large maneuvers that greatly diverges from its flight path. These costly maneuvers are most prevalent in non-cooperative aircraft headings of 270 degrees. To mitigate this, a more complex guidance can be created, which incorporates the benefits of the previously described loiter maneuver. The complex guidance would have the following characteristics:

- If the non-cooperative aircraft is approaching at any head-on-converging heading angle (180°-270°) or a certain section of overtaking heading angles (315°-0°), the morphing potential field is preferable as it provides successful avoidance from the non-cooperative aircraft.
- For all other cases (270°-315°), the loiter maneuver will provide successful voidance with a very small maneuver, reducing the most limiting case from the morphing potential field.

If this complex guidance is used, the most limiting cases are found to be:

- For single sUAS, the largest maneuver occurs for a directly overtaking (0°) crewed aircraft at 145 ft/s, which results in a maneuver width of 3,250 ft, as shown in Appendix I. This results in a corridor width of 6,500 ft.
- For multiple sUAS, the largest maneuver occurs for a directly overtaking (0°) crewed aircraft at 145 ft/s, which results in a maneuver width of 3,250 ft, as shown in Appendix I. This results in a corridor width of 6,500 ft.

H.1.1.3.4 Recommendations Affecting Right of Way Rules

- A 2,000 ft buffer plus an additional GPS uncertainty buffer would be the minimum width required to assure separation from crewed aircraft flying along the corridor boundary.
- An additional buffer must be added to the required minimum required corridor width to account for the effect of relative speed on required corridor width.

H.1.1.4 Reserved Airspace Simulations for a Grid Survey Mission

Figure 262 shows the definition of the grid survey pattern that was used for these simulations. The survey pattern for the sUAS was arbitrarily set to 6,500 feet "north to south" and 4,500 feet "east to west." To allow for cooperative aircraft to fly on the edge of ***any*** reserved airspace without causing an avoidance maneuver, a 2,000-foot buffer is needed at a minimum if there are no GPS inaccuracies on either the sUAS or the crewed aircraft ***and*** if there are no crosswinds. To account for GPS uncertainty and winds, the buffer must actually be larger than 2,000 ft, possibly an extra 100 or so feet.

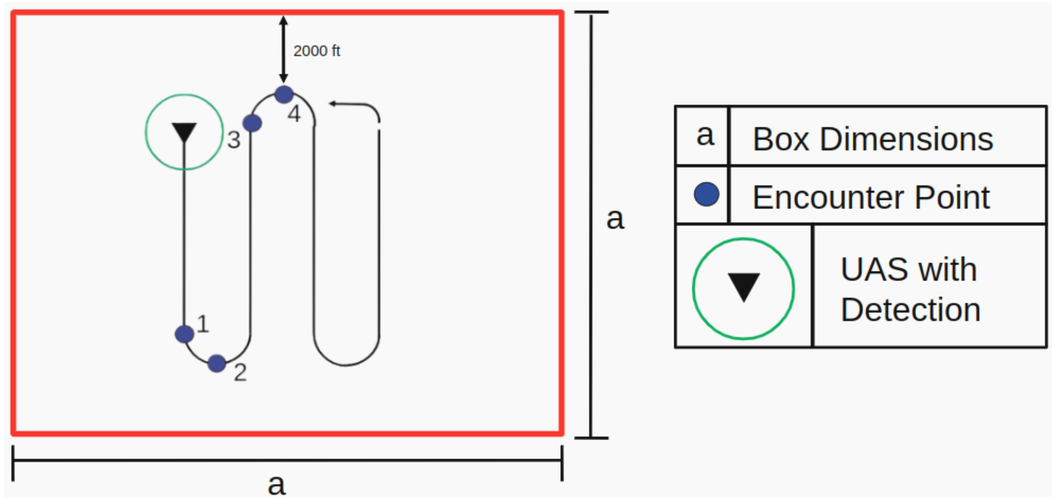


Figure 262. Survey Grid Encounter Point Definitions (Minimum Theoretical 2,000 ft Buffer Distance Shown).

For the 6,500 ft by 4,500 ft survey region, a number of RA sizes were studied. However, the final size selected as the best size for this case was 10,500 ft X 10,500 ft, represented by side length *a* in the figure. Note that the buffers in the east-west direction are greater than in the north-south direction. This is primarily due to the particular separation concept studied. In particular, when the avoidance maneuver begins, the sUAS is directed to one of the four corners of the reserved airspace. This is enabled by an expanded east-west direction buffer.

Preliminary investigations considered a range of sizes of reserved airspace starting at 8,500 ft in both dimensions, which gives the minimum possible north-south buffer size. The number of ROW violations were recorded for all encounter angles. When the size was increased in simulation to 9,500 ft square, the percentage of ROW violations decreased. However, increasing the size to 10,500 ft did not result in any less violations. The remaining ROW violations occurred from having too little detection range and were not a function of the size of the reserved airspace.

Based on preliminary simulations, it was found that the four points indicated in Figure 262were the points for which the sUAS had the highest likelihood for a ROWV. These points are referred to as unmitigated encounter points—the points at which a collision would be predicted if neither the sUAS nor crewed aircraft changes path. Simulations were run for five non-cooperative aircraft heading angles (190-270 degrees), 10 detection distances (2,000-18,000 ft), and three non-cooperative aircraft speeds (145-195 ft/s), for a total of 600 simulations.

For the reserved airspace simulations, a different collision avoidance algorithm, the "corner optimization algorithm" was used in place of the morphing potential field. To maximize the distance from the non-cooperative aircraft, it was decided the sUAS would travel to and loiter in a corner of the reserved airspace until the non-cooperative aircraft was no longer a concern, i.e., the sUAS is in the 'well clear.' To implement this avoidance and select the best corner for the sUAS to loiter in, a cost function with three terms was created. This cost function takes into consideration how much the sUAS would have to turn, $\Delta\psi$, the distance from the sUAS to the corner, Δd , and if the sUAS will have to cross the non-cooperative aircraft path, v_{rel}. The cost function is created for each corner of the reserved airspace when the avoidance maneuver begins, and the sUAS guidance and navigation algorithm chooses to go to the corner with the lowest cost.

$$J = w_1|\Delta\psi| + w_2\Delta d + w_3 v_{rel} \qquad \text{Equation 11}$$

The highest cost is placed on crossing the non-cooperative aircraft path, w_3, which has the highest likelihood of creating the worst-case scenario, a mid-air collision. If there are two available corners without crossing the non-cooperative aircraft path, the sUAS will then decide based on energy minimization, i.e., the closest corner or the one that will require the smallest turn.

Once the non-cooperative aircraft is detected, the sUAS will choose its corner and then solely focus on reaching/loitering in the corner until 'well clear' is reached. After the "well clear" has been confirmed, the sUAS will return to the point on the survey pattern from which it diverged, and then continue surveying. For the completed simulations, the determination of well clear was chosen to be when the non-cooperative aircraft is safely back outside the detection range. This is a design parameter and can be changed so that the sUAS will return to its surveying mission more quickly if desired.

H.1.1.4.1 sUAS In Reserved Airspace

For a single sUAS, the following figures depict a number of snapshots of what an encounter looks like. In each figure, the red circles indicate loiter points that the optimized cost function determined to be non-viable options. The green circles indicate corners that are not across the Cessna's path and would result in a successful avoidance. Ultimately, the sUAS chooses the corner based on its distance or how much it would have to turn. In the case of the figures below, the aircraft chooses the top right corner due to distance, as the cost of distance of the bottom right corner was higher than the cost of the tighter turn for the top right corner.

To highlight the performance of the "corner optimization algorithm", the following figures highlight three scenarios when:

1) The detection range is large, causing the sUAS to successfully avoid the non-cooperative aircraft (Figure 263).
2) The detection range is an intermediate value, which still allows the sUAS to avoid the non-cooperative aircraft but performs a slightly more evasive maneuver (Figure 264).
3) The detection range is too low, causing a ROW violation between the sUAS and the non-cooperative aircraft along with a severe avoidance maneuver (Figure 265).

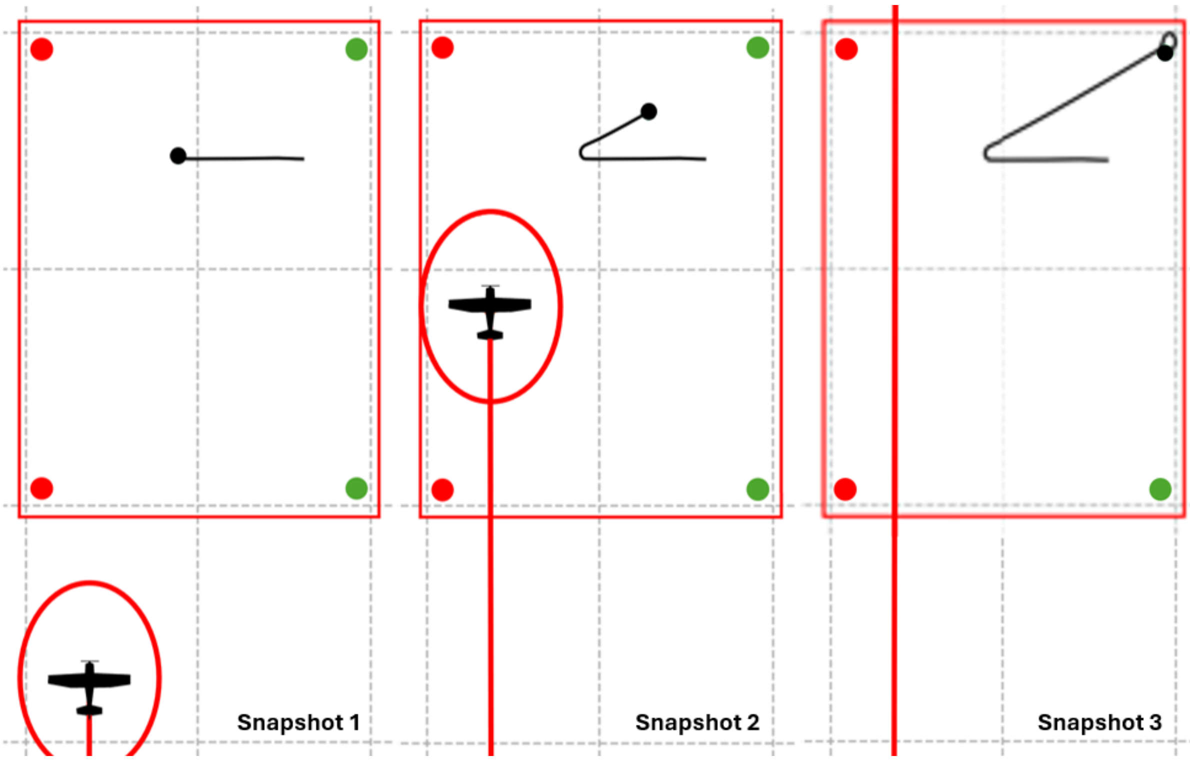


Figure 263. Large Detection Range with Extended Loiter (Green Dots Indicate a Safe Corner).

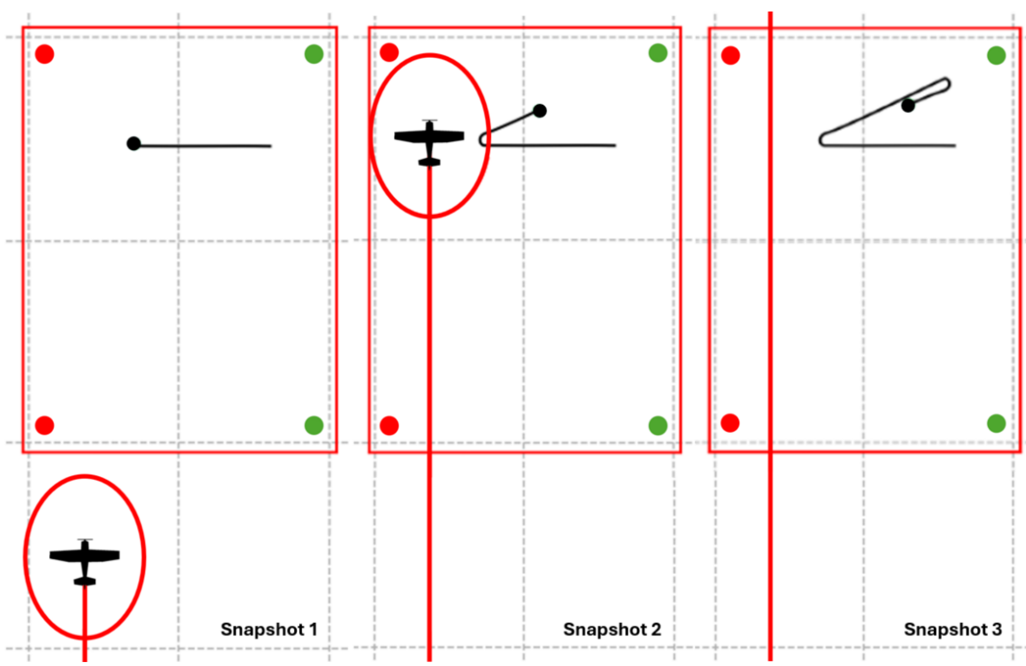


Figure 264. Medium Detection Range with sUAS Returning Before Reaching the Corner.

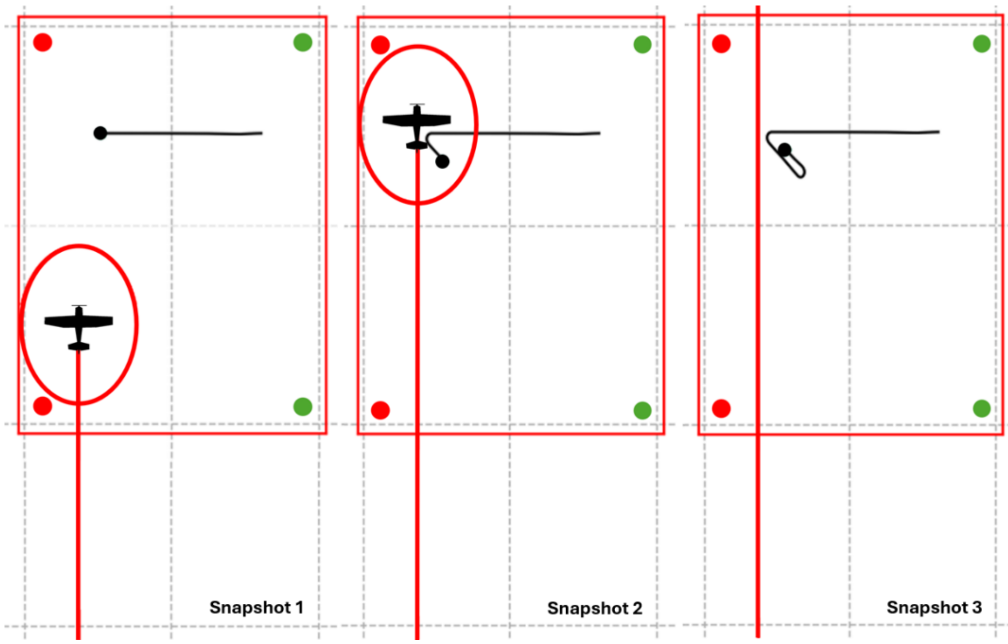


Figure 265. Low Detection Range with ROW Violation.

As done with other scenarios (general encounters, reserved corridor), the roll rates and yaw rate of the sUAS were investigated throughout the encounter. For the case of reserved airspace, there was no correlation between detection distance and magnitude of roll and yaw rates. The magnitude of the roll and yaw rate mainly depended on the location of the sUAS when it detected the crewed aircraft and the corner it ultimately chose. In the figure below, the roll and yaw rates are higher for the encounter on the left, as the sUAS must make a sharp turn backwards due to the geometry of the encounter when the crewed aircraft was detected. In the right encounter, the sUAS is in a better position when the crewed aircraft is detected and does not have to make as sharp of a turn, reducing the roll and yaw rates.

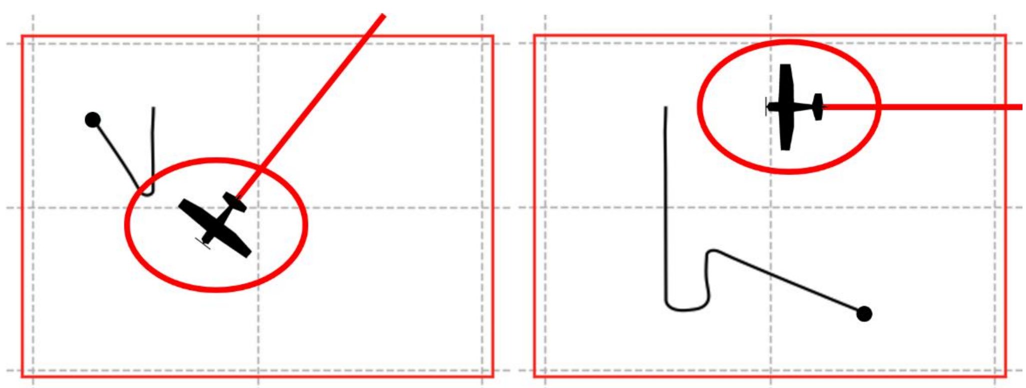


Figure 266. Roll and Yaw Rate Comparison.

The encounter on the left results in a max roll rate of 52 deg/s and yaw rate of 21 deg/s. The encounter on the right results in a max roll rate of 46 deg/s and yaw rate of 18 deg/s. Both roll rates are in the range of undesirable, but not adverse. The maximum yaw rate for both encounters is within desirable ranges for the simulated sUAS. It is evident that for the encounter on the right, both rates are slightly less.

H.1.1.4.2 Multiple sUAS in Reserved Airspace

For further investigation about the reserved airspace concept, simulations were run for multiple sUAS with an non-cooperative aircraft. These cases still used the same four encounter points, which were assumed to be the worst locations for an non-cooperative aircraft to intersect the survey path due to proximity with the boundary and sUAS energy exerted to conduct avoidance maneuvers. The same sUAS detections distances, non-cooperative aircraft heading angles and non-cooperative aircraft airspeed were used as with the single sUAS case.

The collision avoidance algorithm for corner choosing was left unaltered, but a second logic was added to insure the multiple sUAS avoided each other. When flying the survey path, the sUAS are separated 100 ft laterally and fly an identical survey path. However, when the non-cooperative aircraft is detected and the sUAS begin traveling to a corner, they are commanded to different altitudes. One sUAS will rise 15 feet and the other will lower 15 ft. This maneuver is not drastic and allows the multiple UAS to loiter about the same corner point without collision. Once the multiple sUAS returns to the survey path, they are commanded back to the original altitude to complete the survey mission. This method resulted in no collision between the multiple sUAS for all simulations. An example of a successful collision avoidance maneuver with multiple sUAS is highlighted in Figure 267.

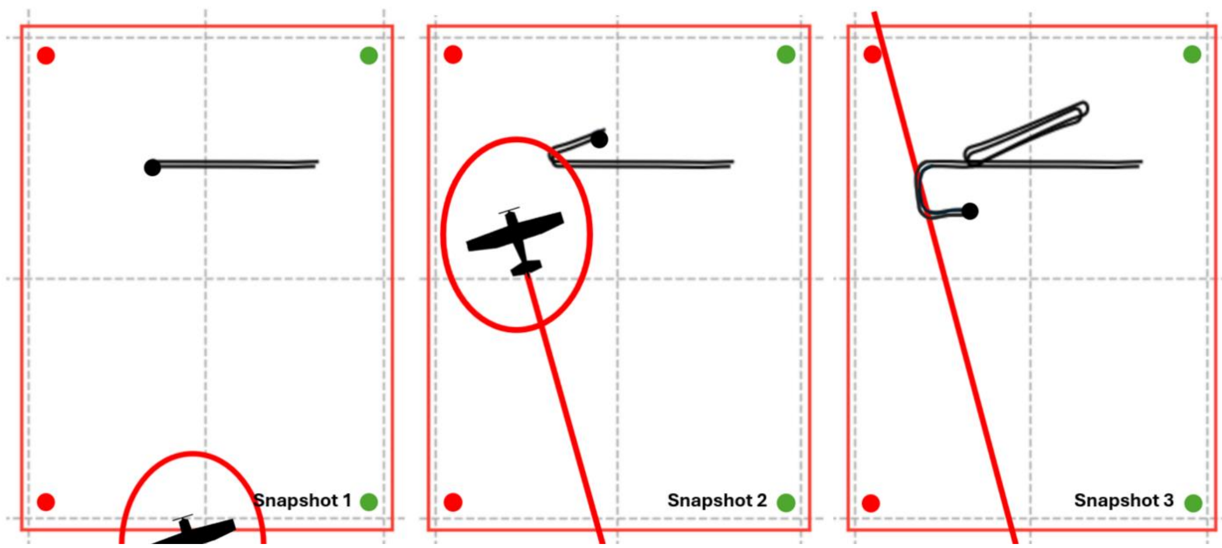


Figure 267. Successful Multiple sUAS Avoidance Maneuver.

After completing simulations of all 1,200 cases, 600 for single sUAS and 600 for multiple sUAS, the data was analyzed to investigate the percentages of ROW violations and NMAC. General comments about data trends and highlighted simulations are presented below.

As can be seen in the graphs and tables of the appendix, encounter point 4 consistently required the highest detection distance out of the rest of the points to ensure there were no NMACs or ROW violations. The only time that another point required the same detection distance was when the Cessna 172 had a velocity of 195 ft/s. The results can be found in Table 144. The results are notable as they give the minimum separation distance that the sUAS must start making its avoidance maneuver if it is to avoid a NMAC and a ROW violation. In some capacities, the minimum detection range also represents the minimum decision range for the sUAS to begin making its avoidance maneuver to avoid NMACs and ROW violations. A larger detection range could likely help an autonomous sUAS or multiple sUAS optimize its avoidance maneuver to let it complete a portion of its remaining mission while still getting “well clear” of the non-cooperative crewed aircraft.

Table 144 Minimum Safe Detection Distance for Single sUAS and Multiple sUAS Flying at 45 ft/s in Surveying Reserved Airspace.

Intruder Airspeed (ft/s)	Single sUAS Minimum Detection Range (ft)	Multiple sUAS Minimum Detection Range (ft)
145	9,600	9,700
170	10,200	10,200
195	11,800	11,800

It can easily be seen that with an increase in intruder airspeed, the minimum safe detection distance increases. This study only investigated three different speeds that are common to a Cessna 172 because this is the crewed aircraft the researchers possessed to conduct flight tests to compare the simulation data. Further, crop duster aircraft fly in a speed range similar to a Cessna 172 and spend much more time flying below 400 ft above ground level. Alternatively, a faster non-cooperative aircraft could lead to more ROW violations, or even NMACs, if the detection distance on the sUAS is not high enough to account for its airspeed. Alternatively, many rotary wing aircraft fly quite slowly, and require lower safe detection distances as reported by ERAU.

It is important to understand that sUAS airspeed will also play a part in the avoidance capability of the system. A slower sUAS will likely need a higher detection range in order to have enough time to maneuver out of the way of a crewed aircraft while a faster sUAS will likely need a lower detection range in order to have enough time to maneuver.

Table 144 also shows that there does not seem to be much of a difference in the avoidance of single sUAS and multiple sUAS. Figure 268 and Figure 269 show a comparison between the 195 ft/s condition for point 4 on the surveying pattern. Although the results look nearly identical, this of course is not the case as there are multiple sUAS that are avoiding the crewed intruder. The simulation is set up that there is a leader sUAS and a follower sUAS, and the leader sUAS avoids the intruder in the same way it would if there was no other sUAS following it. Since the follower sUAS is so close to the leader sUAS, it follows a similar path in its avoidance of the intruder. Furthermore, the small altitude separation allows for the multiple sUAS to converge on the same avoidance path, essentially combining them into a single agent. This gives the impression that there is not much change in the minimum detection distance.

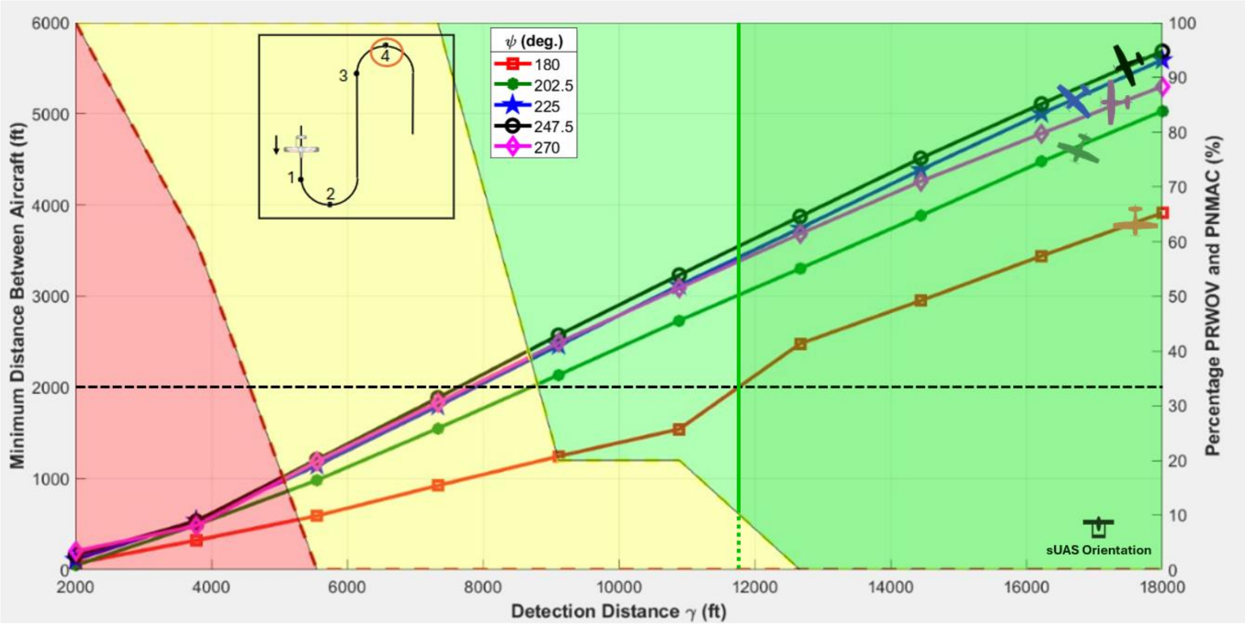


Figure 268. Single sUAS Flying at 45 ft/s Encountering 195 ft/s Crewed Aircraft at Point 4.

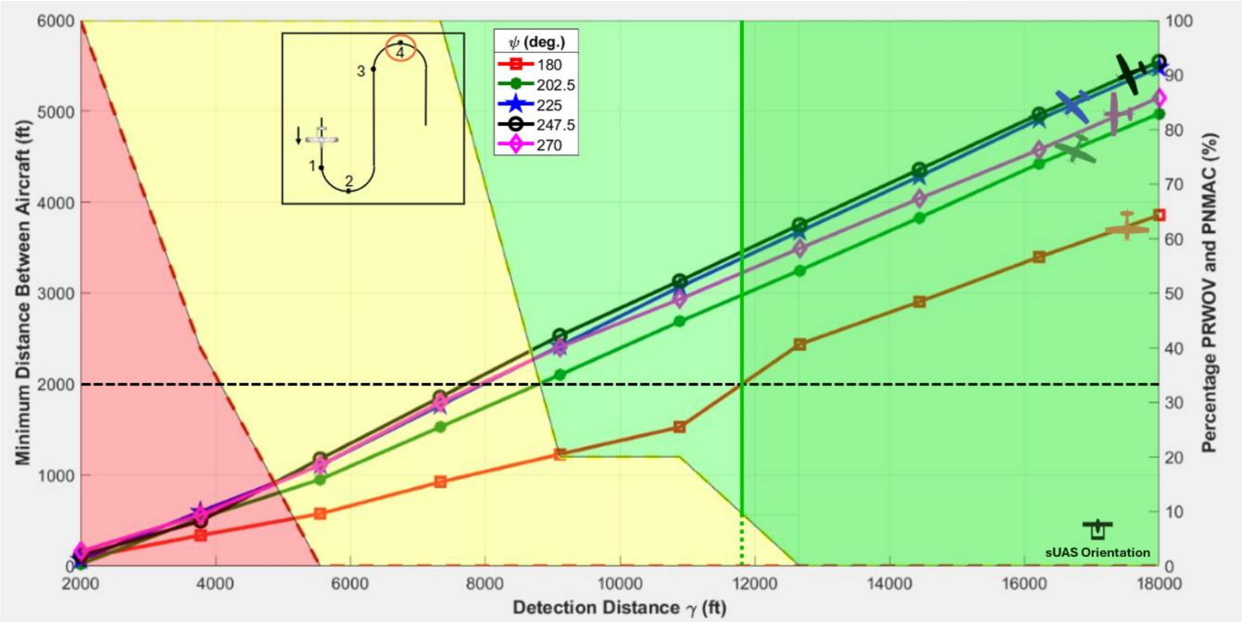


Figure 269. Multiple sUAS Flying at 45 ft/s Encountering 195 ft/s Crewed Aircraft at Point 4.

However, if the distances between the sUAS in formation flight are increased, the required detection distance to avoid a ROW violation would likely increase and a bigger reserved airspace would be required.

H.1.1.4.3 Observations on Reserved Airspace Simulations for Surveying Flight

A graphical representation of the trend of the required detection distances depending on incoming crewed aircraft velocity can be seen in Figure 270.

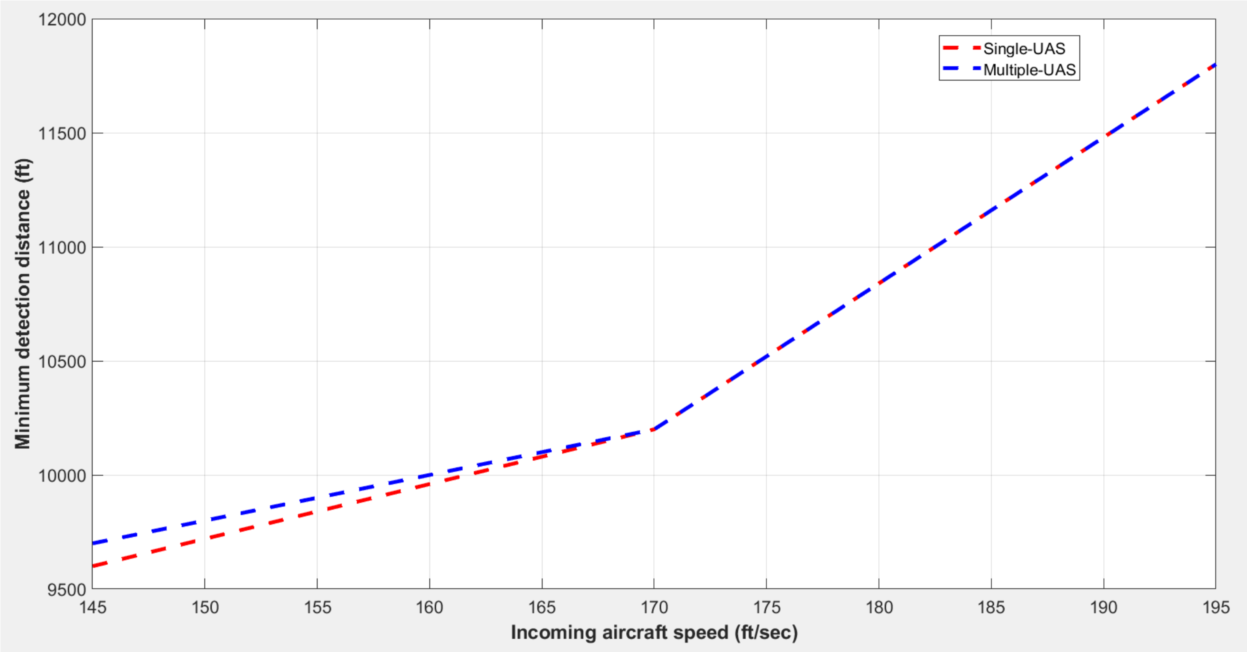


Figure 270. Minimum Detection Distance vs Incoming Crewed Aircraft Velocity for Single and Multiple sUAS Flying at 45 ft/s.

Over the range of incoming aircraft speeds simulated by the University of Kansas Flight Research Team, there appears to be an exponential relationship between the minimum detection distance required to prevent a ROW violation and incoming crewed aircraft speed. To determine the required detection distance for combinations of sUAS and non-cooperative aircraft speed not simulated here, it would be desirable to have a non-dimensional equation. However, the y-intercept of the relationship as well as the nature of the relationship could change dramatically if more incoming aircraft speeds were simulated that were higher or lower than the speeds that have been tested for. Additionally, a higher discretization in the incoming aircraft speeds could introduce additionally non-linearities that do not display themselves currently. Note that considering a linear relationship with the given data set would produce an overly conservative approximation.

For the simulations conducted for an unmitigated collision at point 4—when the sUAS is in the middle of a right turn away from the boundary of the reserved airspace—the required detection distance to avoid a ROWV was the largest. Thus, the minimum detection distance for the single sUAS and multiple sUAS vs. crewed aircraft were derived from simulations for this point.

- For an non-cooperative aircraft flying between 145 and 170 ft/s, the minimum detection distance for a successful avoidance maneuver is predicted to be 10,200 ft.
- For an non-cooperative aircraft flying at 195 ft/s, Further investigation showed that as the closing speed increased, i.e., a faster non-cooperative aircraft, the minimum detection distance for a successful avoidance maneuver is predicted to be 12,000 ft.

Additional data for the other encounter points in Appendix I show that a slower non-cooperative aircraft requires a lower detection distance, but this is not the worst-case scenario.

The derivation of minimum detection distance can have numerous applications, with one case being a minimum "decision-to-avoid" distance. Although a sUAS might have a sensor capable of detecting an non-cooperative aircraft at great distances, the sUAS could remain on its survey path after detecting the non-cooperative aircraft until it must decide to maneuver to avoid a ROW violation. This concept has not been studied in detail.

As with other scenarios, there are some cases where a collision avoidance maneuver requires undesirable roll and yaw rates. This is heavily dependent on the sUAS position at time of detection, as it will prioritize avoiding the non-cooperative aircraft at all costs over smooth, sweeping turns. This is also due to the nature of the guidance used for the reserved airspace. The constrained optimization of choosing the best corner can result in energy-expensive maneuvers to ensure the sUAS does not cross the path of a crewed aircraft.

After examining all results and comparing the different scenarios, one key comparison can be made between the chosen detect-and-avoid system. Although two different approaches were used, the morphing potential field algorithm and corner optimization algorithm, both converged to the conclusion that the minimum detection distance for a crewed aircraft flying at 170 ft/s is 10,200 ft.

As explained earlier, the observed worst-case detection distances for single and multiple sUAS will be used to derive a linear equation that can be applied for a range of closing speeds to provide a conservative estimate for reserved airspace size based on the size of the airspace needed to fly the intended mission. By dividing the worst-case detection distance by the worst-case closing speed, a scaling factor is found. The largest scaling factor will then be used in the final equation. Once again, since both single and multiple sUAS encounter resulted in the same worst-case detection distance for different closing speeds, the final equation can be used for both single and multiple sUAS.

In addition to recommendations about a conservative detection distance, a new equation was created to provide some recommendations about reserving airspace. For the north-south dimension of the survey pattern studied in this report, a 2,000 ft buffer was added along each side. For the east-west dimension of the survey pattern, a larger, arbitrary, 3,000 ft buffer was added along each side to make the reserved airspace square. However, considering GPS uncertainty for both the sUAS and crewed aircraft as well as potential winds, it makes sense to include a “safety factor”, possibly 1.25, multiplied by the minimum buffer size, 2,000 ft. Therefore, the recommended equation to find the required side length of a side of a reserved airspace rectangle, *L,* is found by adding the buffer width to the North/South or East/West dimension of the flight area, *S:*

$$L(ft) = S(ft) + \big(2 \cdot (1.25 \cdot 2000)\big)(ft) = S(ft) + 5000(ft) \qquad \text{Equation 12}$$

Note this recommendation is for the corner optimization algorithm, though simulation with the morphing potential field might also be used for future studies, with either constant or variable sUAS speed.

H.1.1.4.4 Recommendations Affecting Right of Way Rules for sUAS in Reserved Airspace

- For a single or multiple sUAS performing a grid survey mission in a reserved airspace, it is recommended that Equation 12 is used for the required side length of a reserved airspace to be assured that the sUAS will not leave the reserved airspace while performing an avoidance maneuver to prevent a ROW violation with an incoming crewed aircraft.

H.1.1.5 Overall Observations on Simulations

The University of Kansas Flight Research Team explored a variety of encounters between an incoming crewed aircraft and a single sUAS as well as a multiple sUAS. Two types of avoidance algorithms were employed for unrestricted airspace simulations and reserved airspace simulations for flight in a corridor. A third type of avoidance algorithm was employed for reserved airspace simulations for a grid survey mission. The results produced by the team may differ upon the usage of other avoidance algorithms and thus, may not be completely comprehensive. An optimal avoidance algorithm would likely comprise of a few different algorithms that are automatically chosen based on the scenario by the autonomous aircraft. However, this was beyond the scope of this report's focus.

The University of Kansas Flight Research Lab has a total of 13 UAS platforms whose stability and control coefficients were analyzed using Advanced Aircraft Analysis (AAA) and Athena Vortex Lattice (AVL) to get a measure of their maneuverability, in comparison to the SkyHunter UAS used for simulations as well as flight testing. The specific coefficients analyzed were rolling moment coefficient due to aileron deflection ($Cl_{\partial a}$) and yawing moment due to rudder deflection ($Cn_{\partial r}$), vital characteristics for avoidance maneuvers. The weights of all the UAS platforms owned by the flight research lab range from 6 lbs to 74 lbs and their wingspans range from 6 ft to 20 ft. Their $Cl_{\partial a}$ values range from 0.05 to 0.41 and their $Cn_{\partial r}$ range from -0.13 to -0.02, with higher values indicating better maneuverability. The SkyHunter UAS has below average handling characteristics as compared to the rest of the UAS platforms owned by the flight research lab and is capable of making the required maneuvers to ensure aircraft separation standards are met. Thus, all the other UAS platforms analyzed with better coefficient values are more than capable of making the required maneuvers. Additionally, based on this analysis, any UAS within the $Cl_{\partial a}$ and $Cn_{\partial r}$ ranges mentioned above can meet the maneuverability requirements for a successful avoidance maneuver. Handling characteristics of UAS platforms worse than the SkyHunter UAS haven't been tested and can't be spoken for.

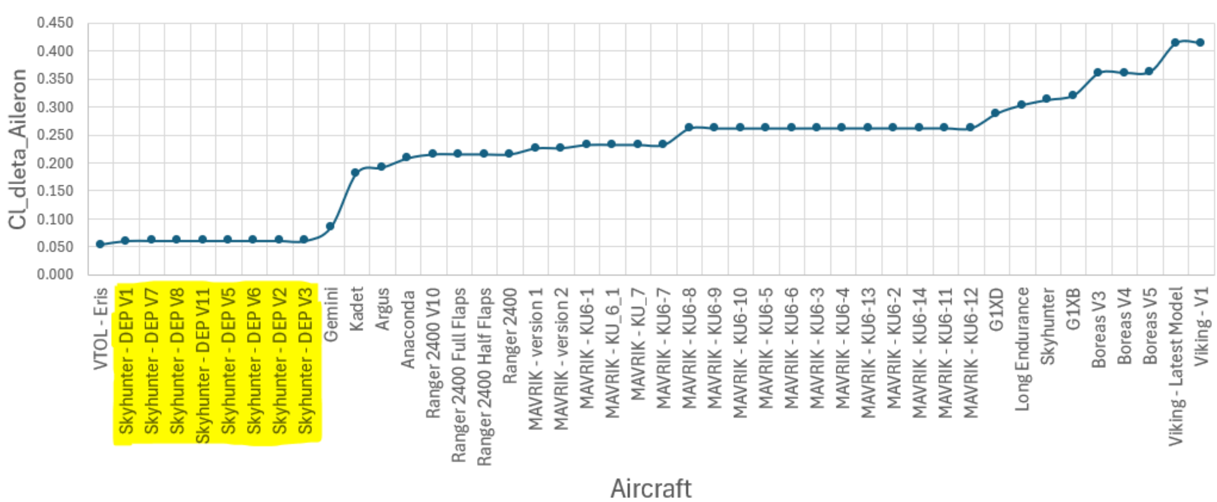


Figure 271. Rolling Moment due to Aileron Deflection for Several KU FRL UAS.

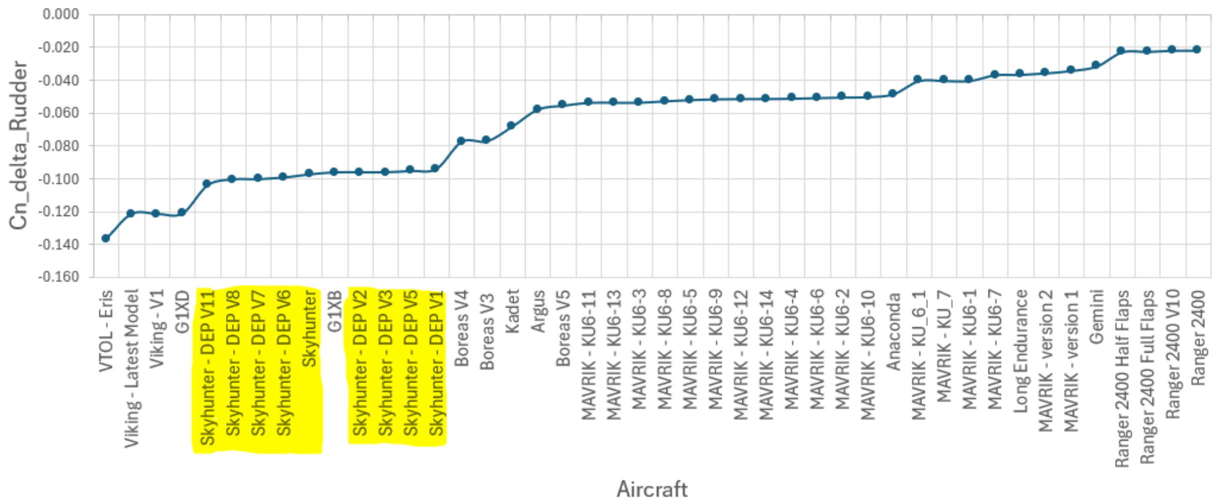


Figure 272. Yawing Moment due to Rudder Deflection for Several KU FRL UAS.

H.1.2 KU Flight Test

All flight testing at KU was accomplished in the vicinity of the Clinton International Academy of Model Aeronautics (AMA) Field, just southwest of Lawrence, Kansas, 7 NM southwest of the Lawrence Regional Airport (LWC). The field is the property of Jayhawk Model Masters, Inc, a club with which KU has a membership. All crewed aircraft flights originate at the Lawrence Regional Airport, which is owned by the City of Lawrence.

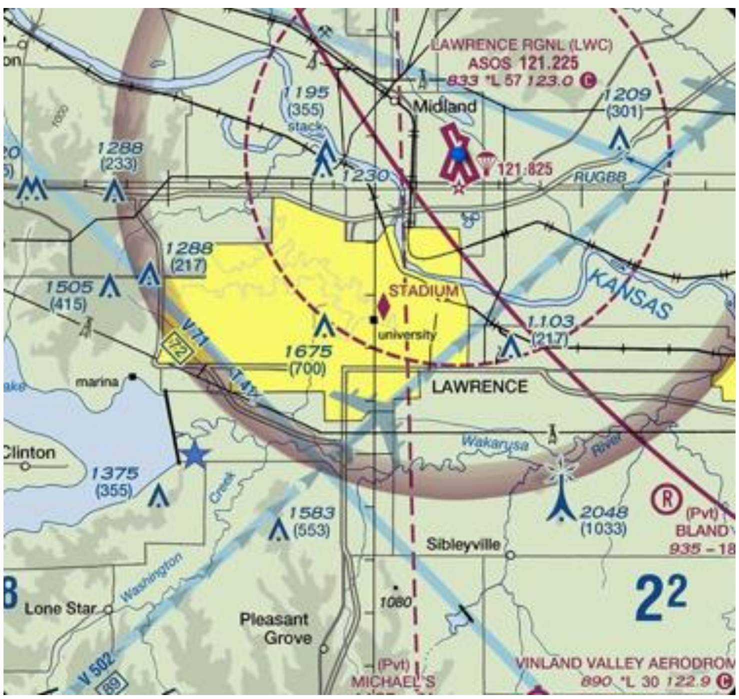


Figure 273. Air Chart Showing LWC (Upper Right) and the AMA Field (Star at Lower Left).

At the AMA field, the KU team uses two grass runways and a pavilion under which the ground station is set up at the AMA field.

Figure 274. Model Masters AMA Airport.

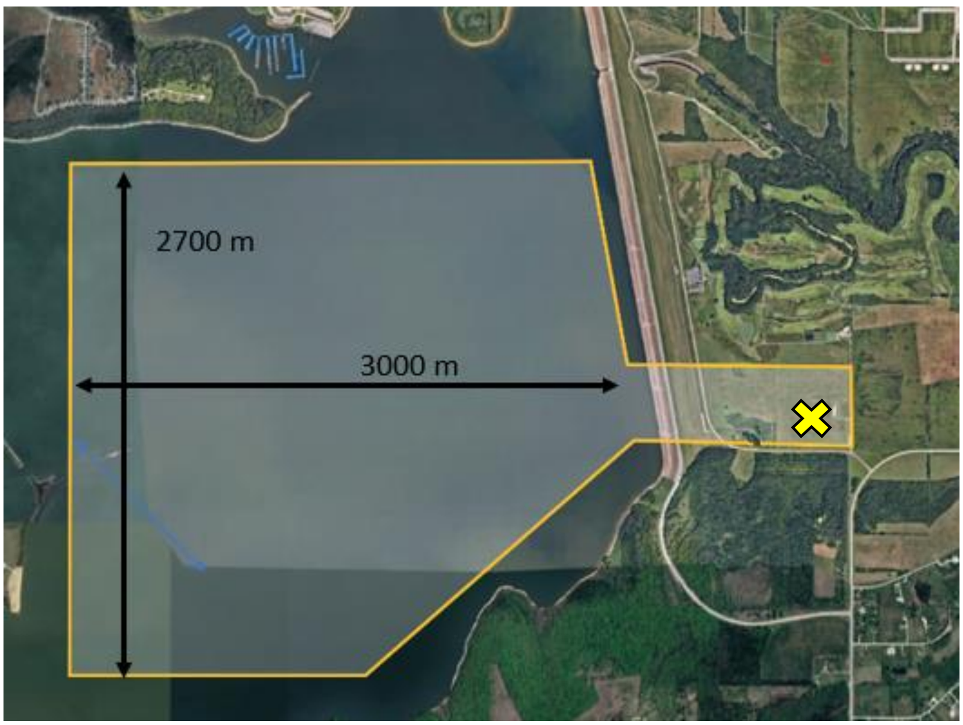


Figure 275. Flight Test Area Over Clinton Lake with Entry Corridor from Model Masters AMA Airport (x).

Figure 276. Path of an sUAS Flying in a Corridor (Orange Path) with Potential Intruding sUAS or Crewed Aircraft Trajectories (Shown as Blue Arrows).

Figure 277. Path of an sUAS Flying a Grid Survey Mission (Orange Path) with Potential Intruding sUAS or Crewed Aircraft Trajectories (Shown as Blue Arrows).

H.1.2.1 Flight Test Vehicles

H.1.2.1.1 Sonic Modell SkyHunter

The SkyHunter UAS is a "kit" sUAS which has been outfitted with the most recent KU AFS and an Automatic Dependent Surveillance-Broadcast (ADS-B) receiver. The KU AFS includes:

- PixHawk with Orange Cube Inertial Measurement Unit and GPS receiver
- 2.4 GHz Spektrum AR8020T 8-channel receiver
- MicroHard P900 900 MHz transceiver
- NVIDIA Jetson Nano computer
- Ping RX Pro ADS-B receiver
- Here 3 GPS receiver
- SDP 33 airspeed sensor
- MRO 915 MHz telemetry module
- PPM encoder

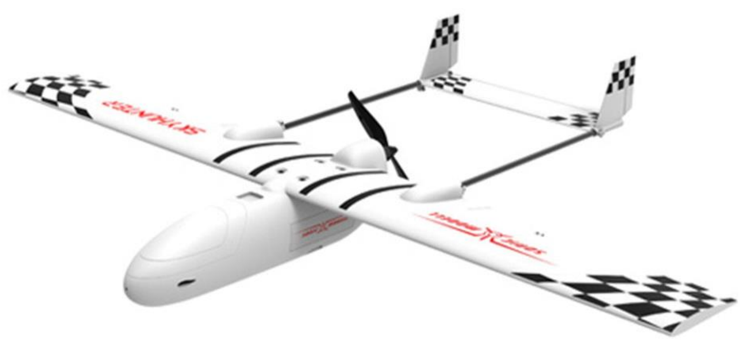


Figure 278 Sonic Modell SkyHunter UAS

Table 145 gives the salient specifications of the SkyHunter.

Table 145. Sonic Modell SkyHunter Specifications.

Parameter	Description	Unit
Aircraft Manufacturer	Sonic Modell	[-]
Aircraft Type	Fixed Wing UAS	[-]
Aircraft Model	SkyHunter	[-]
Service Ceiling	400	[ft]
Stall Speed	22	[mph]
Construction Materials	EPO (Expanded Polyolefin Foam) & Carbon Fiber	[-]

Bare Weight (All Avionics, no batteries)	1	[kg]
Width (Fuselage dimension)	160	[mm]
Length	1,400	[mm]
Height	150	[mm]
Wingspan	1,800	[mm]
Payload Capacity	2 - 2.5	[kg]
Max Speed	58.4	[mph]
Cruise Speed	30.7	[mph]

H.1.2.1.2 Cessna 172

The crewed aircraft is a Cessna 172, certified in the Experimental Category and outfitted with:

- KU AFS (described in the next section)
- L-Com HGV 906U dipole antenna fixed to the left-wing strut
- (FAA-mandated) ADS-B transmitter

Figure 279. Cessna 172 Aircraft.

H.1.2.2 Data Recorded

All flight test data from both the Skyhunter UAS and the Cessna 172 is recorded onto a .bag file and is stored on an SD card. The .bag file records the initial conditions of each aircraft, commanded velocities, commanded altitudes, commanded roll, pitch and yaw values, roll, pitch and yaw rates as well as positional data of both aircraft. All the recorded data from the flight tests are then fed into the simulation code made by the University of Kansas Flight Research Team to reconstruct the actual trajectories in simulation and compare the differences. The team also had reports of visual contact of the Skyhunter UAS from the crew of the Cessna 172 as well as reports from visual observers on the ground to verify that the encounters took place within a visual line of sight.

H.1.2.3 Scenarios Flown

A total of 34 flight tests were conducted for all scenarios with each flight test having two to three encounters. Flight tests were conducted for both head-on-converging and overtaking-converging heading angles for the General Interaction scenario. Only head-on-converging heading angles were flight tested for the reserved airspace scenario in a survey mission. Reserved airspace flights in a corridor were not tested as the required width of the corridor would be inferred from the maximum maneuver widths observed in the General Interactions flight tests. Depending on the availability of the pilot of the Cessna 172, certain flight tests were done using a virtual Cessna 172 and some were done using a real Cessna 172.

H.1.2.3.1 General Interactions

Of all the flight tests that were conducted for the General Interaction scenario, six have been reported in this section, to prevent repetition of flight test cases. They have been separated by incoming Cessna 172 heading angle in Sections H.1.2.3.1.1 Head On Convergingand H.1.2.3.1.2 Overtaking Converging.

H.1.2.3.1.1 Head On Converging

11 flight tests for the head-on-converging heading angles were done using a virtual Cessna 172 as well as a real Cessna 172. Table 146 shows the number of flight tests conducted for the Head-on-converging scenario alongside the flight conditions.

Table 146. Initial Conditions of Crewed Aircraft During Head-On Converging Flight Tests.

Flight Test	Encounter	Flight Test Type	Relative Heading Angle (deg)	Speed of C-172 (ft/s)	Detection Distance (ft)	Minimum Distance Observed (ft)
1	1	Real C172	180	164	10,000	3,721
	2	Real C172	180	154	13,000	4,122
2	1	Real C172	180	165	8,000	2,885
	2	Real C172	180	165	7,000	2,562
	3	Real C172	180	160	5,000	1,298
3	1	Real C172	180	148	8,000	3,615
	2	Real C172	180	152	7,000	3,495
	3	Real C172	180	151	5,000	1,818
4	1	Real C172	225	163	8,000	2,605
5	1	Real C172	135	162	8,000	2,368
	2	Real C172	135	161	8,000	1,769
6	1	Virtual C172	180	170	10,000	2,746
	2	Virtual C172	180	170	8,000	2,184

H.1.2.3.1.2 Overtaking Converging

The University of Kansas Flight Research Team attempted to flight test the overtaking-converging heading angles. However, there was an error in the algorithm logic being used which resulted in a failed flight test for the scenario. This faulty algorithm logic was later corrected but there was no opportunity to flight test the improved algorithm.

H.1.2.3.2 Reserved Airspace

Three flight tests were conducted for the reserved airspace scenarios, with two shown in Table 147 to prevent repetition of flight test cases. All flight tests for this scenario at all heading angles were done using a virtual Cessna 172. Table 147 shows the number of flight tests conducted for the reserved airspace scenario alongside the flight conditions.

Table 147. Initial Conditions of Crewed Aircraft During Reserved Airspace Flight Tests.

Flight Test	Encounter	Flight Test Type	Heading Angle of C-172 (deg)	Speed of C-172 (ft/s)	Detection Distance (ft)	Minimum Distance Observed (ft)
1	1	Virtual C172	135	150	10,000	2,003
	2	Virtual C172	225	150	10,000	2,330
2	1	Virtual C172	135	150	5,280	1,998
	2	Virtual C172	225	150	5,280	2,146

H.1.2.4 Observations on Flight Testing

Of the thirty-four flight tests that were conducted by the University of Kansas, only eight flight tests are discussed in this section. Out of those eight flight tests, seventeen aircraft encounters were studied. Head-on-converging heading angles were tested using both a virtual and a real C-172. Overtaking-converging heading angles were not flight tested due to issues with the avoidance algorithm and geographic restrictions at the field. All the flight testing conducted helped the University of Kansas Flight Research Team discover minor flaws in the avoidance algorithms being used which were later examined and fixed. In most cases, the fixed avoidance algorithms were then implemented in subsequent flight tests, ensuring that the patches implemented worked as intended.

As expected, there was a 1 second latency in all ADS-B signals received, and there was only a small number of dropouts, though as long as10 seconds. The dropouts observed were 10, 2, 3, and 5 seconds.

In almost all flight tests, there were no major issues reported. However, during at least one instance in flight testing, the visual observers on the ground reported the sUAS in a “Fly Away” condition upon making the expected automated avoidance maneuver. This caused the pilot-in-command to take back manual control of the aircraft. At no point was there an actual loss of control of the sUAS from the pilot-in-command. Since the avoidance is happening autonomously, its actions may be unexpected to those overserving the sUAS’s behavior.

Additionally, the University of Kansas Flight Research Team conducted some post flight test analysis to get an estimate on the altitude uncertainty of the SkyHunter sUAS. Figure 280 shows a comparison between the commanded altitude and the actual altitude attained of the SkyHunter sUAS during a flight test involving both loiter and MPF waypoint navigation. As can be seen, the actual altitude varies approximately +/- 15 ft of the commanded altitude. The L2+ and LN Avoidance guidance methods had a root mean square altitude error of 4.33 and 5.01 respectively. These guidance methods are considered to be leading in the field in comparison to other guidance methods where the error can be on the order of 100 feet.

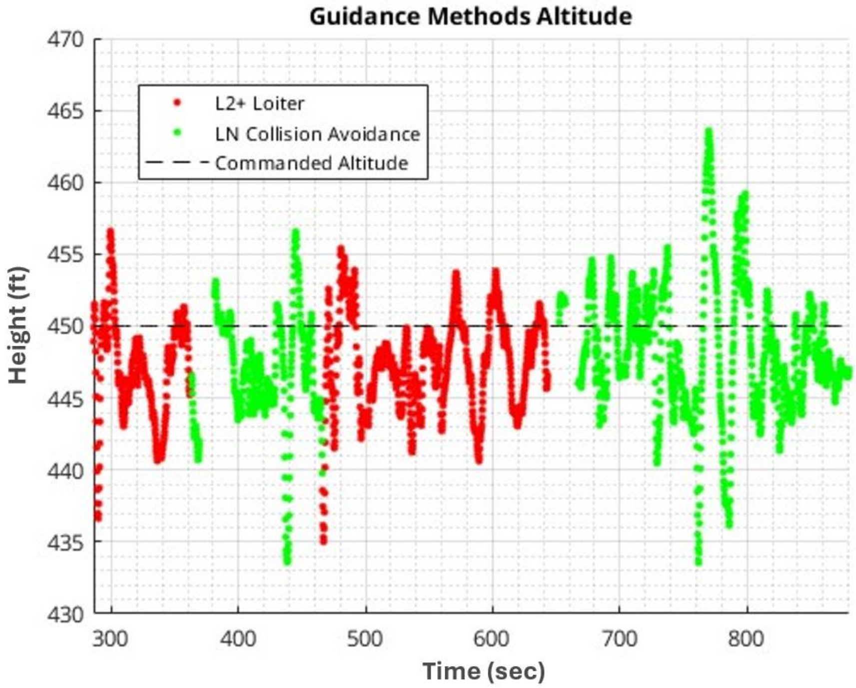


Figure 280. Actual vs Commanded Altitude During Flight Test.

H.1.3 Comparison of Flight Test and Simulations

H.1.3.1 General Interactions and Reserved Airspace

During the flight test campaign, seventeen (17) actual flight test encounters were conducted between the SkyHunter UAS and a Skyhawk Cessna C-172. The primary goal of this campaign was to assess the quality and reliability of simulation environments for right-of-way research.

The collected flight test data were compared to six degrees of freedom simulations, which used aerodynamic and propulsive forces and moments generated by engineering-level software such as AVL and AAA. Identical guidance, navigation, and control algorithms, including morphing potential field avoidance logic, were implemented for both simulated and real-world flight scenarios.

Statistical analysis of the post-flight test data of the seventeen flights demonstrated that the simulations were highly accurate in predicting the behavior of a UAS and the minimum distance between the non-cooperative general aviation aircraft (e.g., Cessna C-172) and the UAS. The comparison of minimum distance between the UAS and general aviation aircraft in flight tests and simulations revealed an average accuracy of 89 feet in 76% of the simulations. The consistency of results across different flight scenarios (88%) provides strong evidence for the reliability of these simulations. The root mean square error between all flight tests and simulation results was calculated to be 265 feet.

A comparison of the flight test data revealed that the accuracy of the simulation results can be influenced by several factors, either individually or in combination. These factors include: (1) ADS-B position and velocity dropouts, (2) UAS wind estimation errors and precision of UAS GPS position and velocity data, (3) the nonlinearity of avoidance algorithms, and (4) the accuracy of the simulator's physics-based models.

Since 2020, the FAA has required ADS-B equipment to be installed on most General Aviation (GA) aircraft operating in US national airspace. During the flight test campaign, and in all seventeen flight tests, the Cessna C-172 was equipped with ADS-B. One of the primary inputs to the UAS avoidance algorithm is the GA aircraft's position and velocity data provided by ADS-B. The avoidance algorithm, which utilizes a morphing potential field, is a highly nonlinear function. Like other nonlinear functions, it is highly sensitive to initial conditions, making accurate input data (e.g., GA aircraft's position and velocity) critical for reliable performance. As it is implemented in the flight test systems used for this work, the UAS acts upon the latest position and velocity information from any aircraft it may have to avoid. Nonlinear systems, such as those used in these flight test scenarios, are highly impacted by such dropouts. The highly nonlinear morphing potential field algorithm, outlined previously in this report, directly takes the relative position and velocity of the UAS and crewed aircraft as inputs to make the correct collision avoidance maneuvers. If the UAS is forced to make avoidance maneuver decisions on old information, these "initial conditions" will unpredictably impact the remainder of the avoidance maneuver. When using ADS-B information (operating at a 1Hz update rate), even just one missed ADS-B message can result in a difference of over 200 ft in position location error (when analyzing a head-on geometry case between the C-172 and SkyHunter UAS) since this position error is directly a function of the aircraft relative velocities. This error substantially grows if the dropout exceeds just a single missed ADS-B message, thus hindering performance even more. Moreover, the relative location between aircraft during a dropout plays a vital role in maneuver decisions. In locations with higher potential (the UAS is closer to the aircraft it is trying to avoid), the UAS will need to make more aggressive maneuvers to avoid a well-clear violation. Such dropouts in this scenario will lead to even more unpredictable UAS behavior leading to differences in simulated versus real-world avoidance encounters.

As the renowned statistician George Box once said, "All models are wrong, but some are useful." Inherent uncertainties in the physics-based dynamic model of a UAS can largely impact the accuracy of simulation results, particularly when these simulations involve the integration and accumulation of errors over time.

The avoidance algorithms are designed based on the aircraft's inertial velocity (North, East, Down) which means accurately simulating expected wind conditions is crucial for algorithm performance. While GPS velocity in real-world applications inherently includes the effects of wind on the UAS, estimating the wind field that UAS encountered is essential for meaningful post-processing comparisons.

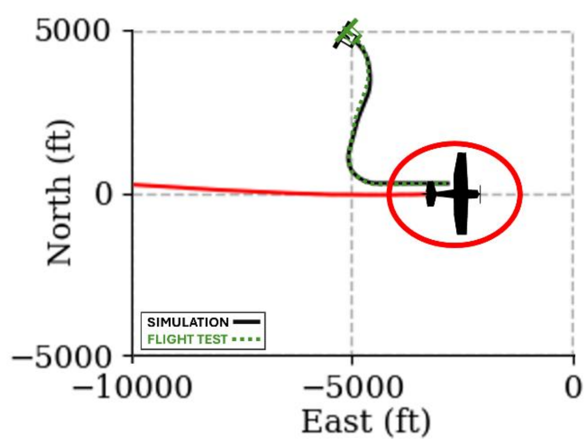
Finally, similar to the case of data dropouts between the UAS and the aircraft it is trying to avoid. Uncertainty in GPS location in a highly nonlinear environment can lead to large differences in the avoidance maneuver of the UAS during flight tests and simulations. During the flight test campaign, the KU team utilized GPS with an RTK system, achieving an average positional root mean square error of 6.6 feet. However, many UASs lack RTK capability, resulting in significantly higher uncertainty in their position and velocity, which can lead to substantial errors when comparing flight test data with simulation results.

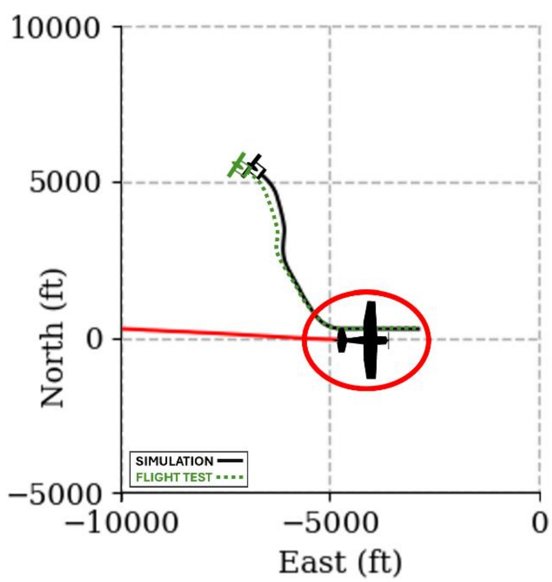
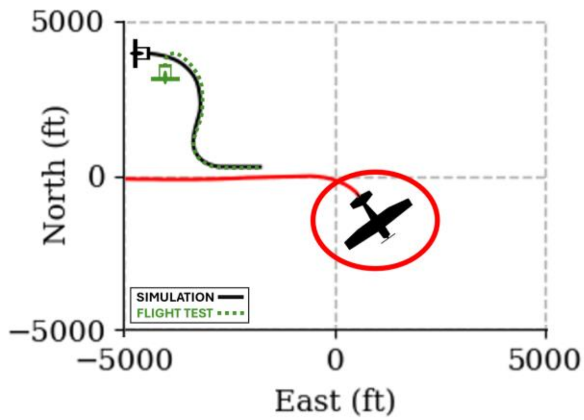
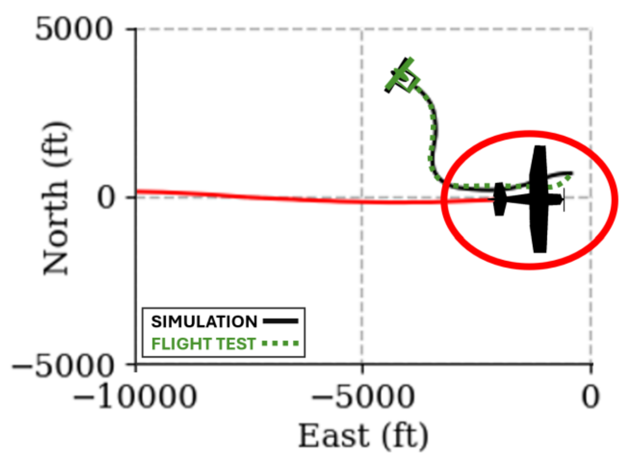
H.1.3.2 Overall Observations

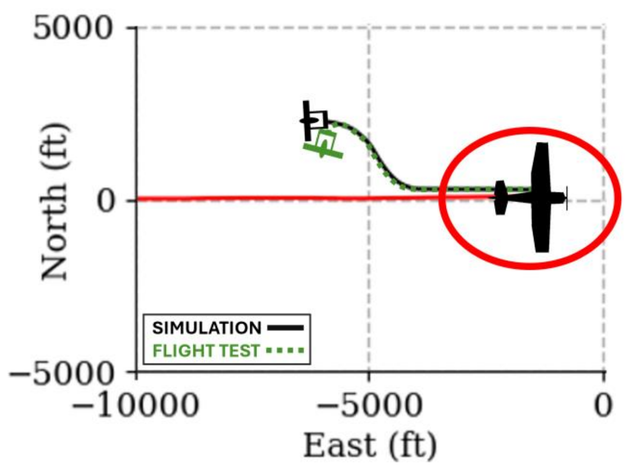
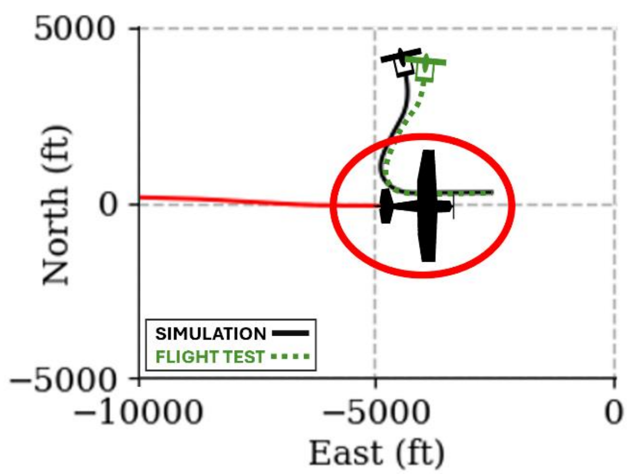
KU conducted a total of thirty-four flight tests with eight compared below. Those compared below include six flight tests for Cessna 172 vs. sUAS general encounters and two successful flight tests for Cessna 172 vs. single sUAS surveying encounters.

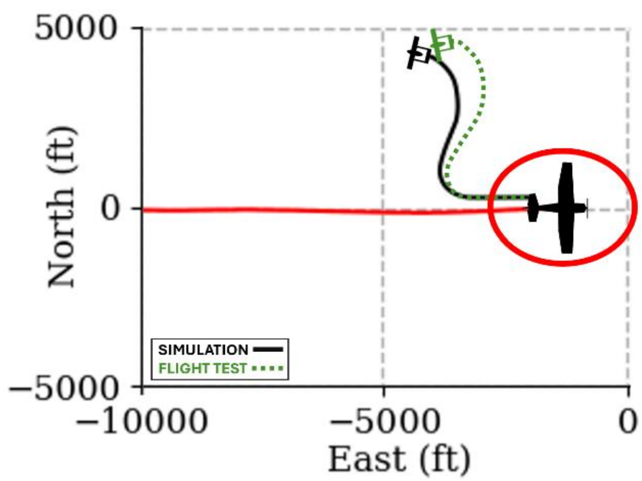
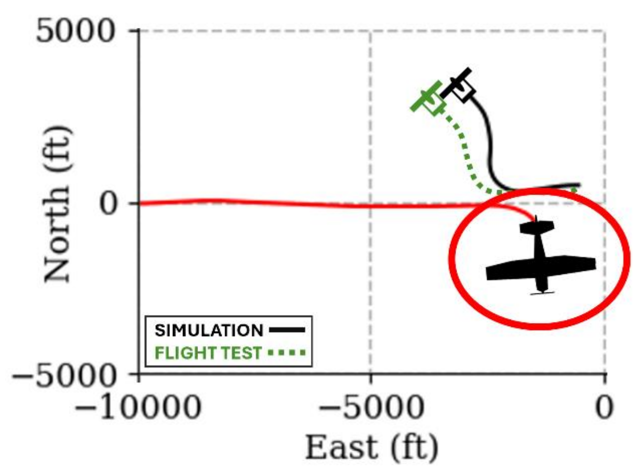
For each flight test, multiple converging aircraft encounters were completed. These encounters were flown with a relative heading angle of $180° \pm 45°$ between the Cessna 172 and sUAS. For some of these flight tests, which are denoted in Table 148, a virtual Cessna 172 was used in place of a real Cessna 172. The use of a virtual Cessna 172 was beneficial for faster turnaround times between flight tests and high-fidelity preliminary validation for real manned aircraft tests. After these flight tests were completed, simulations were run under the same conditions. These simulations did not account for wind, GPS error, or any other uncertainties, therefore discrepancies are seen between flight test and simulation results. The following tables show pass/fail of flight test vs. simulation. Pass/fail is dependent on the sUAS complying with right of way regulations.

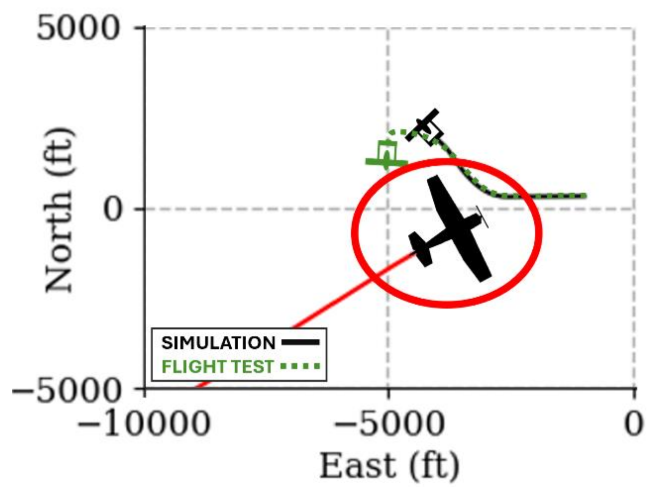
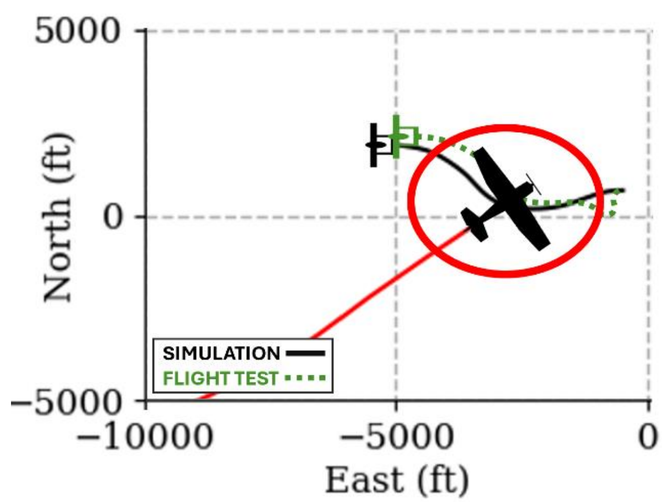
Table 148. Comparison between Flight Test and Simulation of Real sUAS vs Real Crewed Aircraft Encounters (ψ is C-172 Heading Angle, V is C-172 Velocity, and DD is the Set Detection Distance).

Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
1	**Encounter 1: Head On** $\psi = 180°$ $V = 163.71\ ft/s$ $DD = 10{,}000\ ft$	**Pass**	**Pass**	

Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
	Encounter 2: Head On $\psi = 180°$ $V = 153.64\ ft/s$ $DD = 13{,}000\ ft$	**Pass**	**Pass**	
2	**Encounter 1: Head On** $\psi = 180°$ $V = 165.64\ ft/s$ $DD = 8{,}000\ ft$	**Pass**	**Pass**	
	Encounter 2: Head On $\psi = 180°$ $V = 165.06\ ft/s$ $DD = 7{,}000\ ft$	**Pass**	**Pass**	

Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
	Encounter 3: Head On $\psi = 180°$ $V = 158.41\ ft/s$ $DD = 5{,}000\ ft$	**Fail**	**Pass**	
3	**Encounter 1: Head On** $\psi = 180°$ $V = 147.98\ ft/s$ $DD = 8{,}000\ ft$	**Pass**	**Pass**	

Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
	Encounter 2: Head On $\psi = 180°$ $V = 152\ ft/s$ $DD = 7{,}000\ ft$	**Pass**	**Pass**	
	Encounter 3: Head On $\psi = 180°$ $V = 151.25\ ft/s$ $DD = 5{,}000\ ft$	**Fail**	**Fail**	

Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
4	**Encounter 1: Front Right** $\psi = 225°$ $V = 162.57\ ft/s$ $DD = 8{,}000\ ft$	**Pass**	**Pass**	
5	**Encounter 1: Front Left** $\psi = 135°$ $V = 161.83\ ft/s$ $DD = 8{,}000\ ft$	**Pass**	**Pass**	

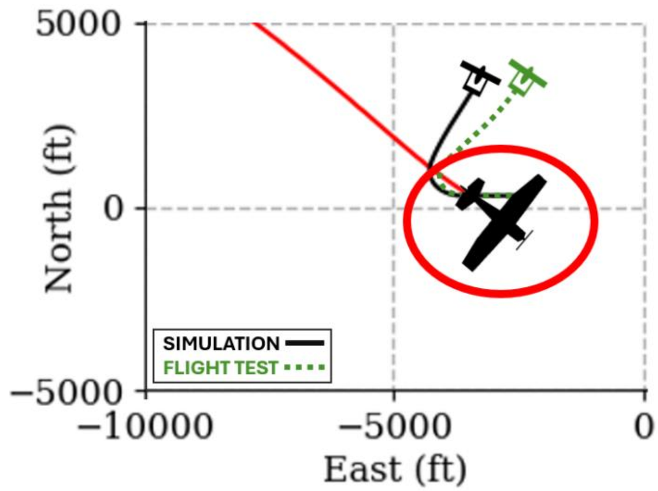
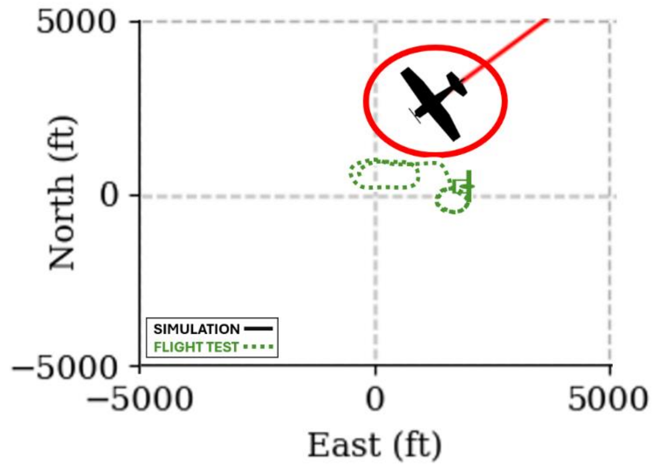
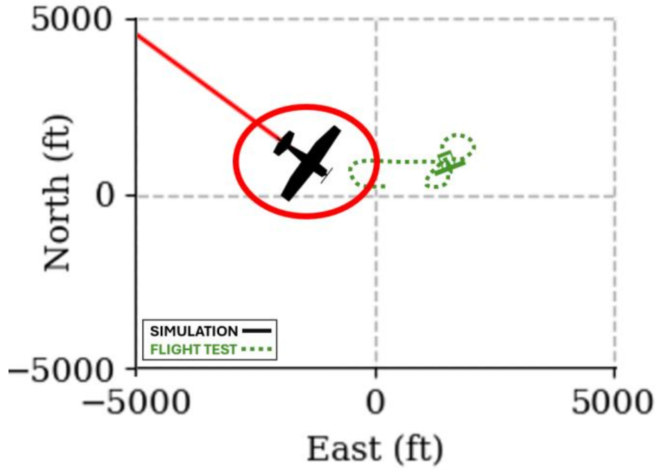
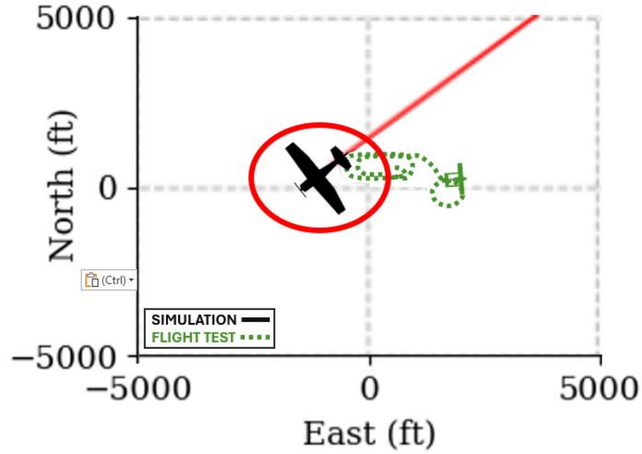
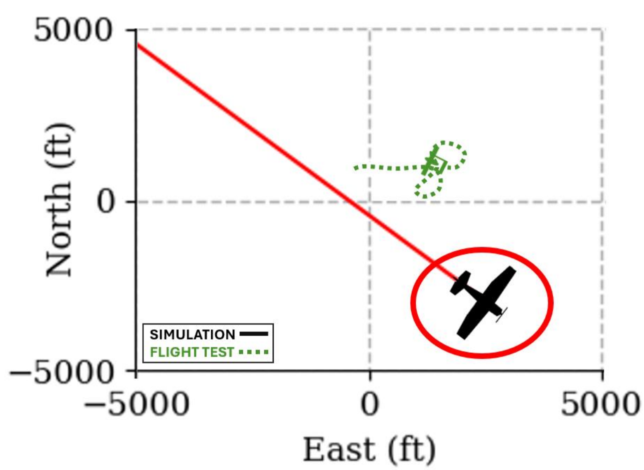
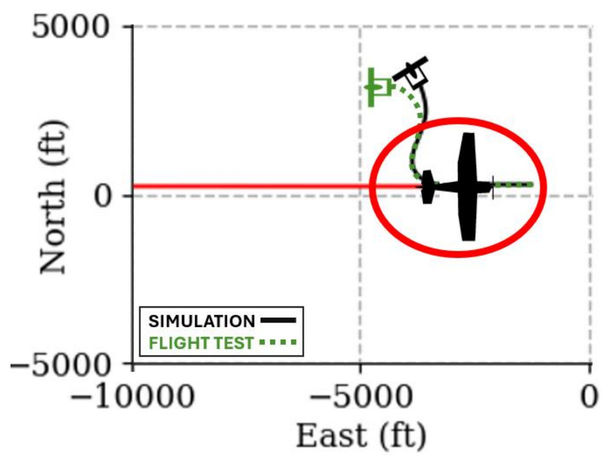
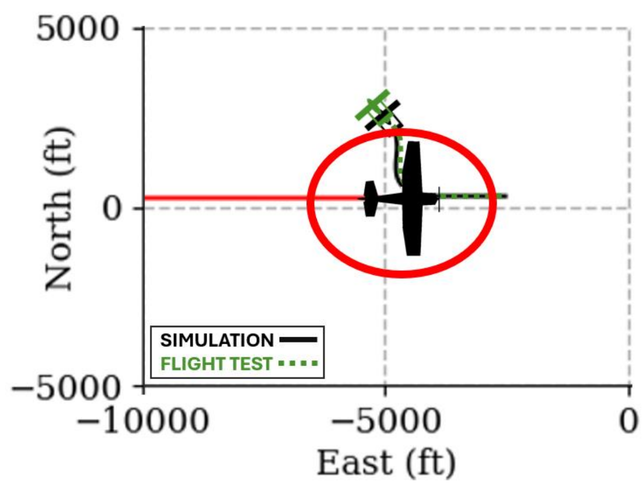
Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
	Encounter 2: Front Left $\psi = 135°$ $V = 160.5\ ft/s$ $DD = 8{,}000\ ft$	**Fail**	**Pass**	

Table 149. Comparison Between Flight Test and Simulation of Real sUAS vs Virtual Crewed Aircraft Encounters (ψ is C-172 Heading Angle, V is C-172 Velocity, and DD is the Set Detection Distance).

Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
1	**sUAS Surveying Encounter 1: Front Left** $\psi = 135°$ $V = 150\ ft/s$ $DD = 10{,}000\ ft$	**Pass**	**N/A**	 **SIMULATION PLOT UNAVAILABLE**

Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
	sUAS Surveying Encounter 2: Front Right $\psi = 225°$ $V = 150\ ft/s$ $DD = 10{,}000\ ft$	**Pass**	**N/A**	 **SIMULATION PLOT UNAVAILABLE**
2	**sUAS Surveying Encounter 1: Front Left** $\psi = 135°$ $V = 150\ ft/s$ $DD = 5{,}280\ ft$	**Fail**	**N/A**	 **SIMULATION PLOT UNAVAILABLE**
	sUAS Surveying Encounter 2: Front Right $\psi = 225°$ $V = 150\ ft/s$ $DD = 5{,}280\ ft$	**Pass**	**N/A**	

Flight Test	C-172 Approach Parameters	FT Result	SIM Result	Plotted Results
				SIMULATION PLOT UNAVAILABLE
3	**Encounter 1: Head On** $\psi = 180°$ $V = 170\ ft/s$ $DD = 10{,}000\ ft$	**Pass**	**Pass**	
	Encounter 2: Head On $\psi = 180°$ $V = 170\ ft/s$ $DD = 8{,}000\ ft$	**Pass**	**Pass**	

Flight tests one and two from Table 150 present the results from actual-virtual encounters between the SkyHunter UAS and a Cessna C-172 GA aircraft. During the surveying flight tests, the SkyHunter encountered the Cessna C-172 at two approach angles: 225 and 135 degrees, with detection ranges of 10,087 feet and 5,295 feet, respectively. Although the avoidance maneuvers were initiated earlier with the larger detection range (10,087 feet), the loiter position was spatially fixed (as determined by the optimization algorithm) for both detection ranges. Consequently, no significant differences were observed in the minimum distances between the UAS and the GA aircraft (2,002 feet versus 1,997 feet). The primary difference was the ability to pass the minimum threshold when the aircraft had a greater detection range.

Table 150. Under 250 ft Difference Between Flight Test and Simulation.

Flight Test	Encounter Number	Flight Test and Simulation Error (Difference Between Closest Approach Distance)	FT Result	SIM Result
1	1	-13 ft	Pass	Pass
	2	40 ft	Pass	Pass
	3	38 ft	Pass	Pass
2	1	-78 ft	Pass	Pass
	2	30 ft	Pass	Pass
	3	-5 ft	Fail	Fail
3	1	200 ft	Pass	Pass
	2	-243 ft	Pass	Pass
4	1	90 ft	Pass	Pass
	2	-62 ft	Fail	Fail
5	1	142 ft	Pass	Pass
6	1	-73 ft	Fail	Fail
7	1	-154 ft	Fail	Fail
	Root Mean Squared Error	114.5 ft		
	Absolute Average	89.9 ft		
	Standard Deviation	119.0 ft		

Table 151. Over 250 ft Difference Between Flight Test and Simulation.

Flight Test	Encounter Number	Flight Test and Simulation Error (Difference Between Closest Approach Distance)	FT Result	SIM Result
3	3	588 ft	Fail	Pass
5	2	-468 ft	Pass	Fail
	3	-583 ft	Fail	Fail
7	3	-354 ft	Pass	Pass
	Root Mean Squared Error	507.4 ft		
	Absolute Average	498.25 ft		
	Standard Deviation	**4.4 ft**		

H.1.3.3 Summary

The University of Kansas Flight Research Team conducted a thorough analysis of the minimum detection distances required and minimum corridor widths required for single as well as a multiple sUAS to prevent a ROWV or an NMAC with an incoming crewed aircraft. These simulations were done using a six degree of freedom dynamic model of a C172 and a SkyHunter sUAS at three different speeds, 10 heading angles and 10 detection distances. Three different collision avoidance algorithms were employed for this analysis. To validate the results of the simulations, the team proceeded to implement the avoidance algorithms used in simulation to flight tests. The flight tests helped the team fix minor errors in the avoidance algorithms as well as validate the results of the simulations. The conclusions made from the simulations closely resemble the results found in flight tests. ***As such, the predictions of required detection distance determined from simulations may be judged to be credible.*** That said, as with all safety-related assessments, some factor of safety should be considered.

For future studies, a higher discretization of detection distances, heading angles as well as incoming crewed aircraft speeds would be worth investigating as it was found that the required detection distance as well as the maneuvering distance of the sUAS widely changed as a function of relative velocity, relative approach angle, and relative position of the incoming crewed aircraft with respect to the UAS. Other avoidance concepts should also be considered to ensure the study is more comprehensive.

APPENDIX I – FINAL TASK 3 AND 4 RESULTS AND INTERPRETATIONS FROM KU GRAPHS AND FIGURES

I.1 General Interactions, Single sUAS

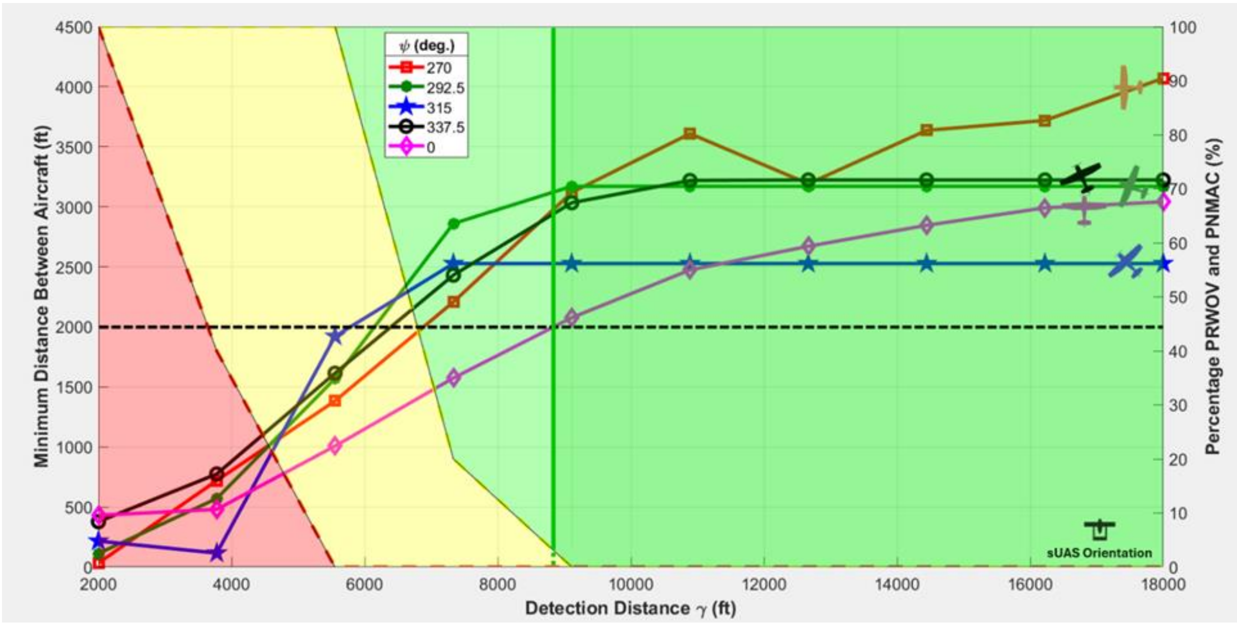


Figure 281. Cessna 172 Flying at 145 ft/s Overtaking Single sUAS Flying at 45 ft/s .

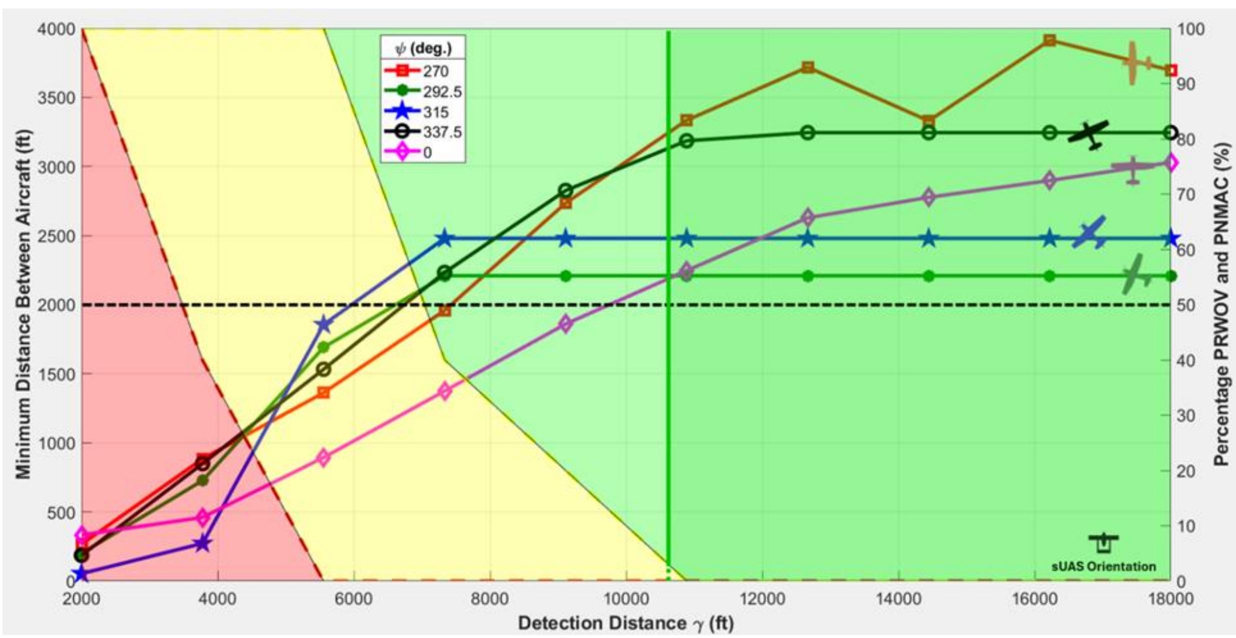


Figure 282. Cessna 172 Flying at 170 ft/s Overtaking Single sUAS Flying at 45 ft/s.

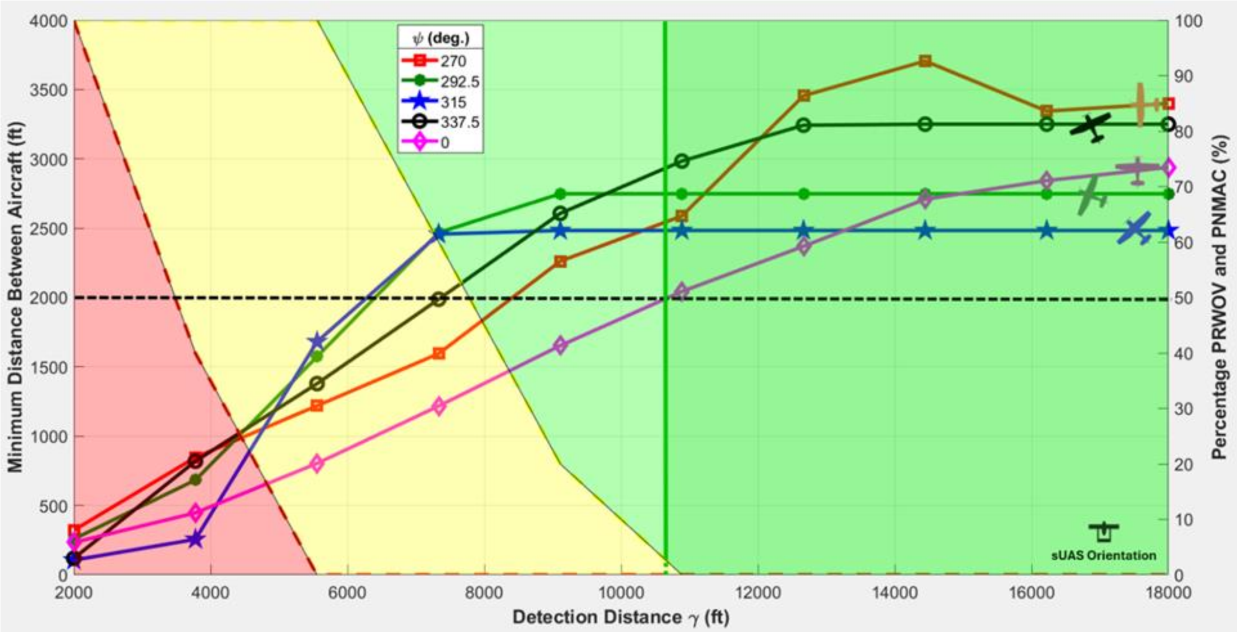


Figure 283. Cessna 172 Flying at 195 ft/s Overtaking Single sUAS Flying at 45 ft/s.

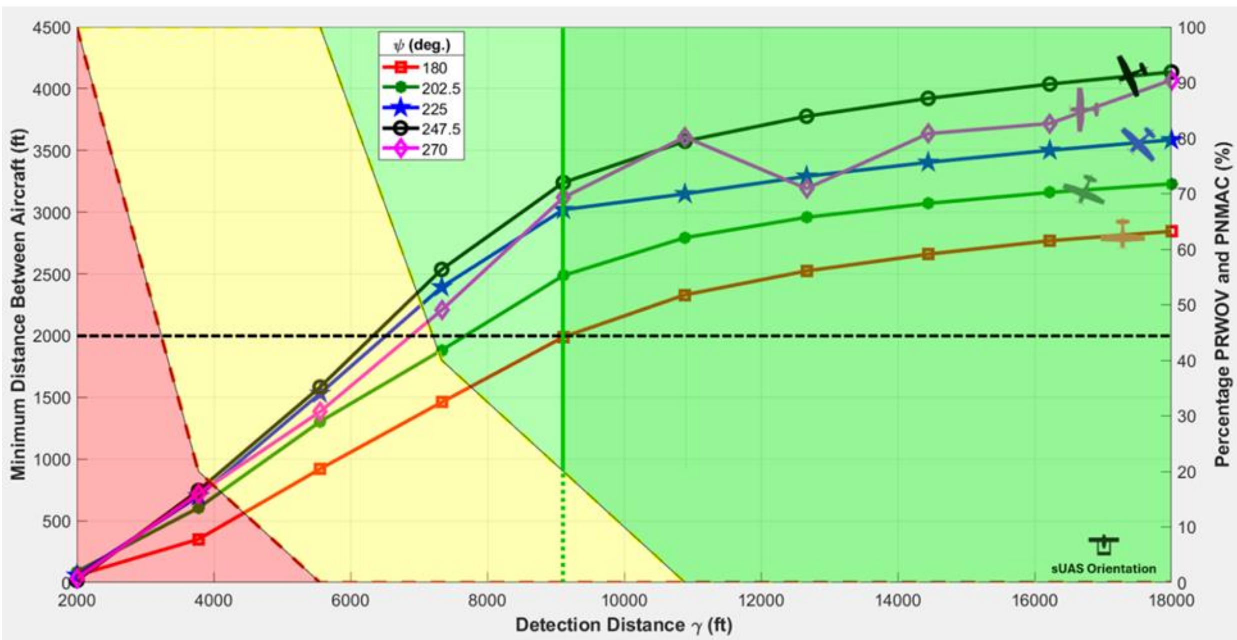


Figure 284. Cessna 172 Flying at 145 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

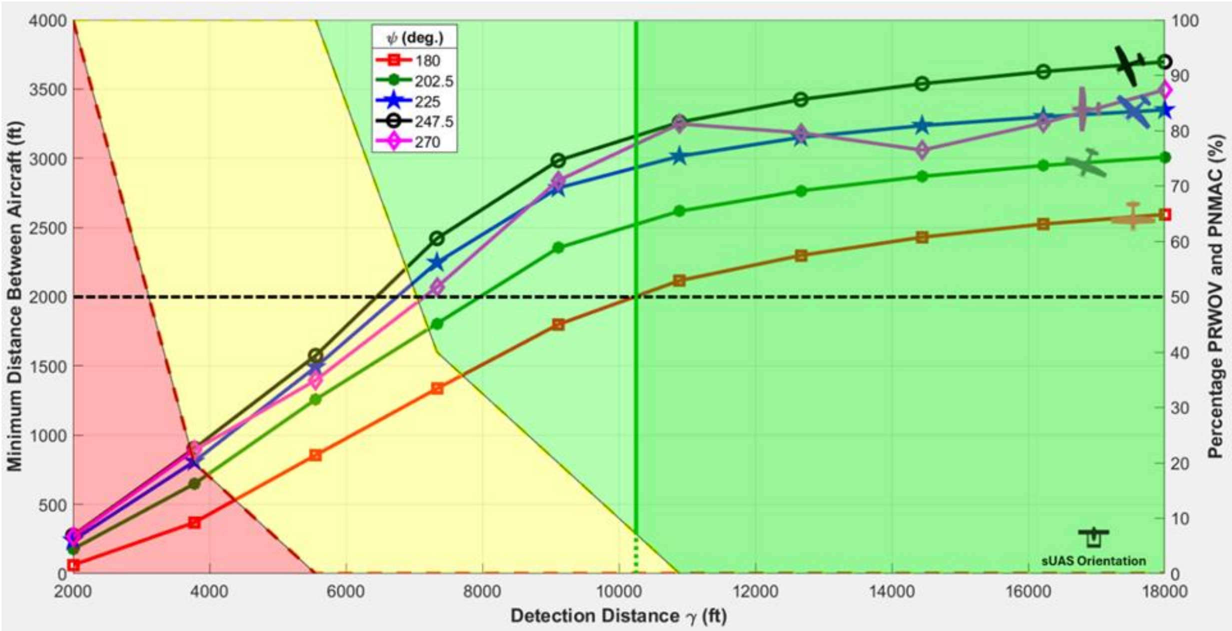


Figure 285. Cessna 172 Flying at 170 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

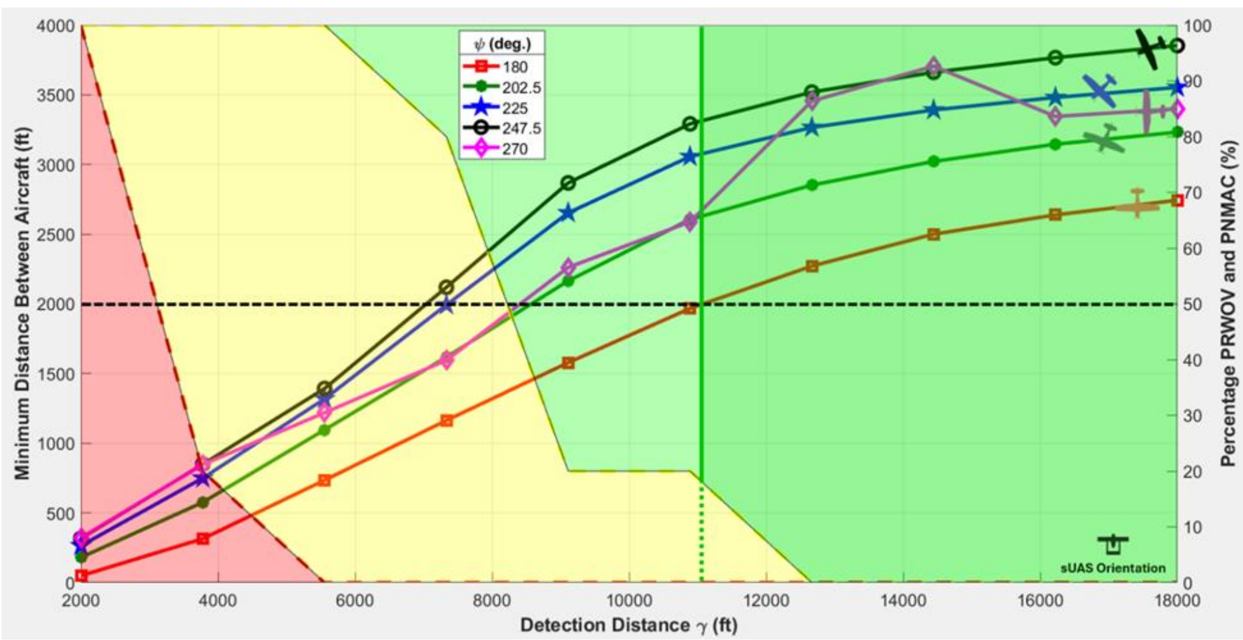


Figure 286. Cessna 172 Flying at 195 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

I.2 General Interactions, Multiple sUAS

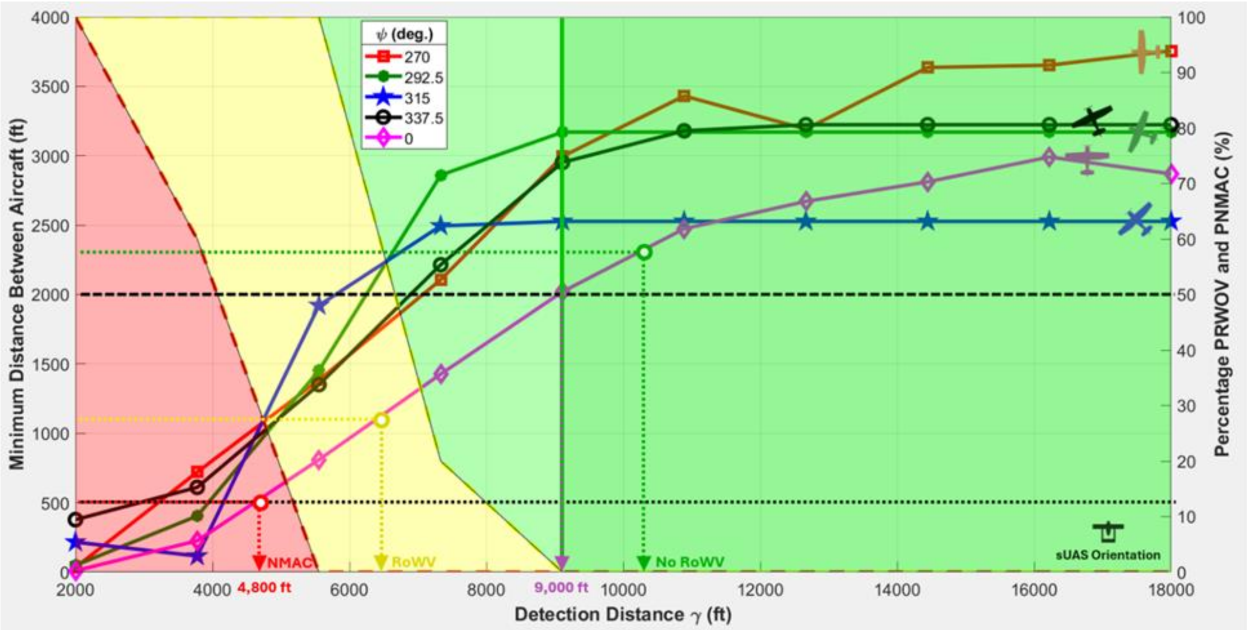


Figure 287. Cessna 172 Flying at 145 ft/s Overtaking Multiple sUAS Flying at 45 ft/s.

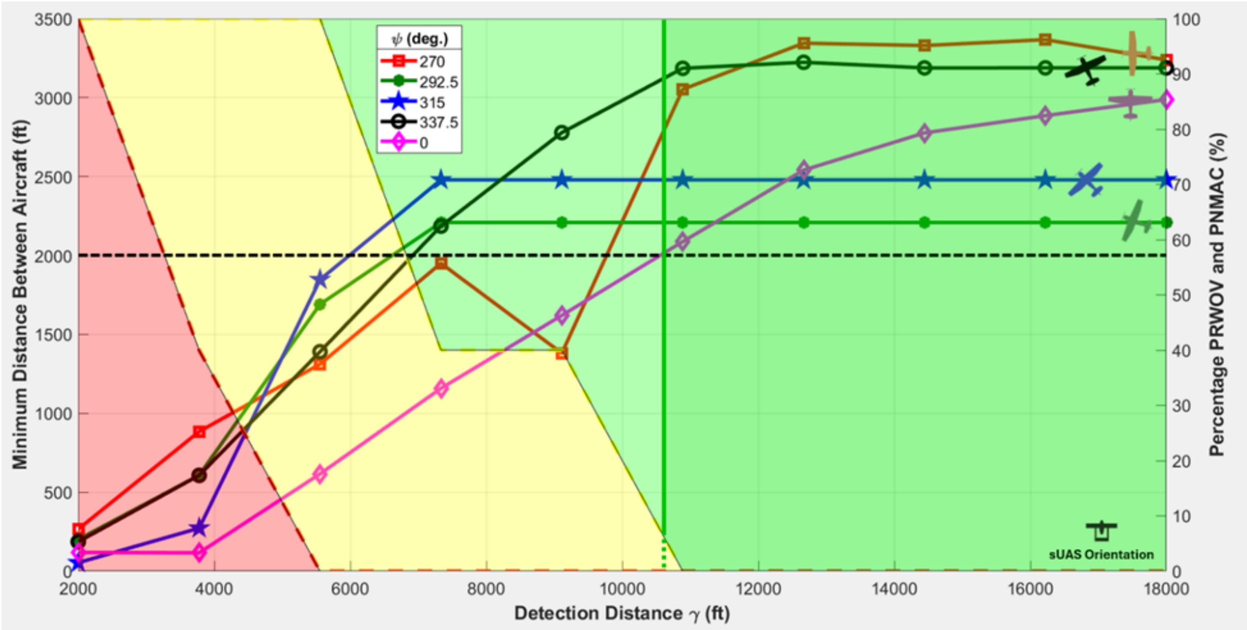


Figure 288. Cessna 172 Flying at 170 ft/s Overtaking Multiple sUAS Flying at 45 ft/s.

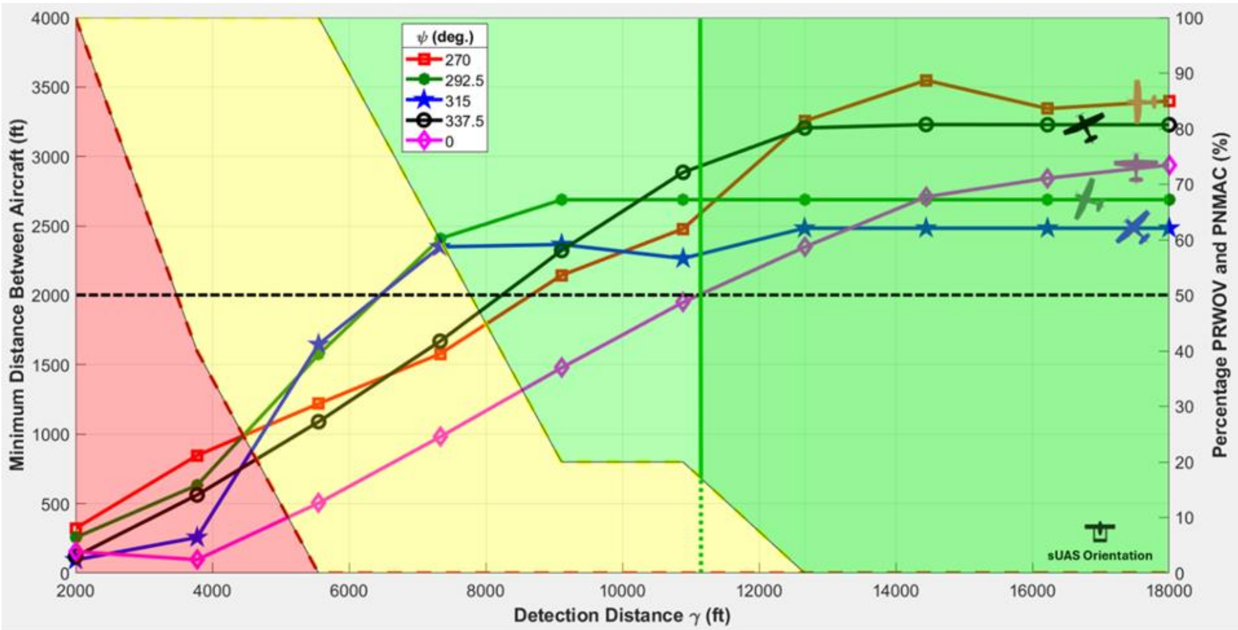


Figure 289. Cessna 172 Flying at 195 ft/s Overtaking Multiple sUAS Flying at 45 ft/s.

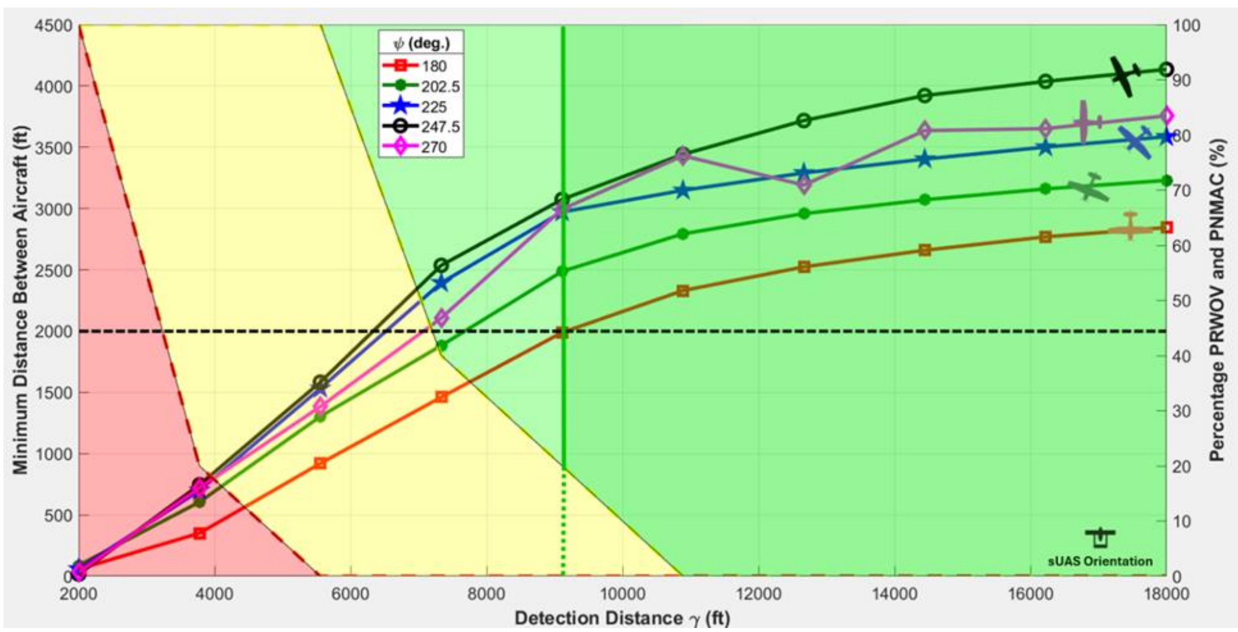


Figure 290. Cessna 172 Flying at 145 ft/s Head-On Converging Multiple sUAS Flying at 45 ft/s.

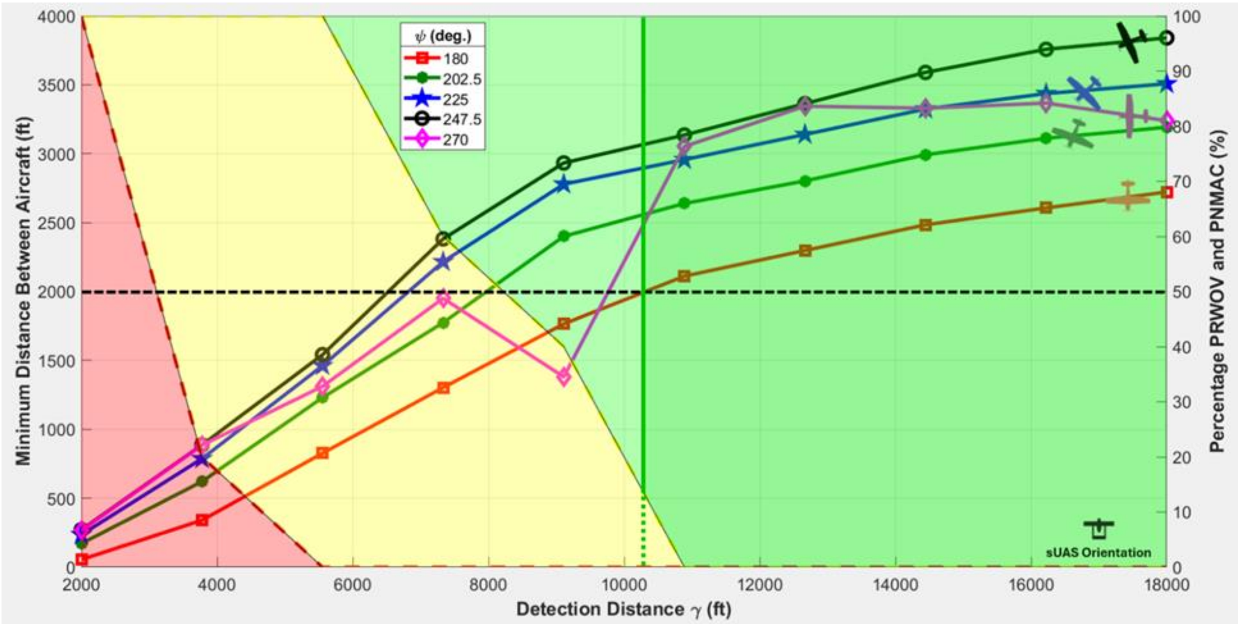


Figure 291. Cessna 172 Flying at 170 ft/s Head-On Converging Multiple sUAS Flying at 45 ft/s.

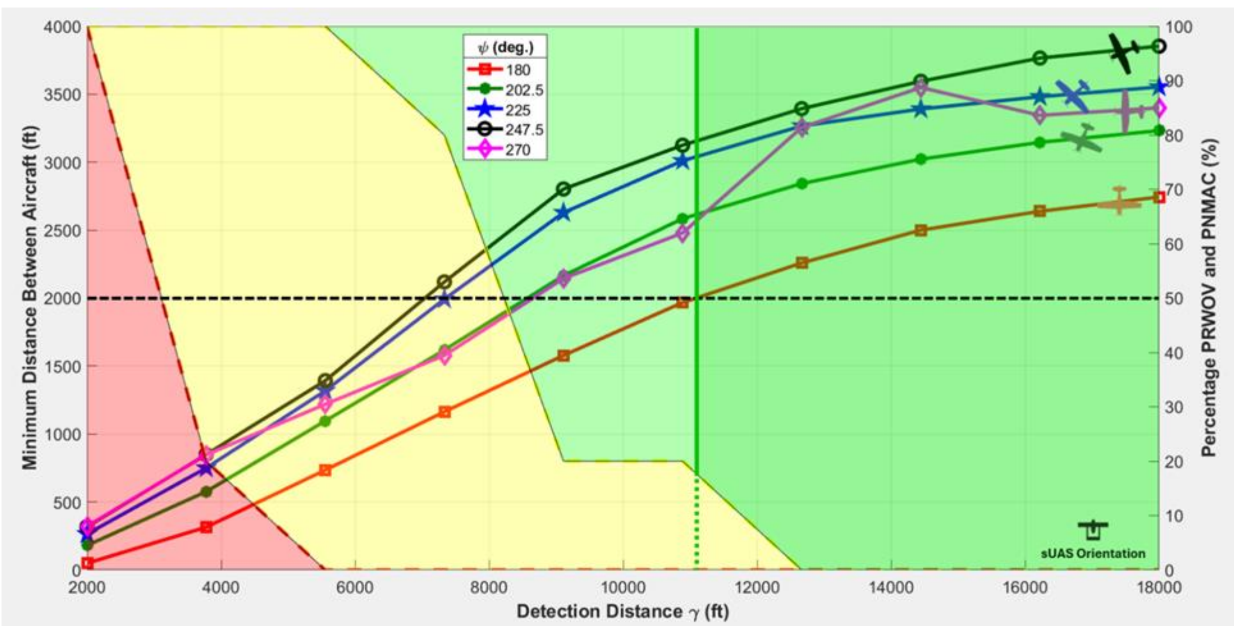


Figure 292. Cessna 172 Flying at 195 ft/s Head-On Converging Multiple sUAS Flying at 45 ft/s.

I.3 Reserved Airspace Flight in a Corridor Single sUAS Morphing Potential Field Algorithm

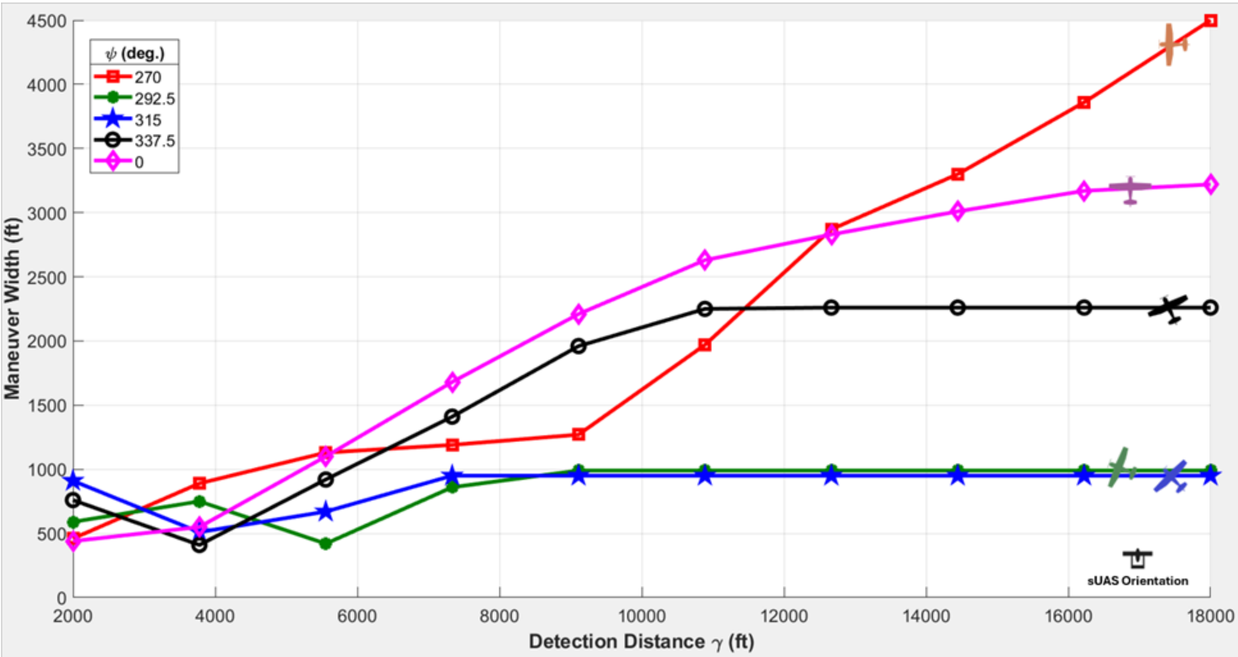


Figure 293. Cessna 172 Flying at 145 ft/s Overtaking Single sUAS Flying at 45 ft/s.

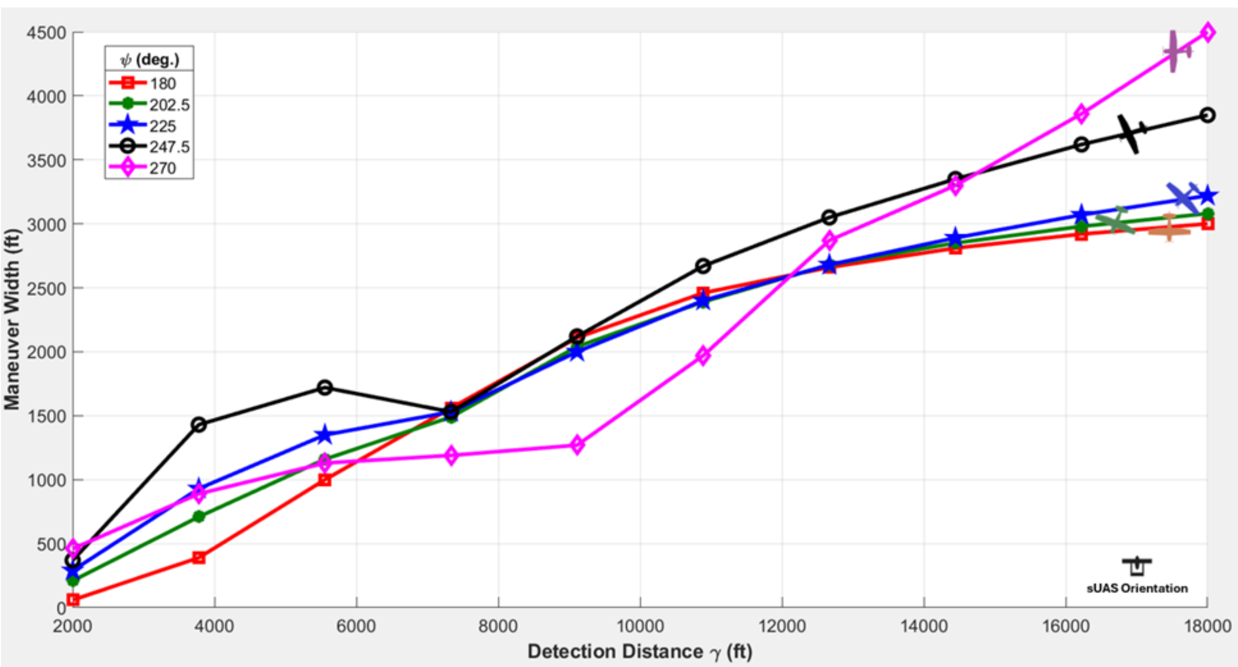


Figure 294. Cessna 172 Flying at 145 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

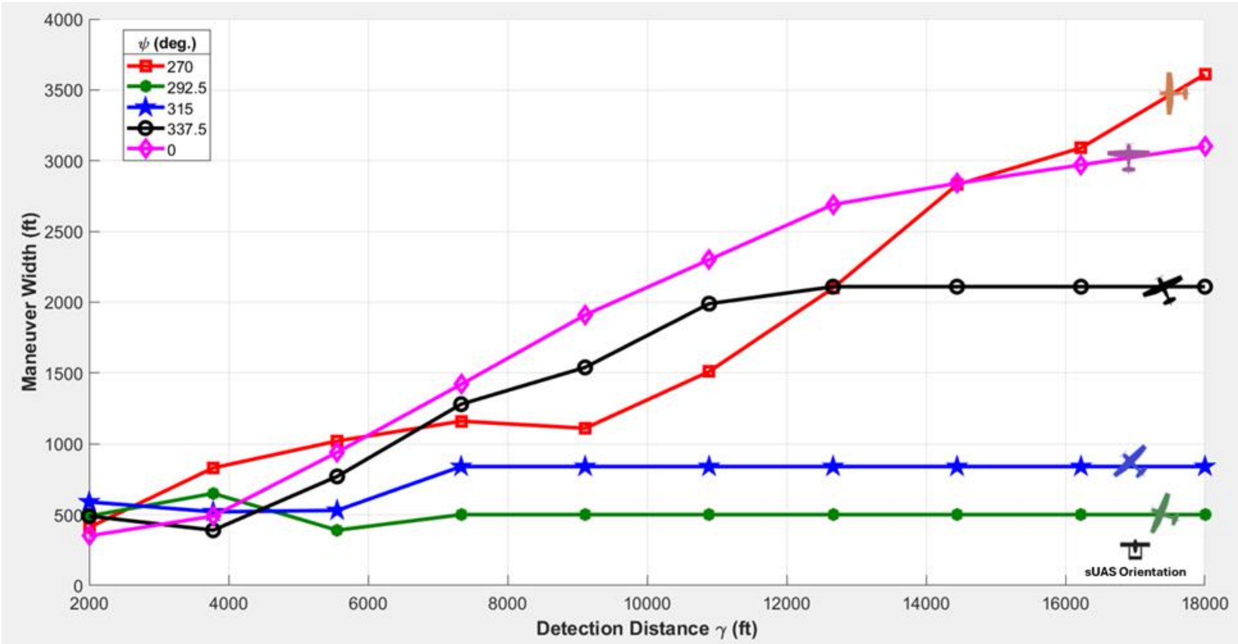


Figure 295. Cessna 172 Flying at 170 ft/s Overtaking Single sUAS Flying at 45 ft/s.

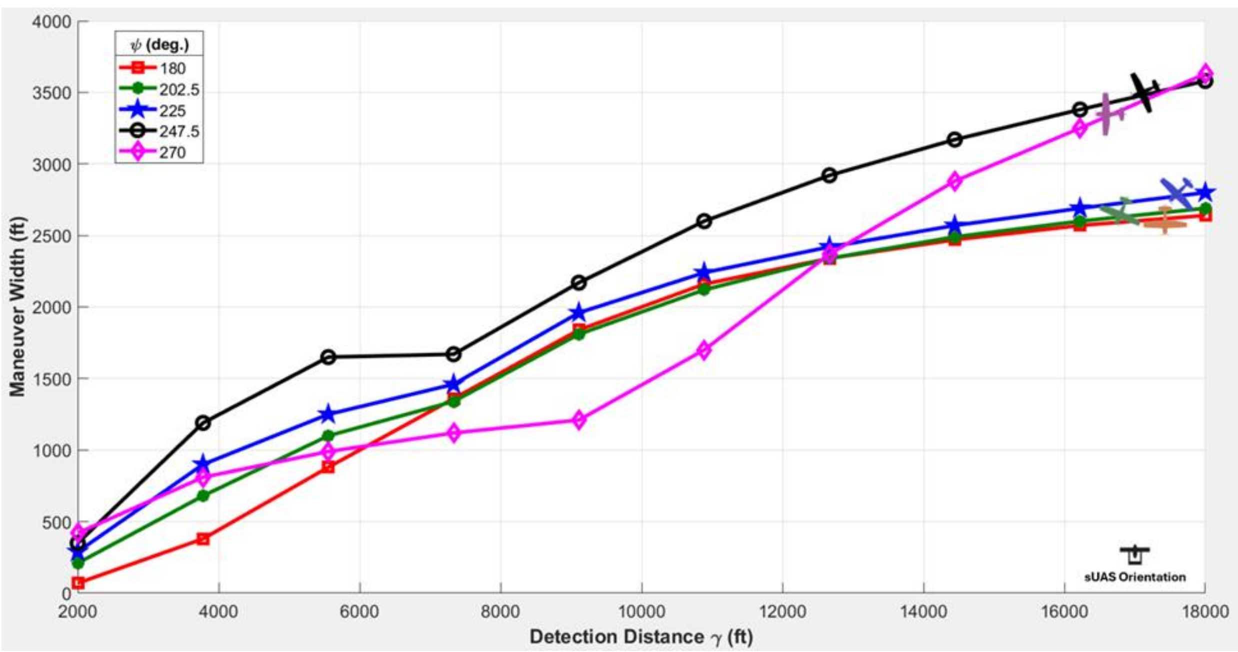


Figure 296. Cessna 172 Flying at 170 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

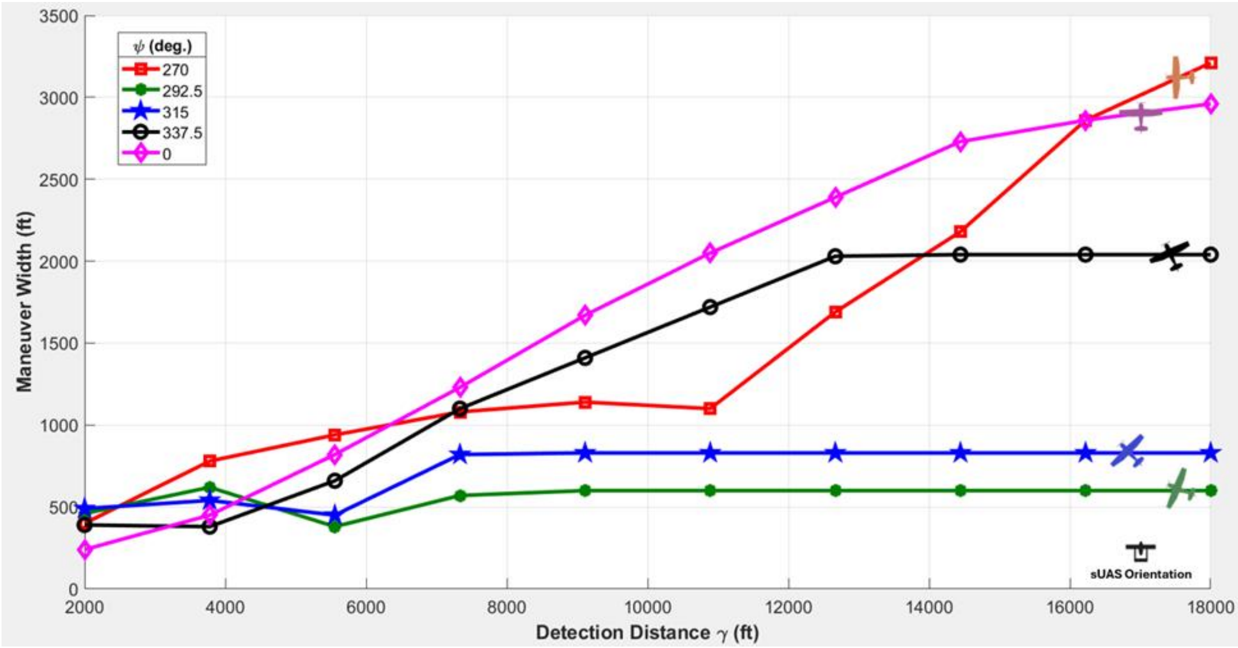


Figure 297. Cessna 172 Flying at 195 ft/s Overtaking Single sUAS Flying at 45 ft/s.

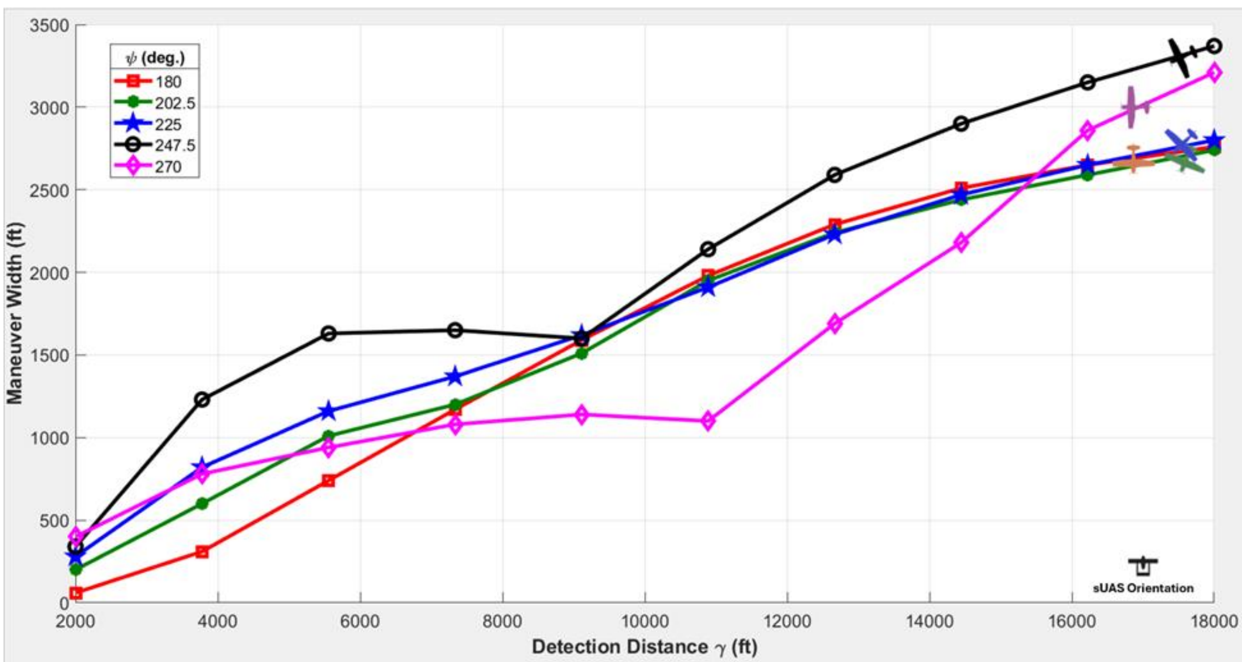


Figure 298. Cessna 172 Flying at 195 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

I.4 Reserved Airspace Flight in a Corridor Single sUAS Loiter Guidance Algorithm

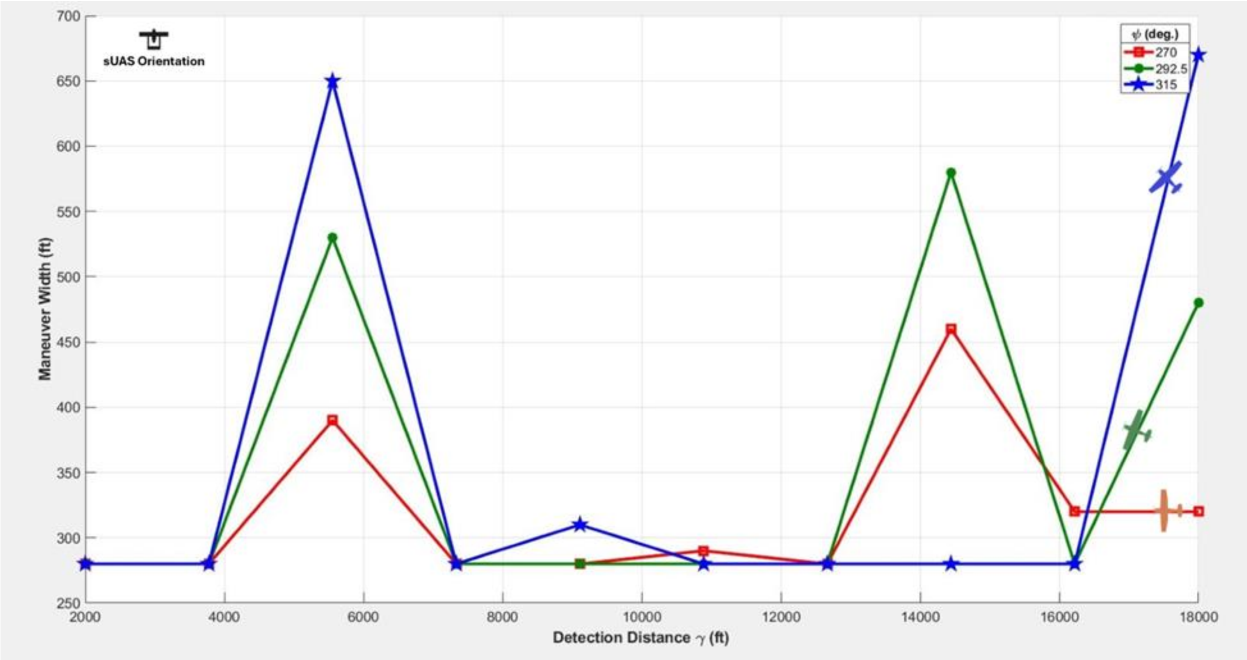


Figure 299. Cessna 172 Flying at 145 ft/s Overtaking Single sUAS Flying at 45 ft/s.

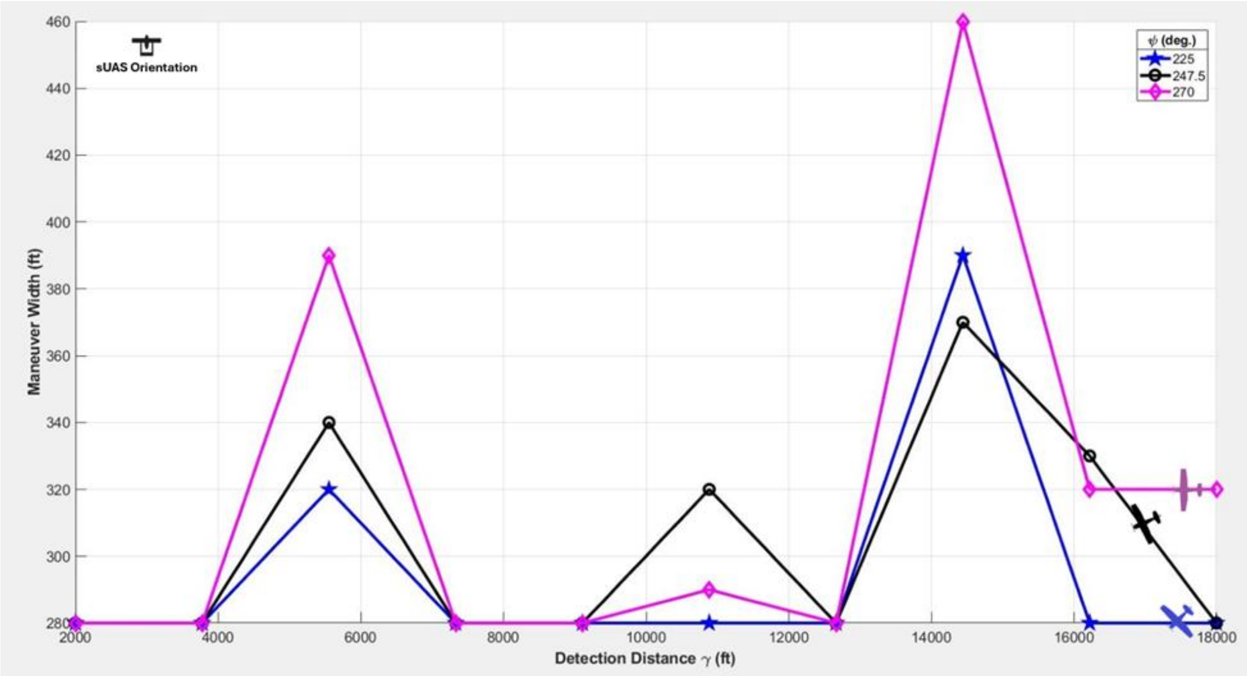


Figure 300. Cessna 172 Flying at 145 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

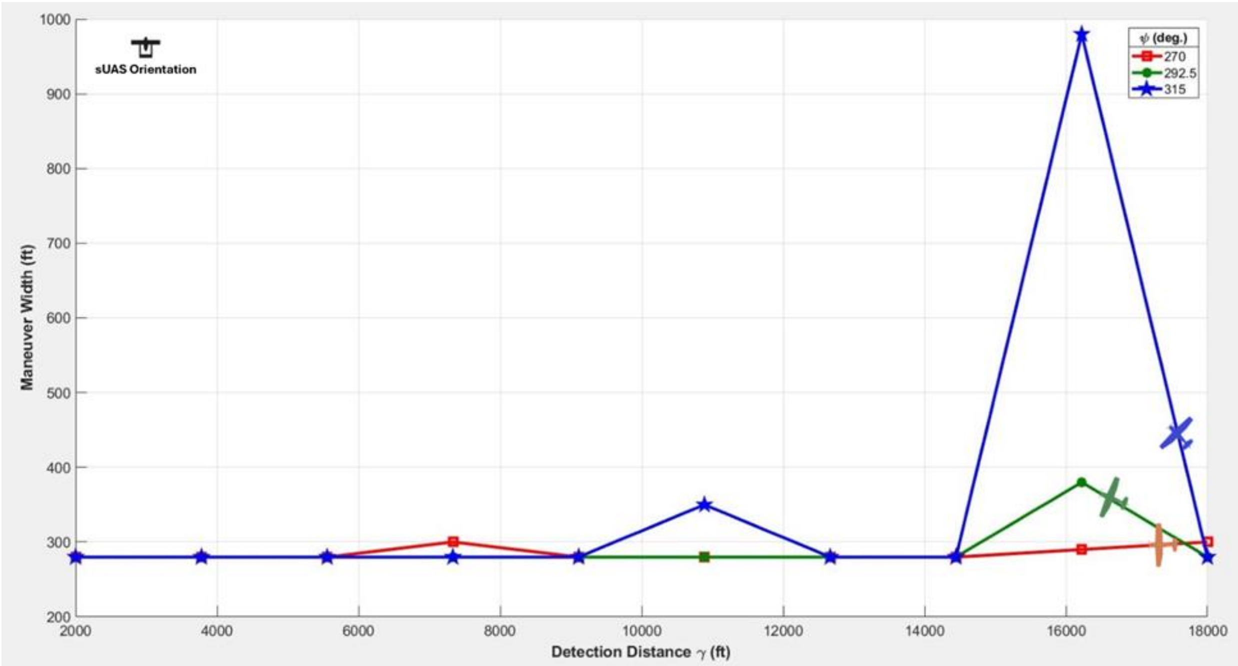


Figure 301. Cessna 172 Flying at 170 ft/s Overtaking Single sUAS Flying at 45 ft/s.

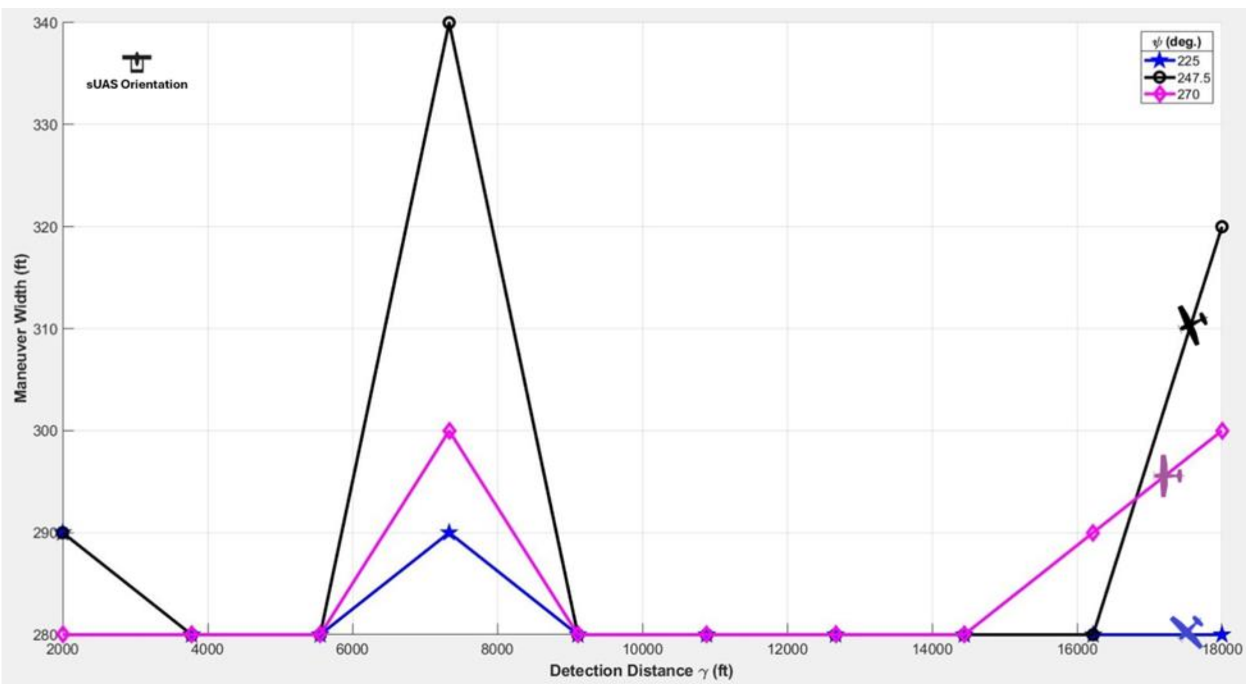


Figure 302. Cessna 172 Flying at 170 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

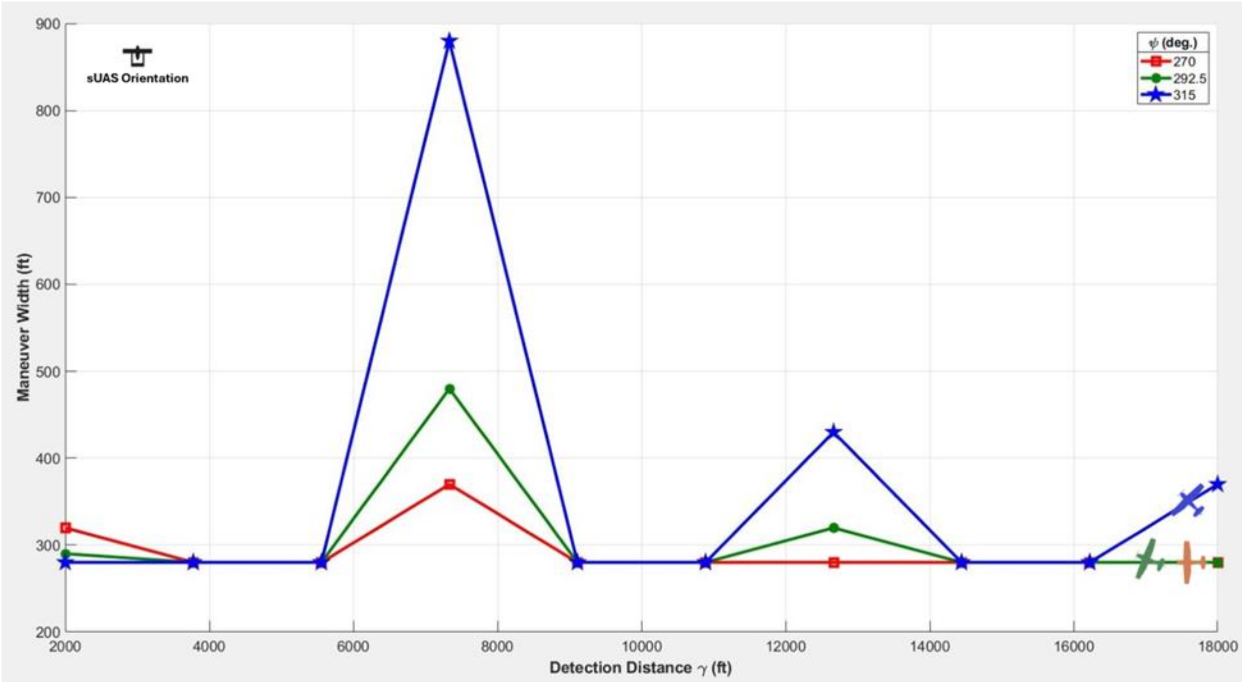


Figure 303. Cessna 172 Flying at 195 ft/s Overtaking Single sUAS Flying at 45 ft/s.

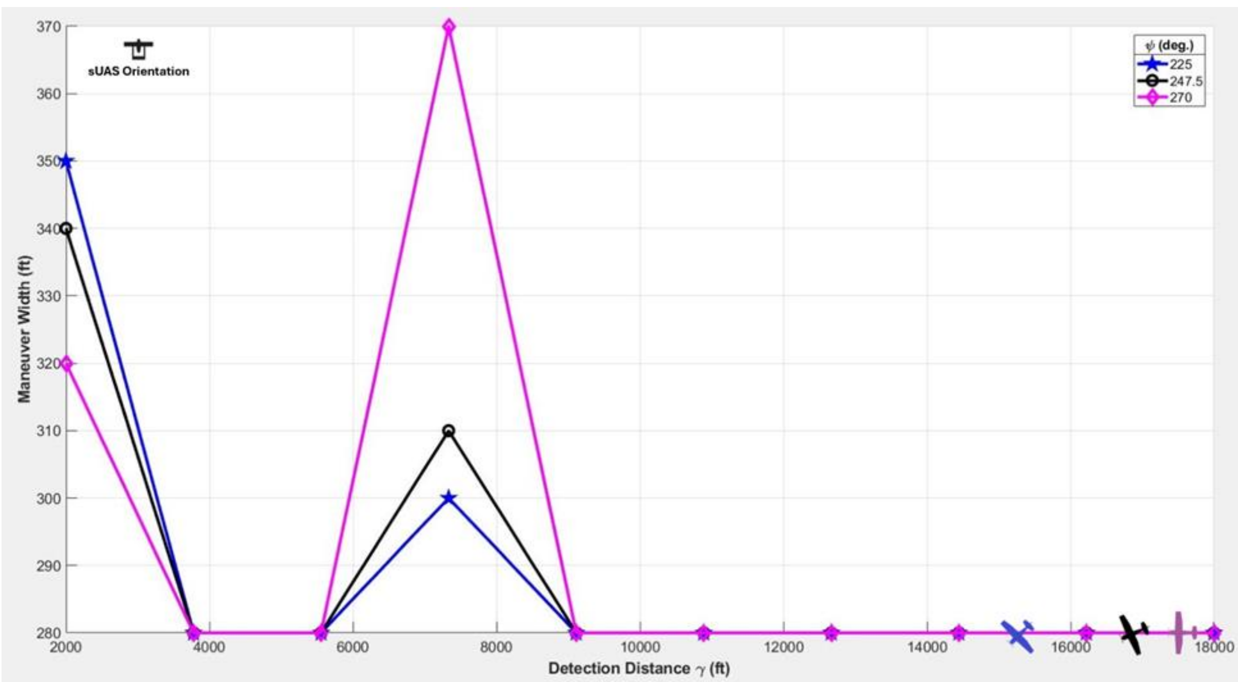


Figure 304. Cessna 172 Flying at 195 ft/s Head-On Converging Single sUAS Flying at 45 ft/s.

I.5 Reserved Airspace Flight in a Corridor, Multiple sUAS

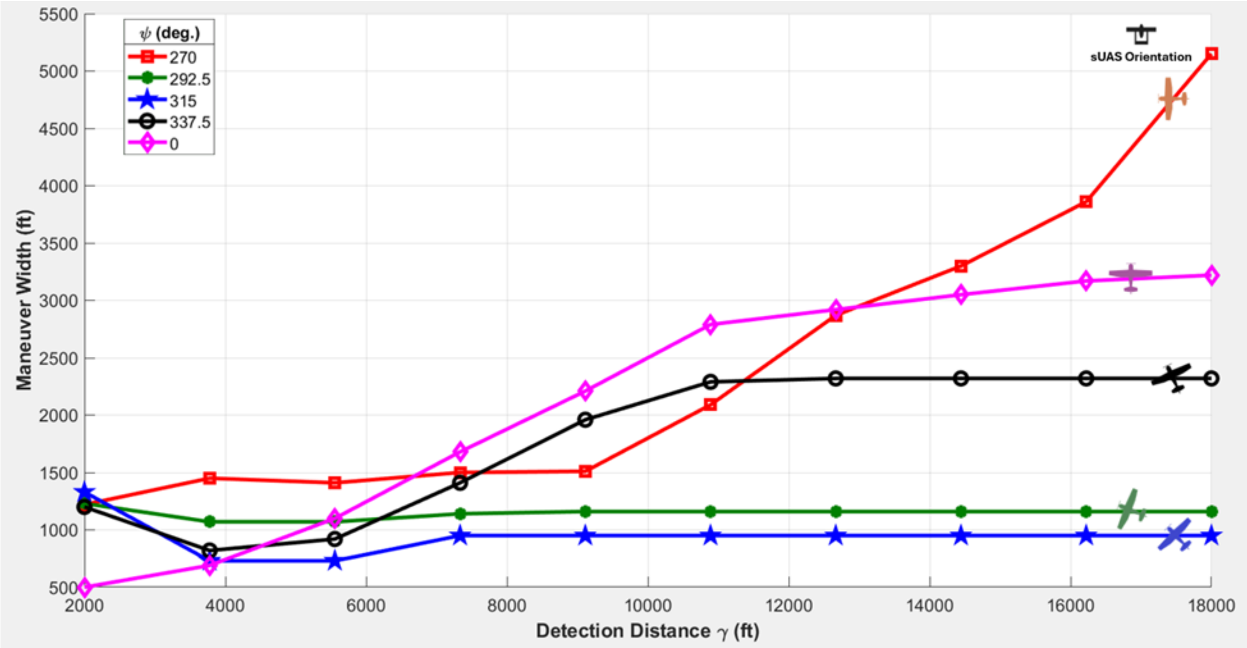


Figure 305. Cessna 172 Flying at 145 ft/s Overtaking Multiple sUAS Flying at 45 ft/s.

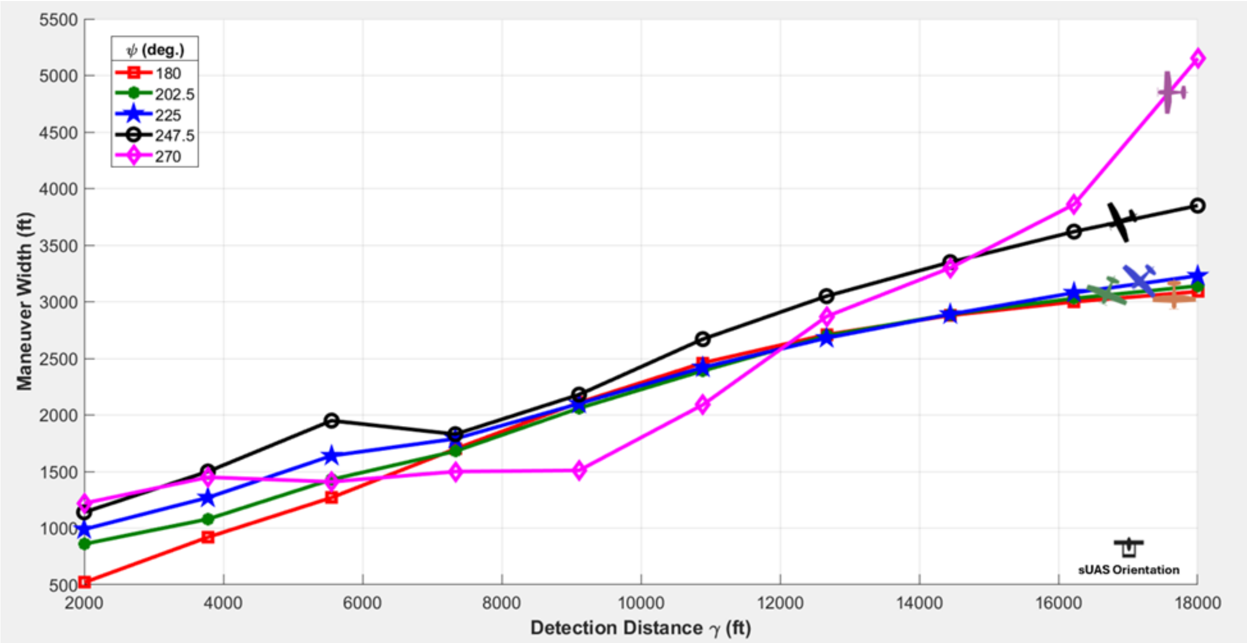


Figure 306. Cessna 172 Flying at 145 ft/s Head-On Converging Multiple sUAS Flying at 45 ft/s.

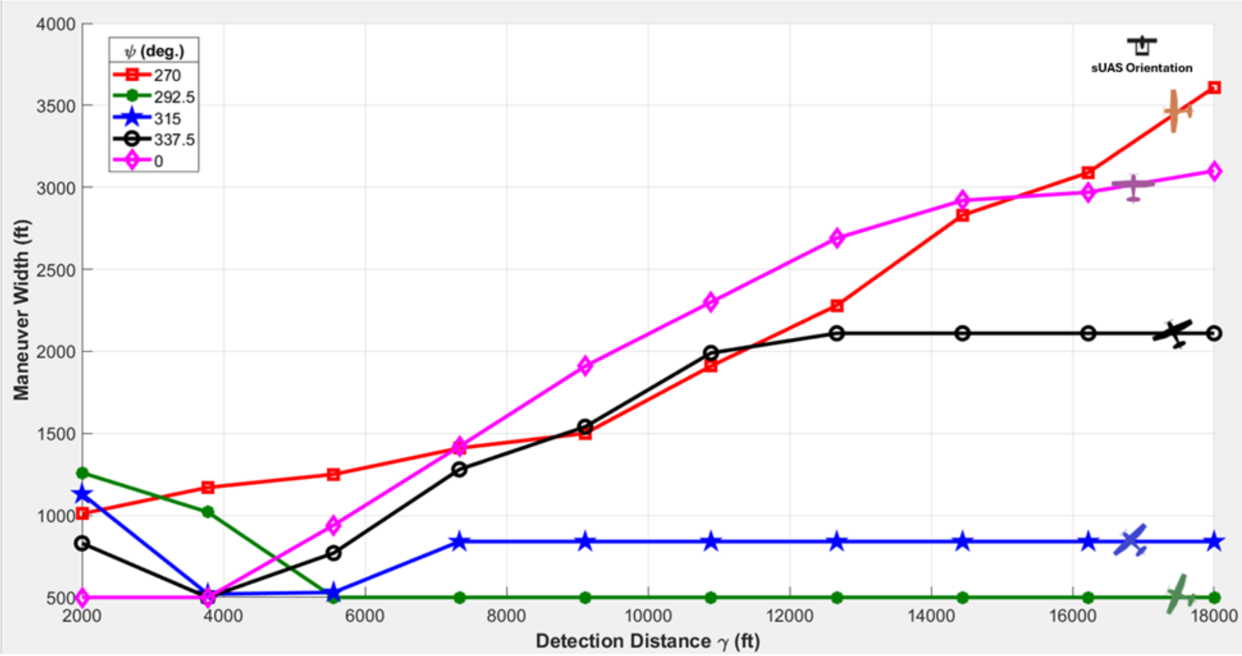


Figure 307. Cessna 172 Flying at 170 ft/s Overtaking Multiple sUAS Flying at 45 ft/s.

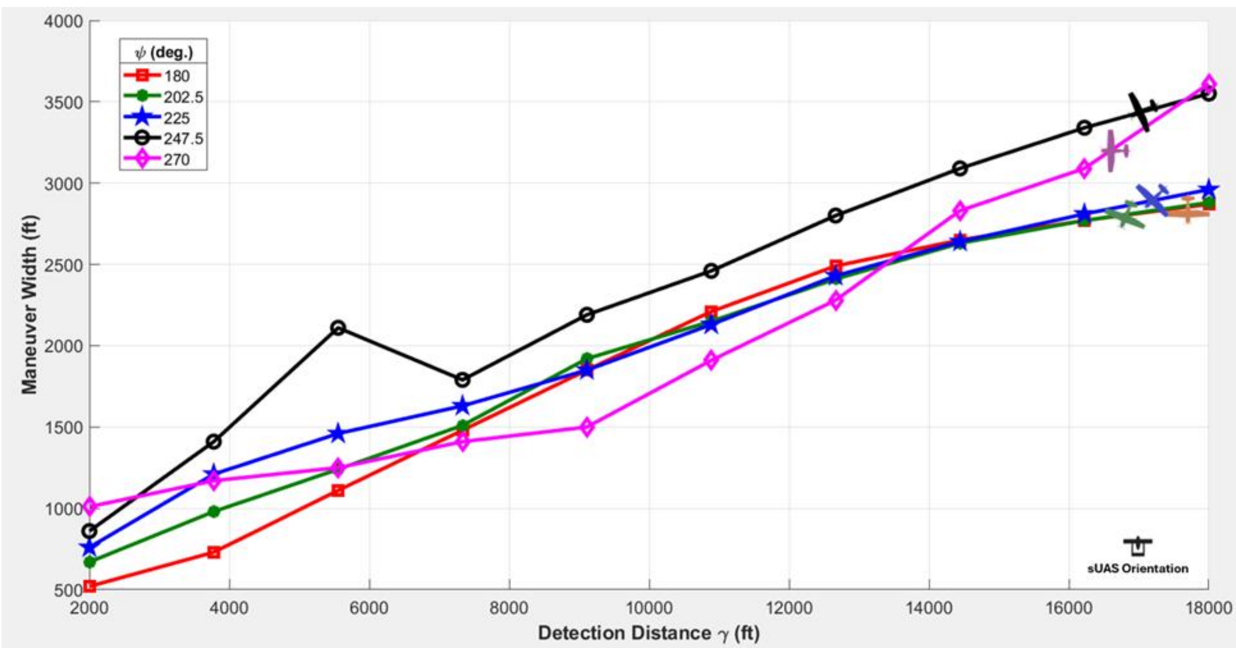


Figure 308. Cessna 172 Flying at 170 ft/s Head-On Converging Multiple sUAS Flying at 45 ft/s.

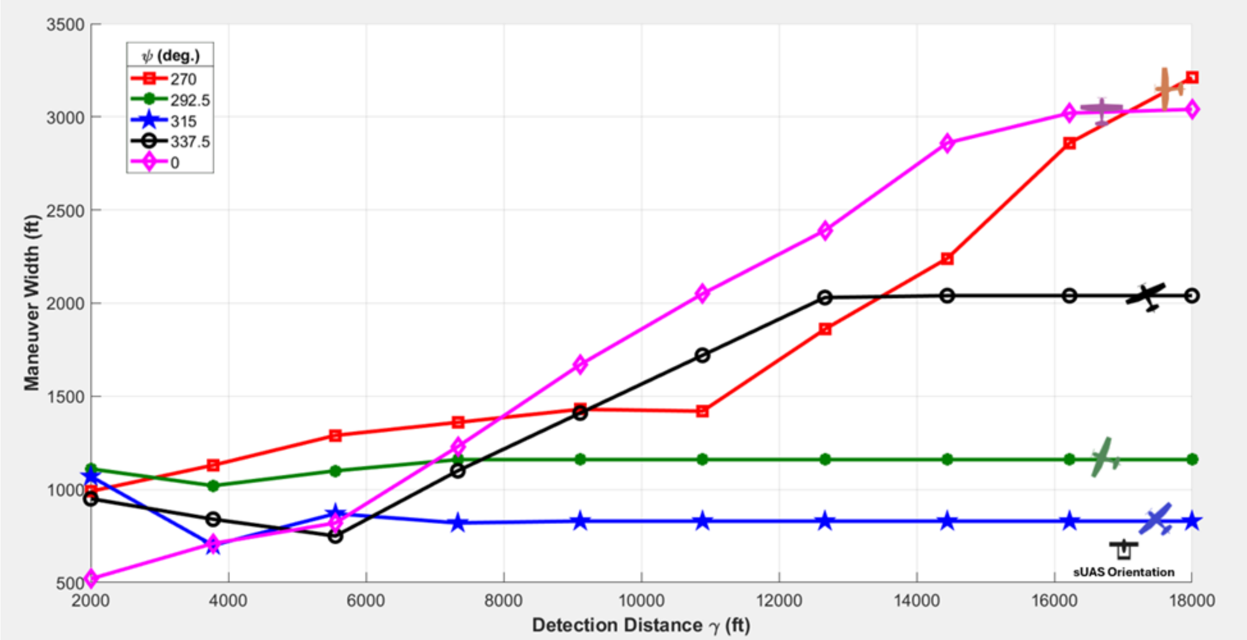


Figure 309. Cessna 172 Flying at 195 ft/s Overtaking Multiple sUAS Flying at 45 ft/s.

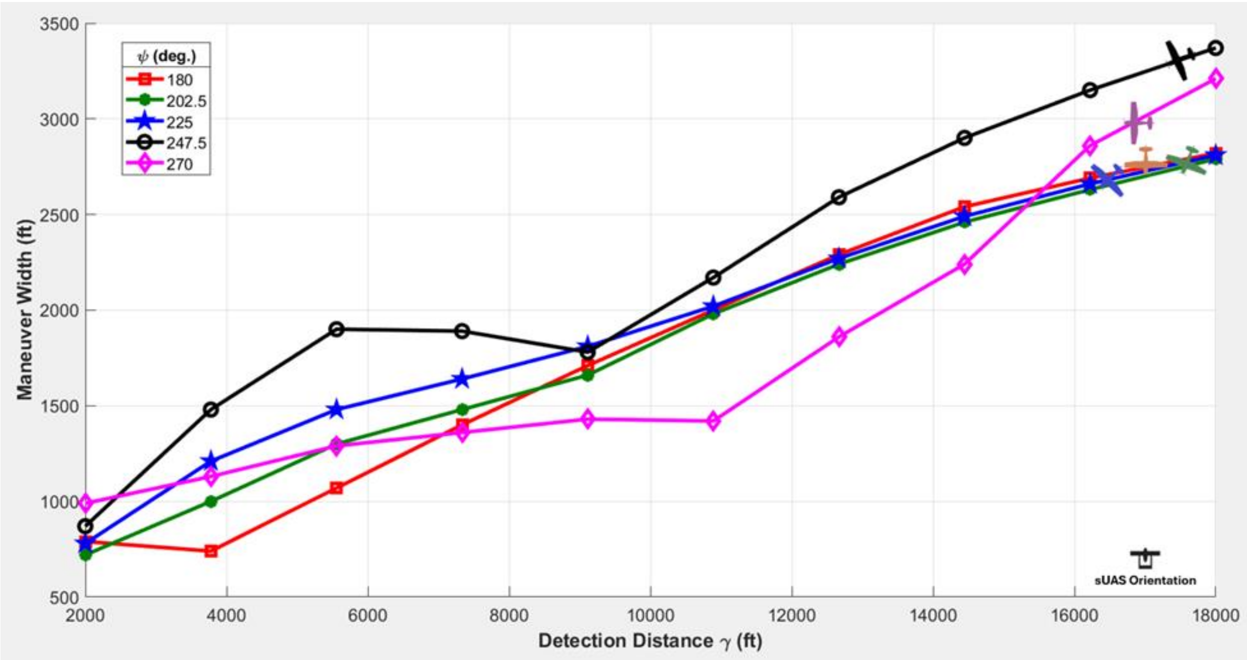


Figure 310. Cessna 172 Flying at 195 ft/s Head-On Converging Multiple sUAS Flying at 45 ft/s.

I.6 Survey Pattern, Single sUAS

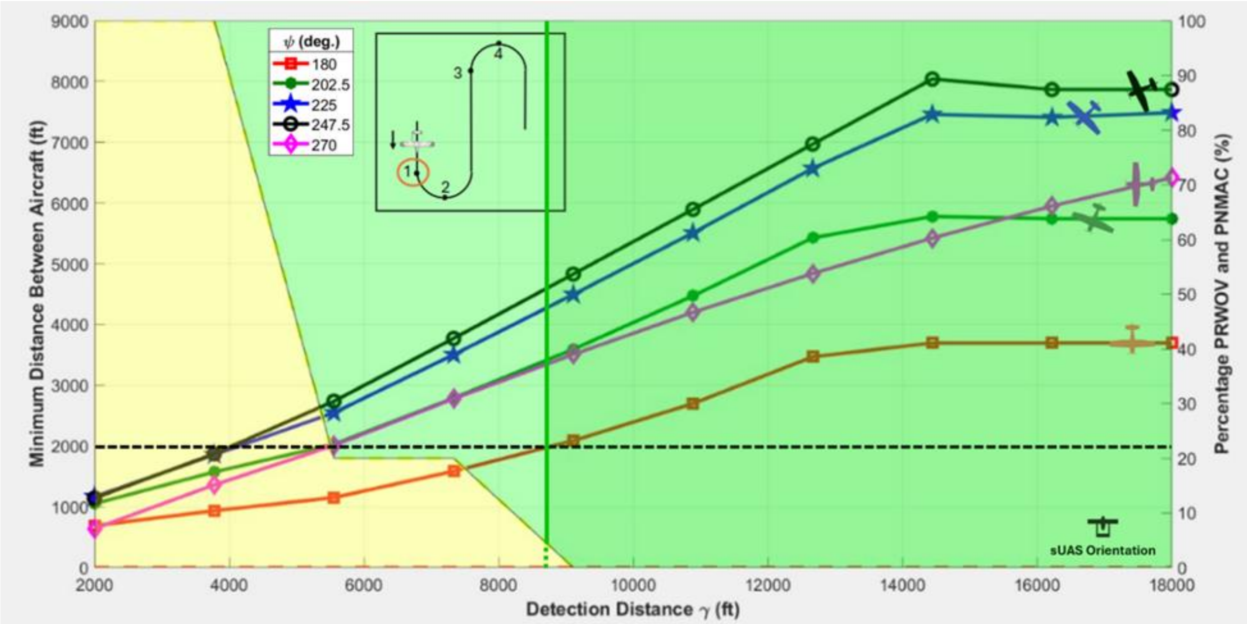


Figure 311. Cessna 172 Flying at 145 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 1.

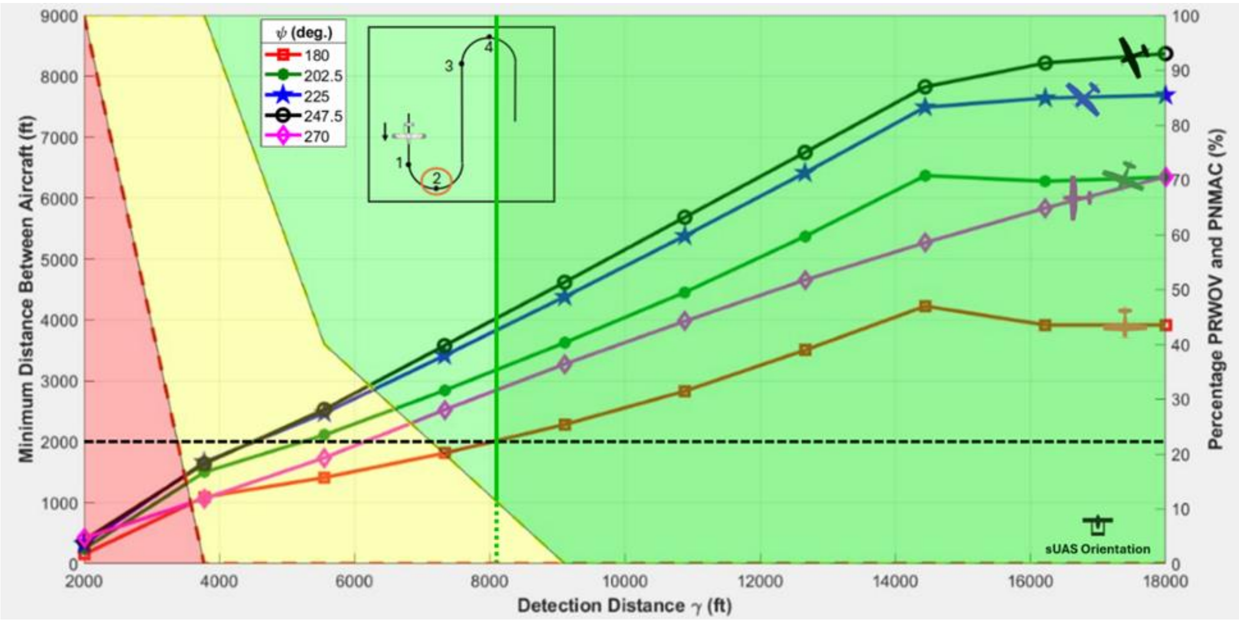


Figure 312. Cessna 172 Flying at 145 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 2.

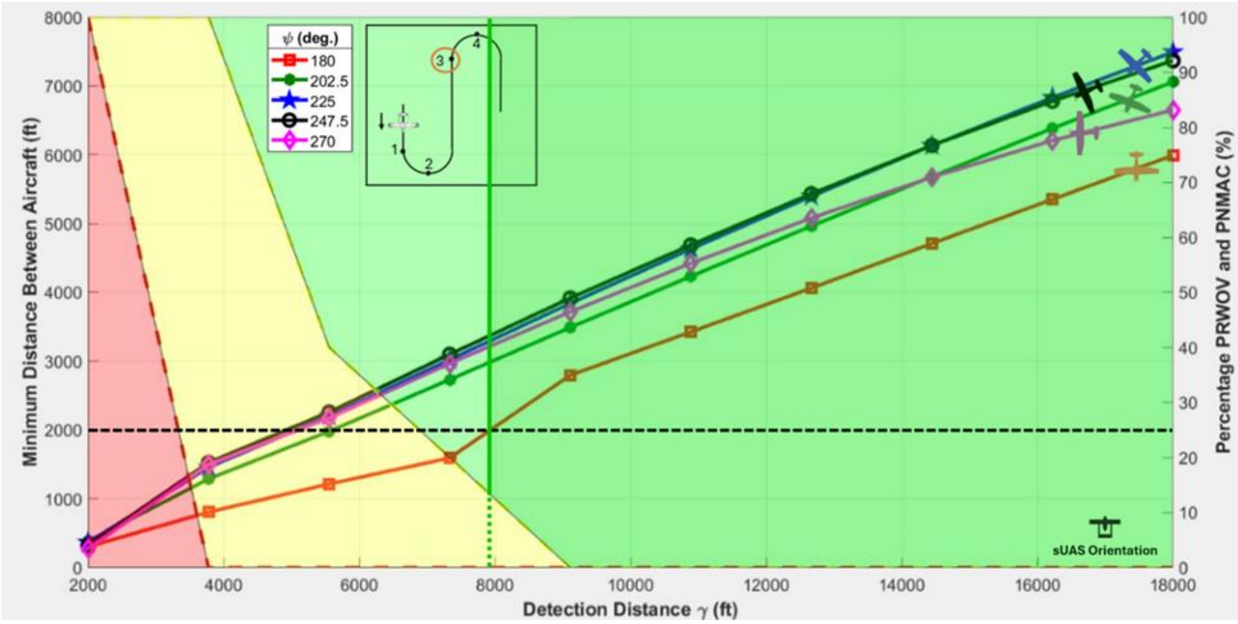


Figure 313. Cessna 172 Flying at 145 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 3.

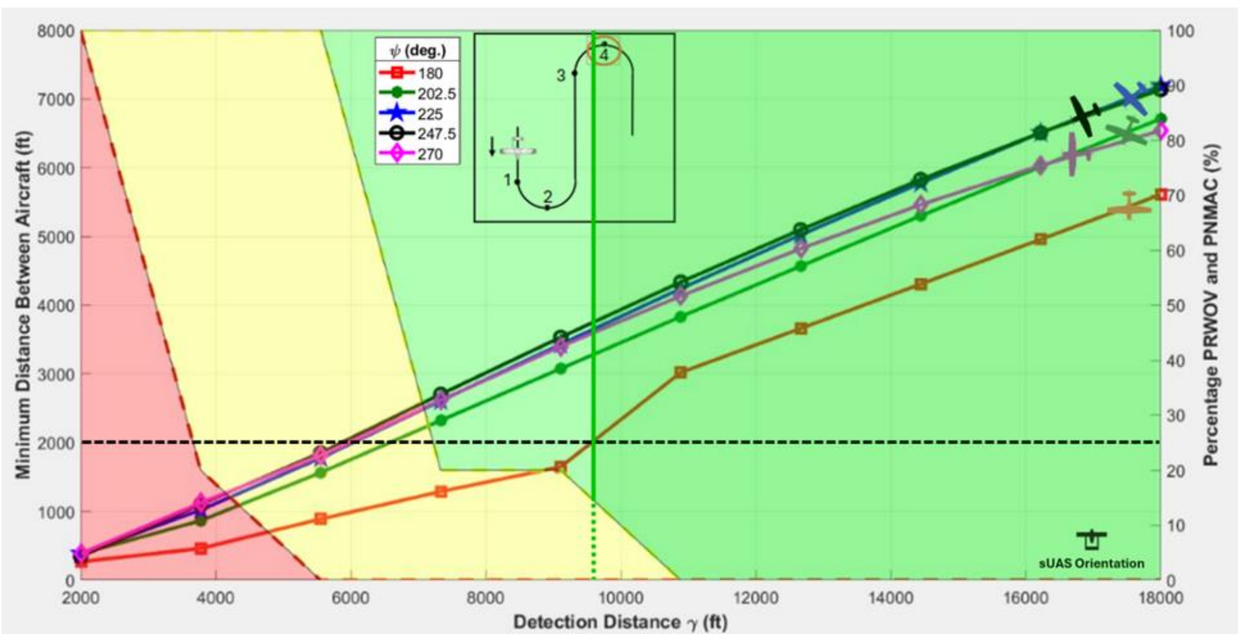


Figure 314. Cessna 172 Flying at 145 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 4.

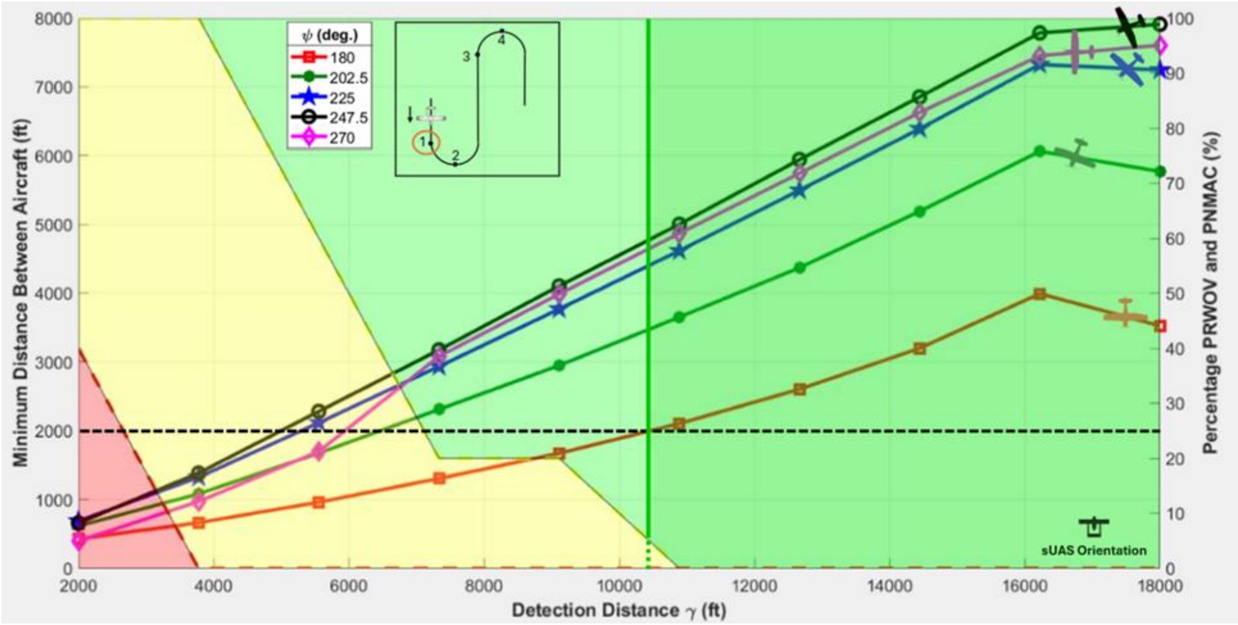


Figure 315. Cessna 172 Flying at 170 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 1.

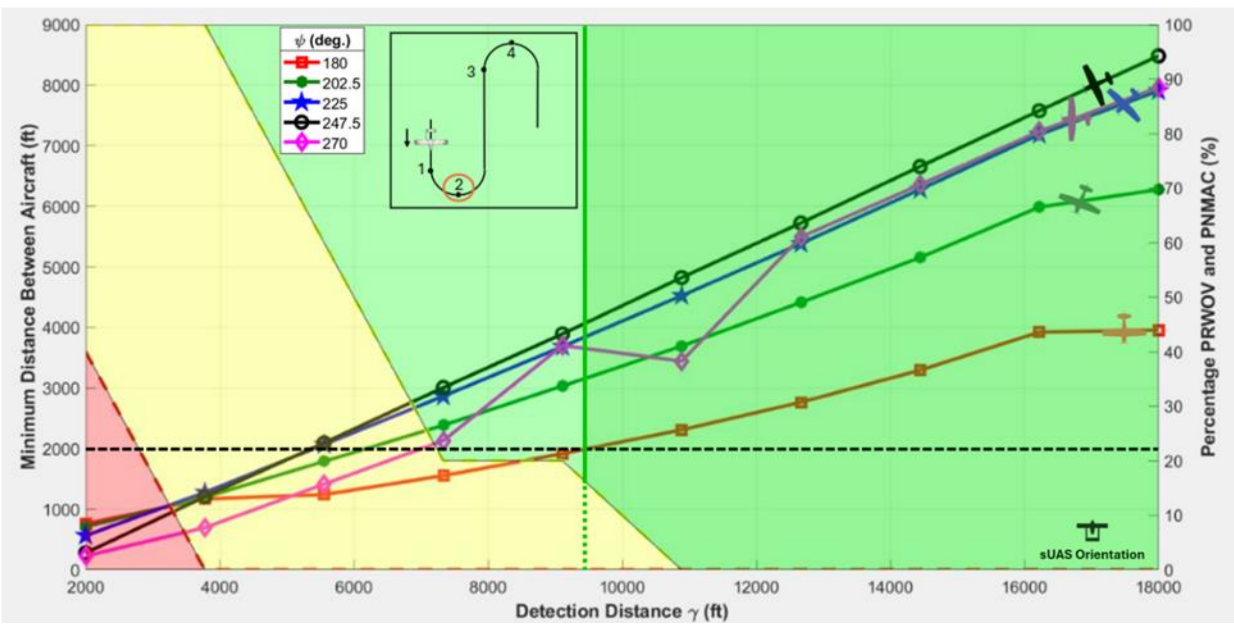


Figure 316. Cessna 172 Flying at 170 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 2.

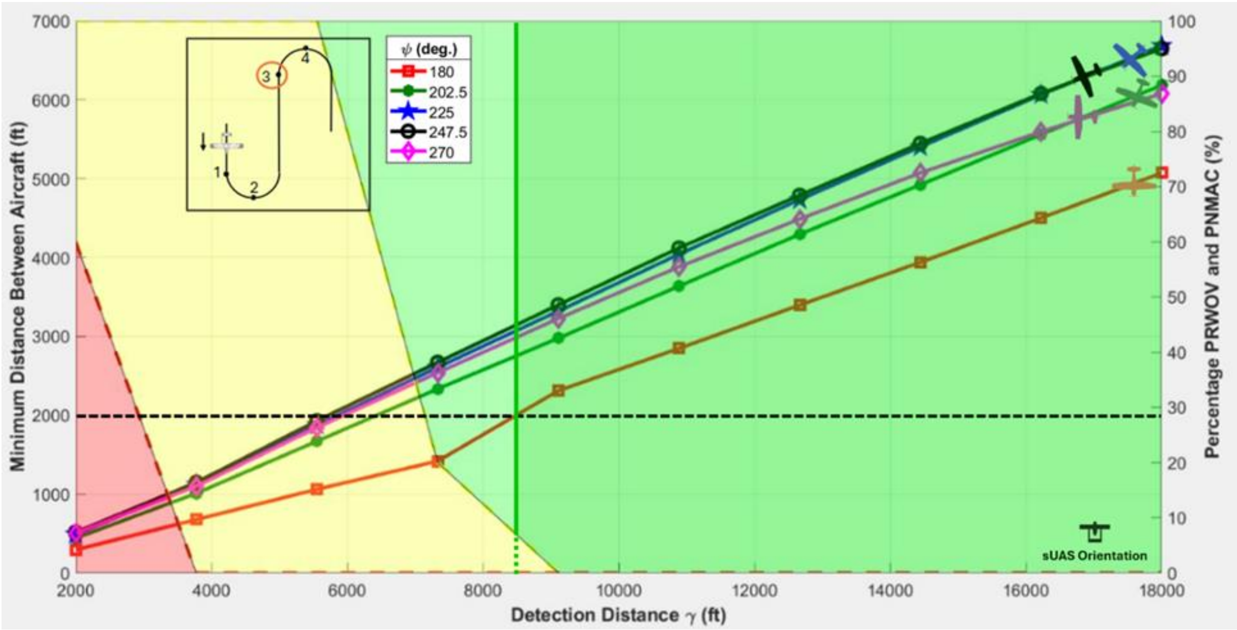


Figure 317. Cessna 172 Flying at 170 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 3.

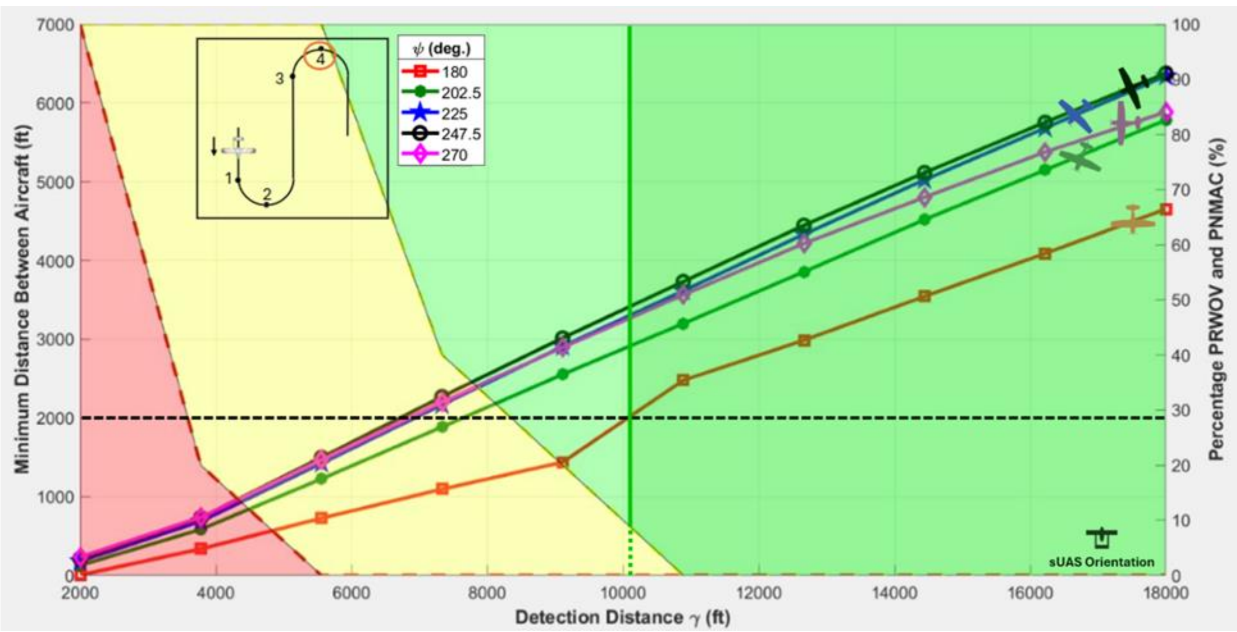


Figure 318. Cessna 172 Flying at 170 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 4.

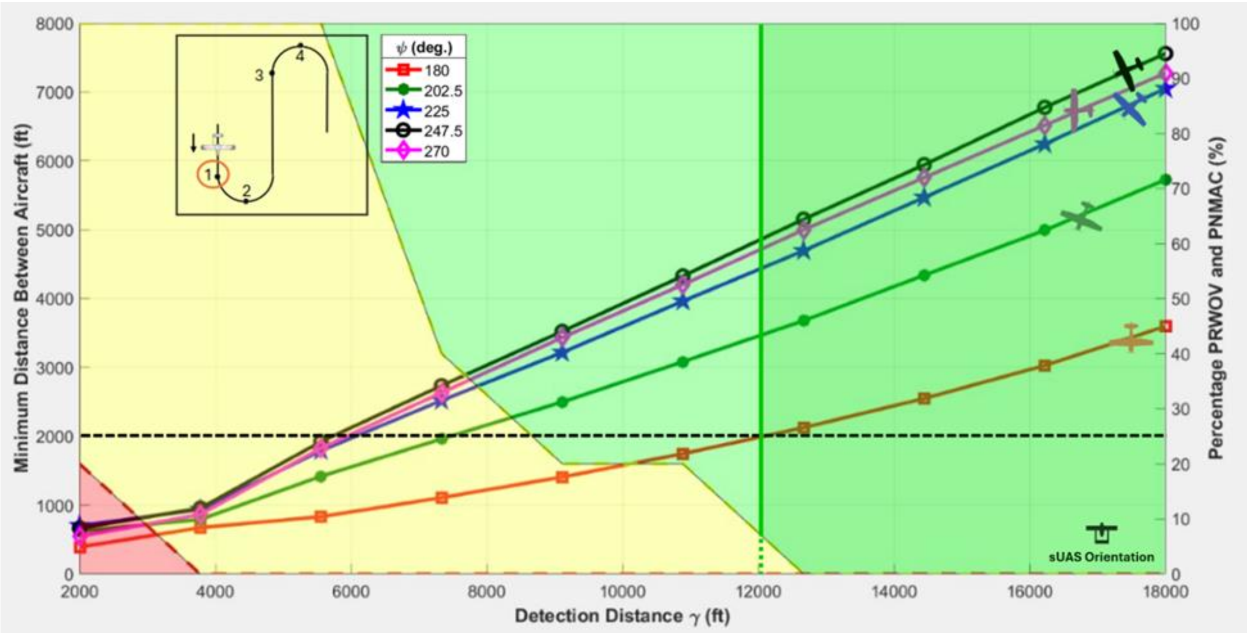


Figure 319. Cessna 172 Flying at 195 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 1.

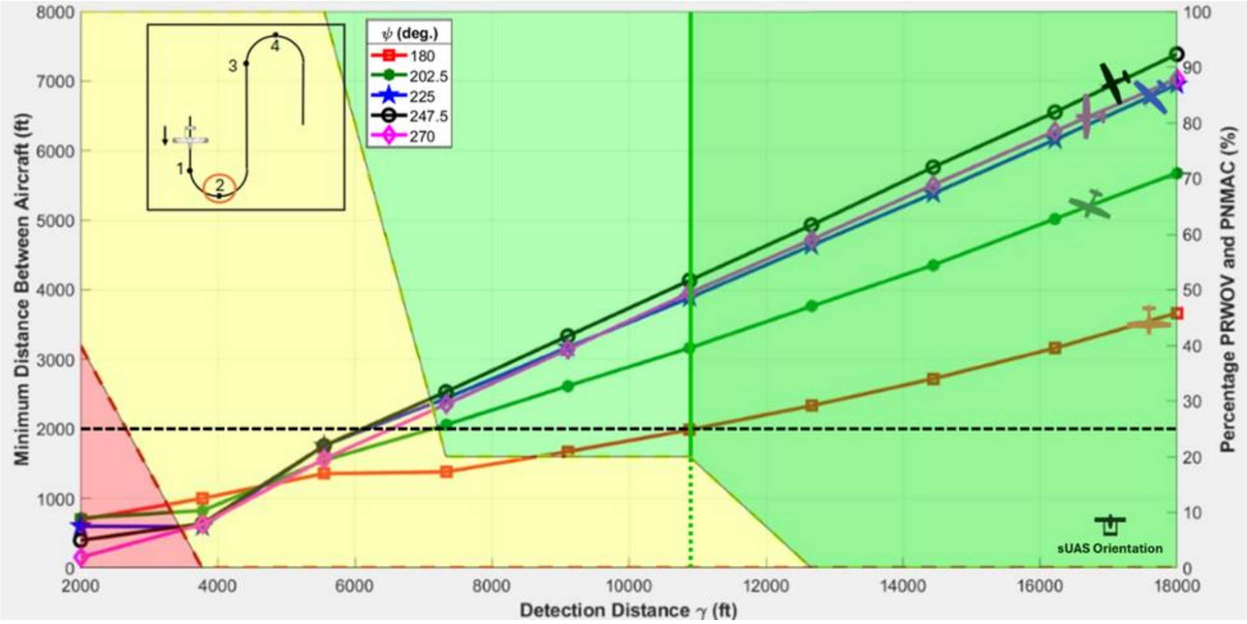


Figure 320. Cessna 172 Flying at 195 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 2.

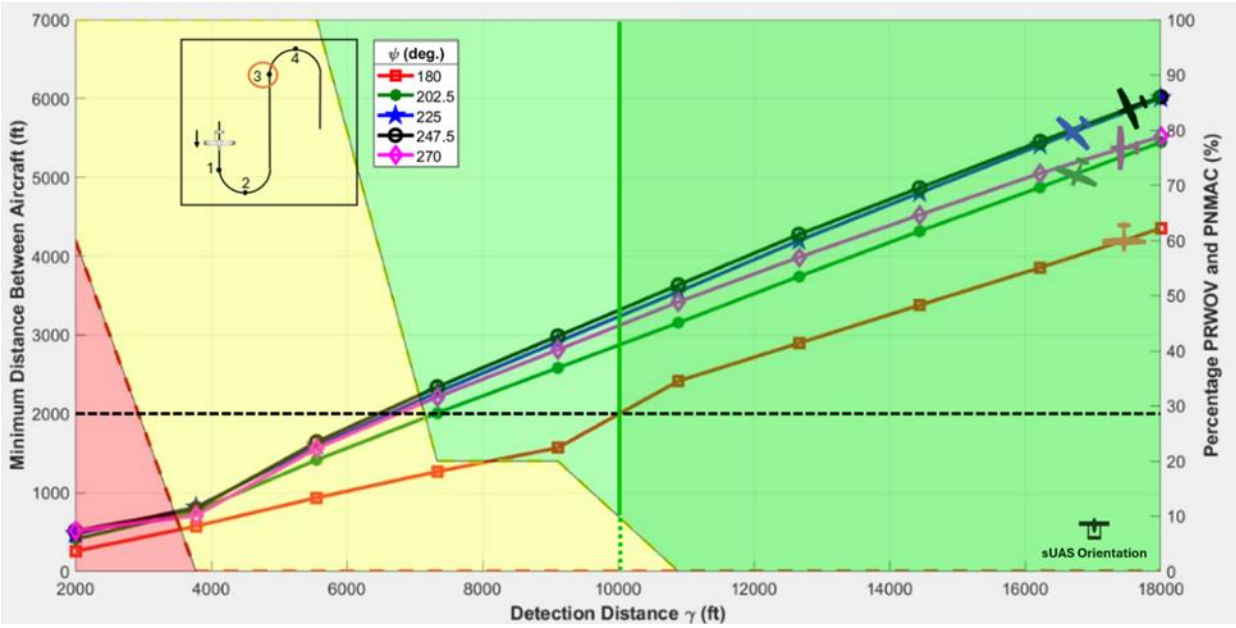


Figure 321. Cessna 172 Flying at 195 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 3.

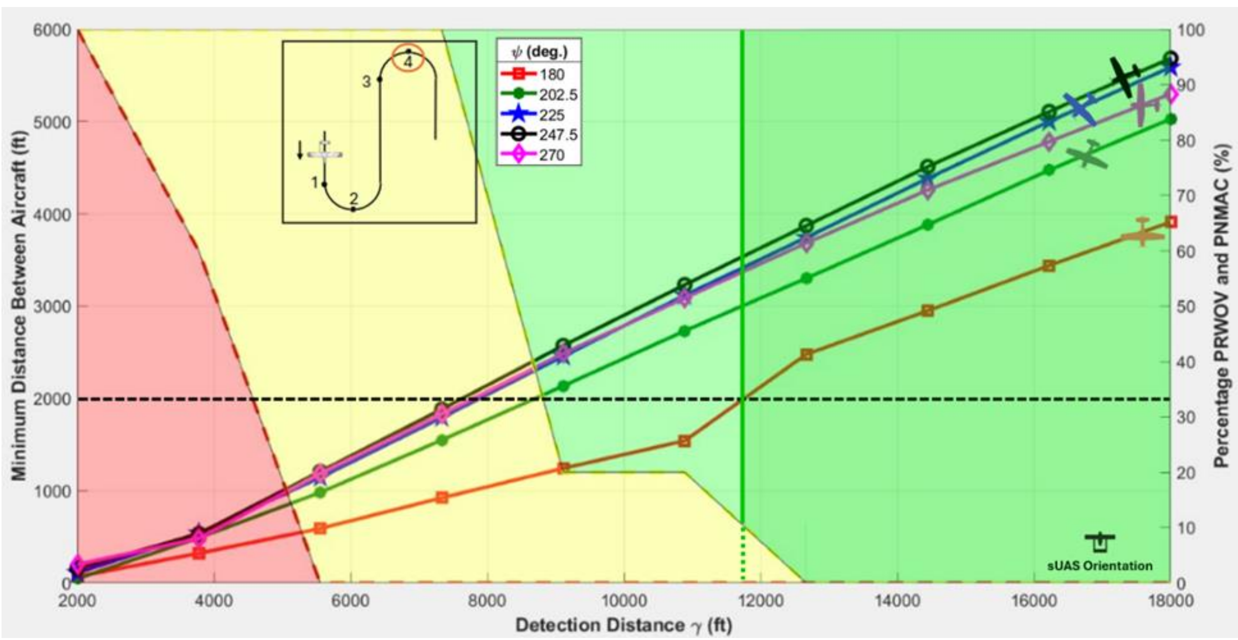


Figure 322. Cessna 172 Flying at 195 ft/s Encountering Single Survey sUAS Flying at 45 ft/s at Point 4.

I.7 Survey Pattern, Multiple sUAS

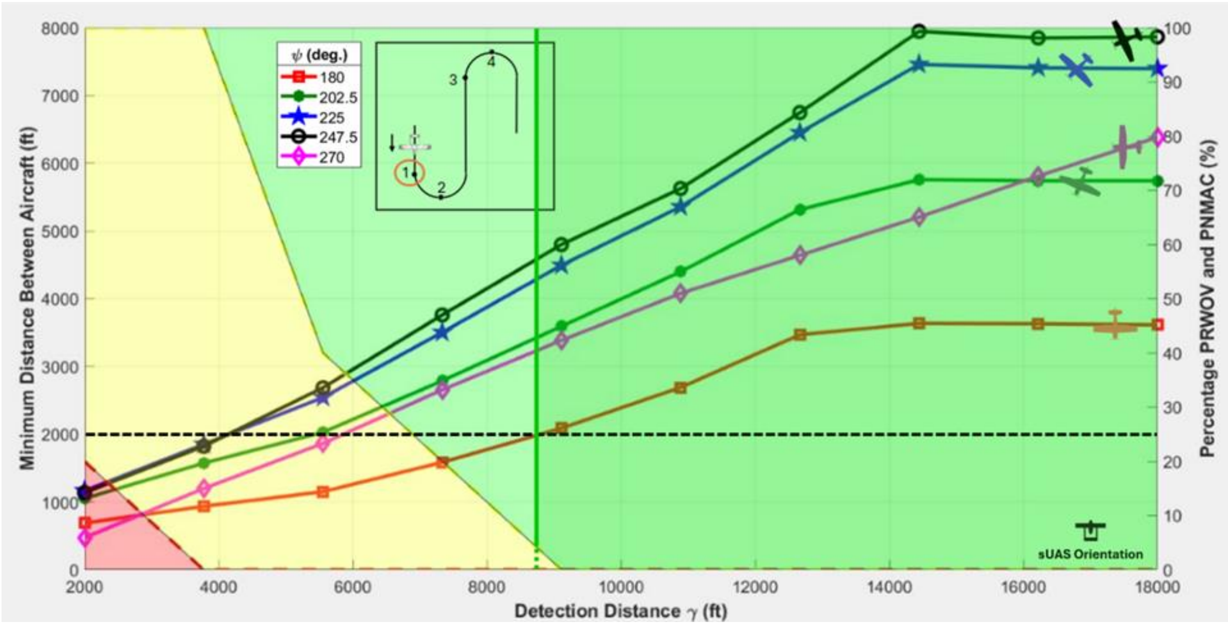


Figure 323. Cessna 172 Flying at 145 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 1.

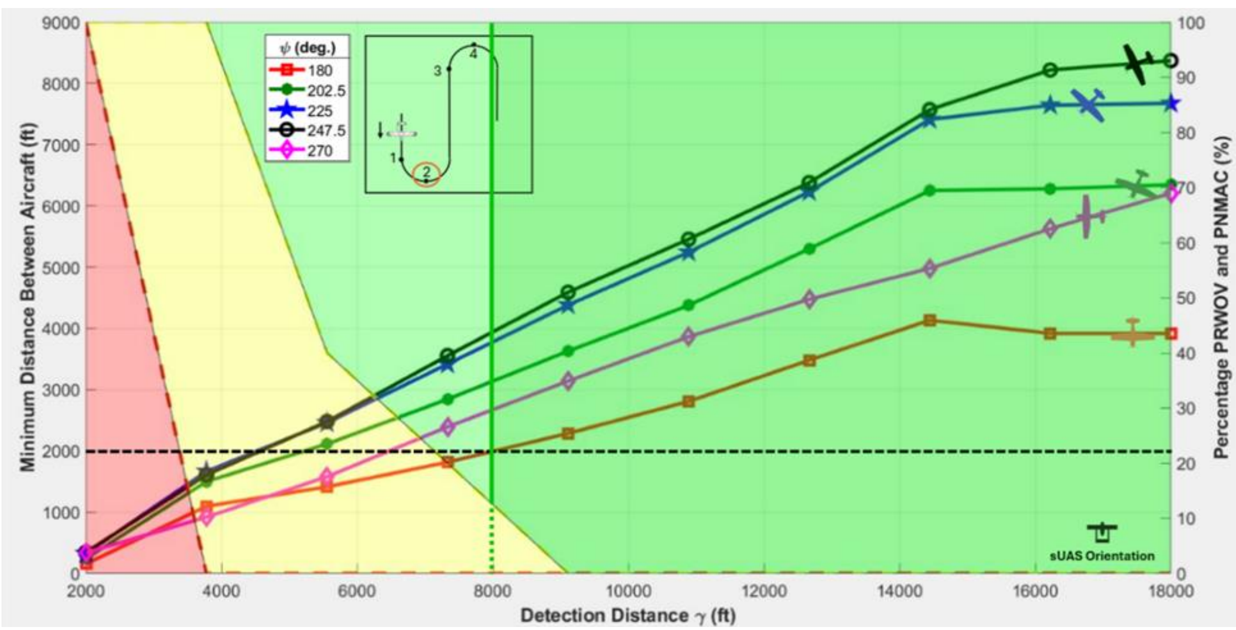


Figure 324. Cessna 172 Flying at 145 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 2.

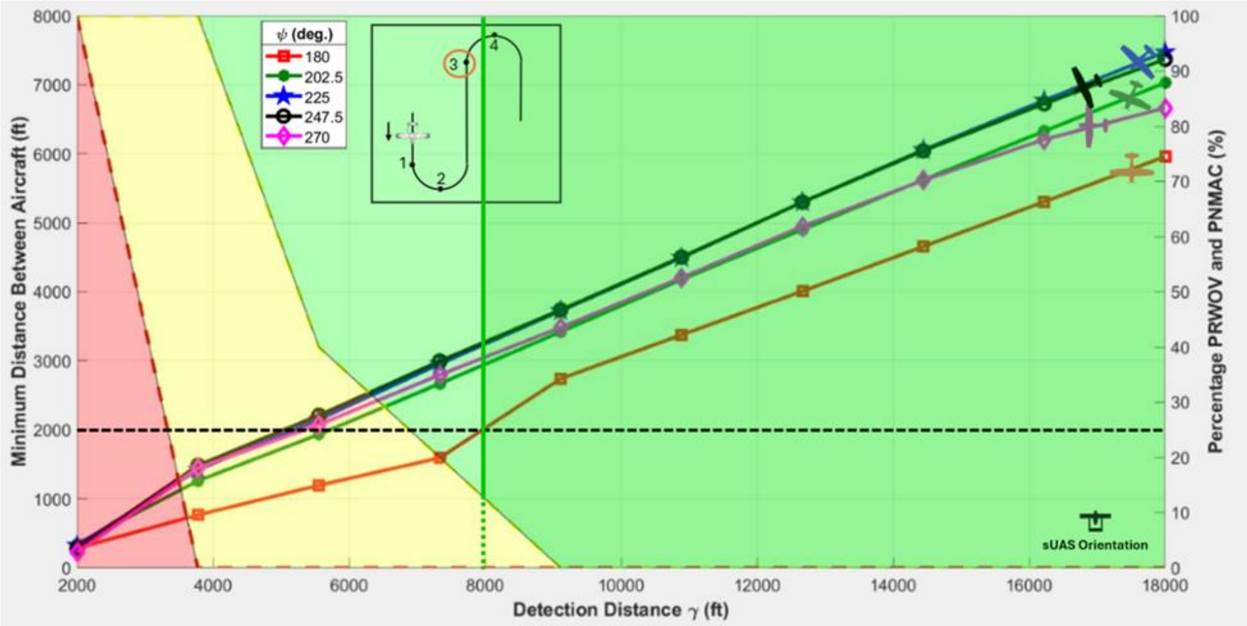


Figure 325. Cessna 172 Flying at 145 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 3.

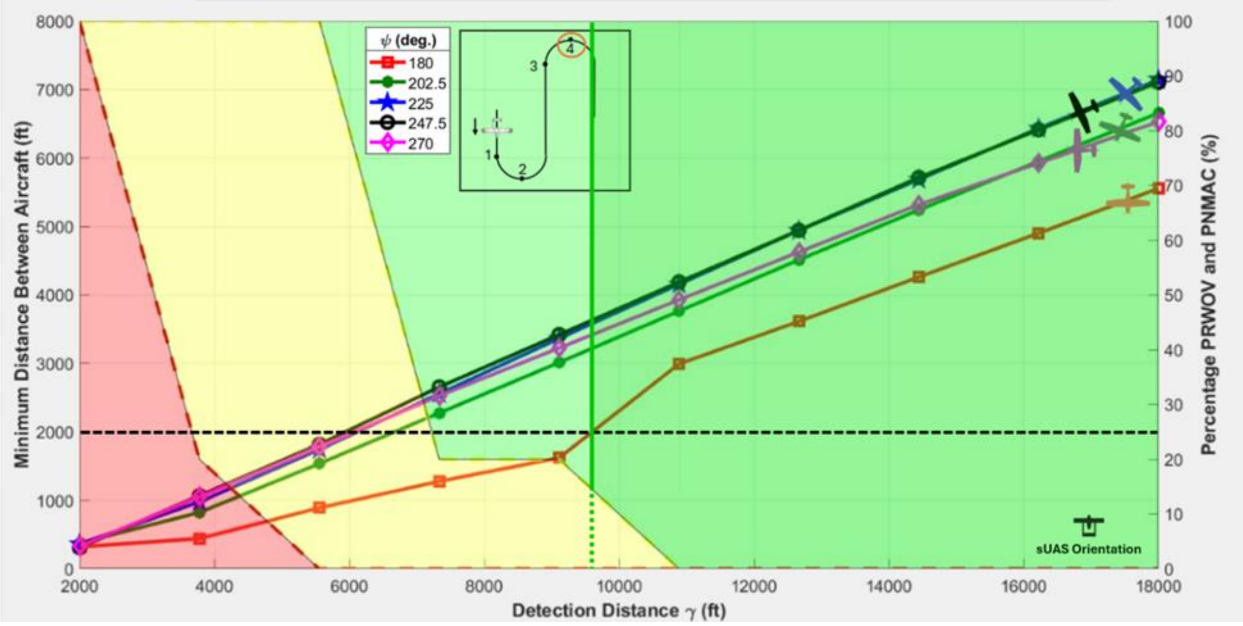


Figure 326. Cessna 172 Flying at 145 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 4.

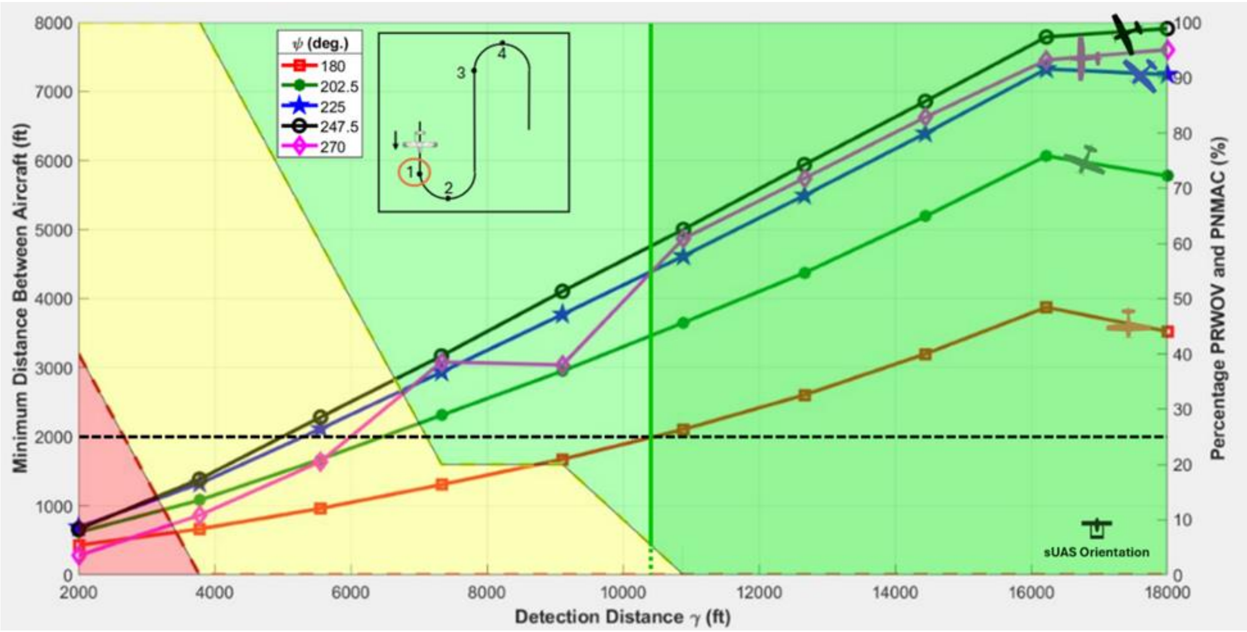


Figure 327. Cessna 172 Flying at 170 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 1.

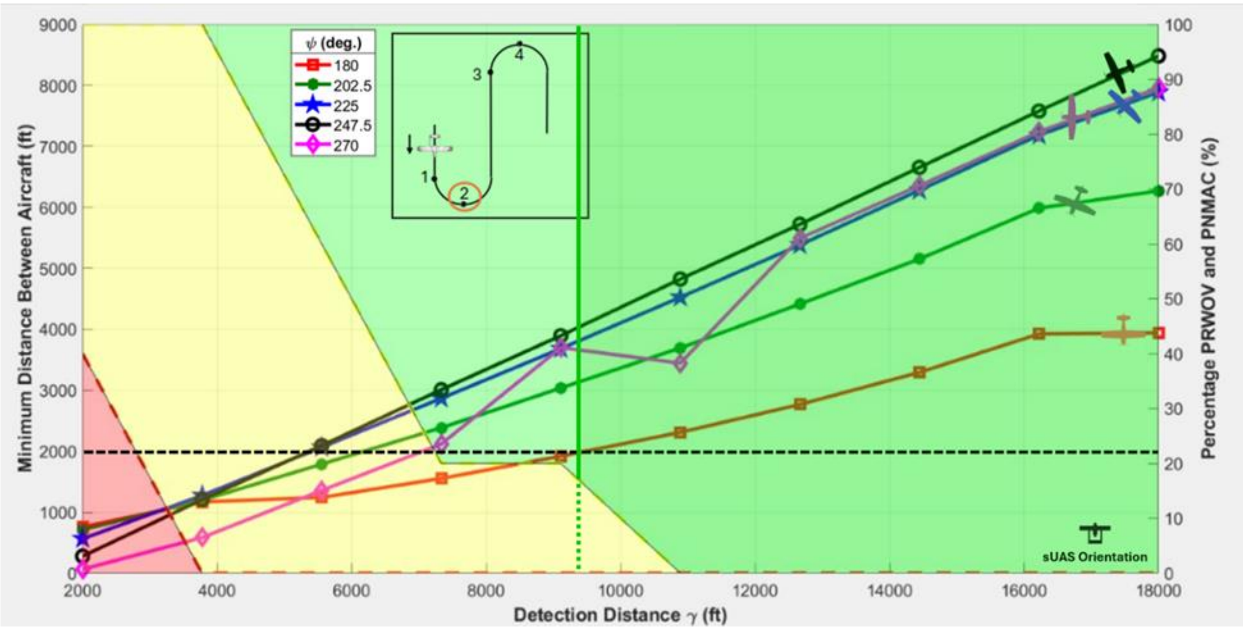


Figure 328. Cessna 172 Flying at 170 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 2.

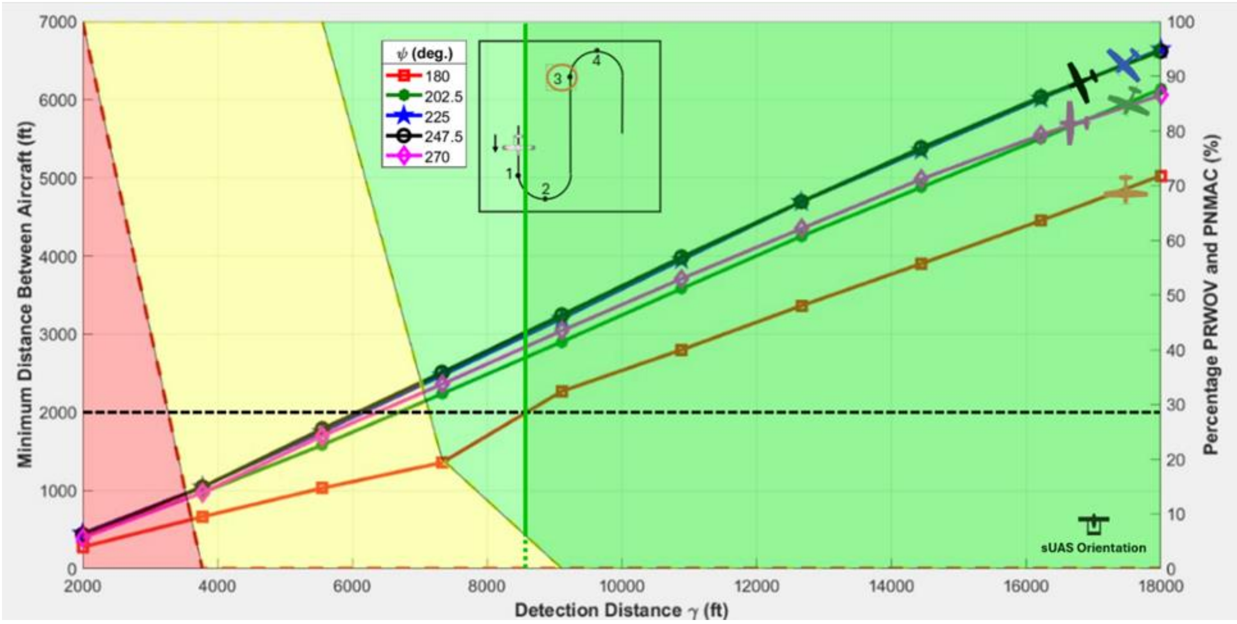


Figure 329. Cessna 172 Flying at 170 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 3.

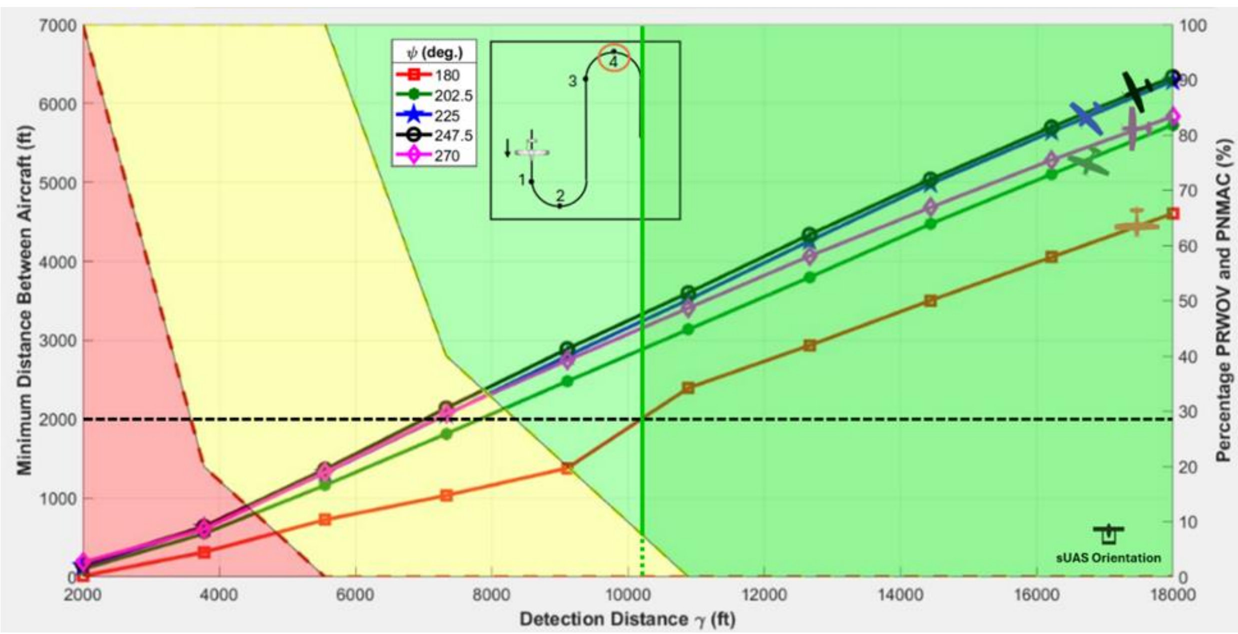


Figure 330. Cessna 172 Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 4.

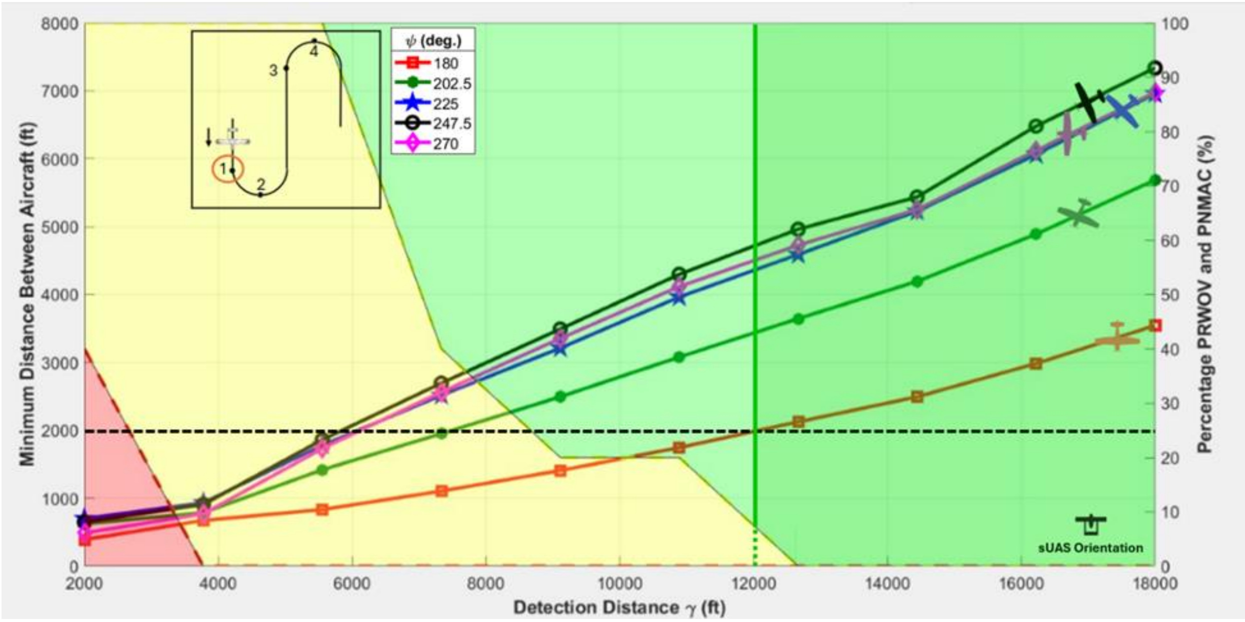


Figure 331. Cessna 172 Flying at 195 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 1.

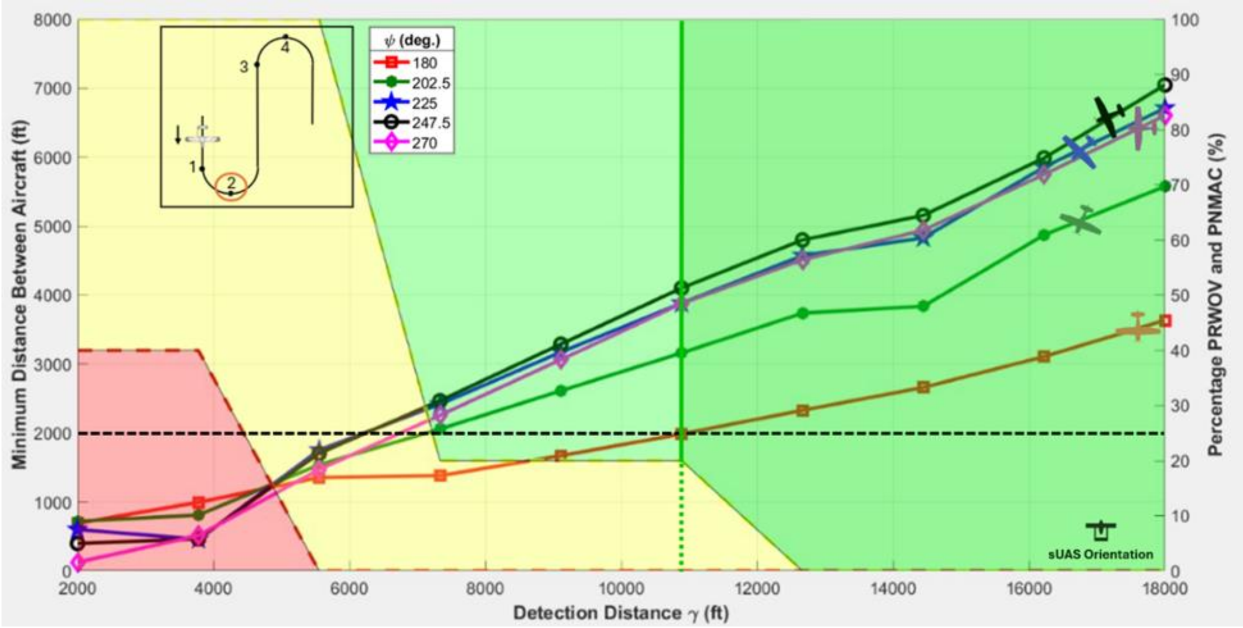


Figure 332. Cessna 172 Flying at 195 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 2.

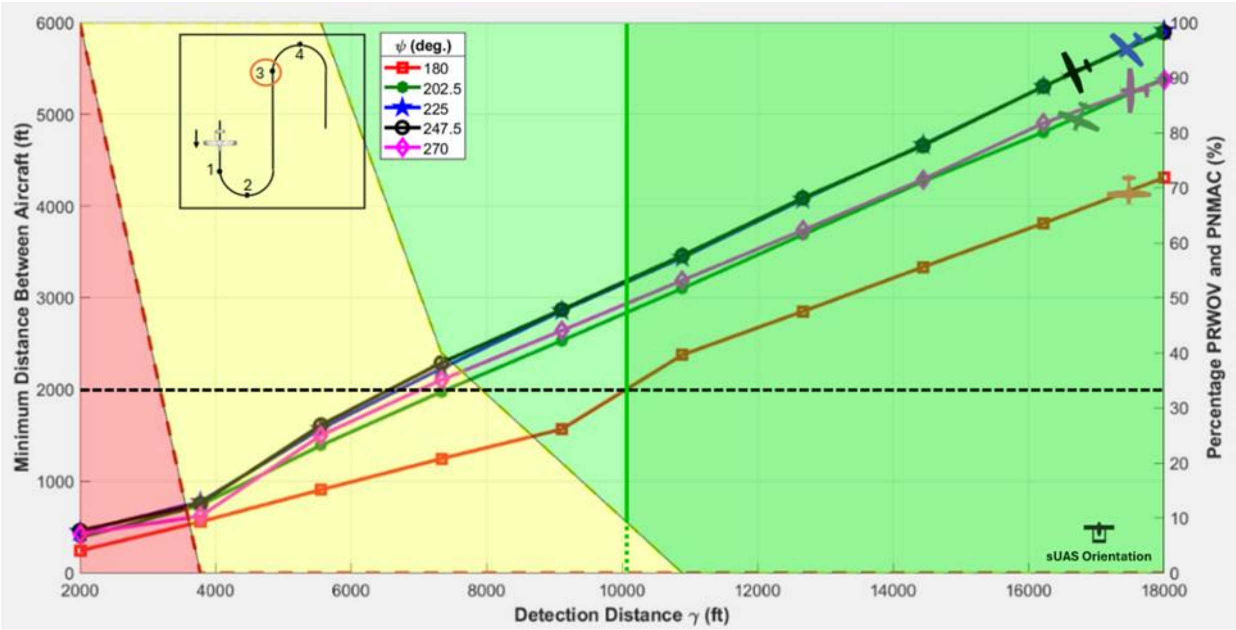


Figure 333. Cessna 172 Flying at 195 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 3.

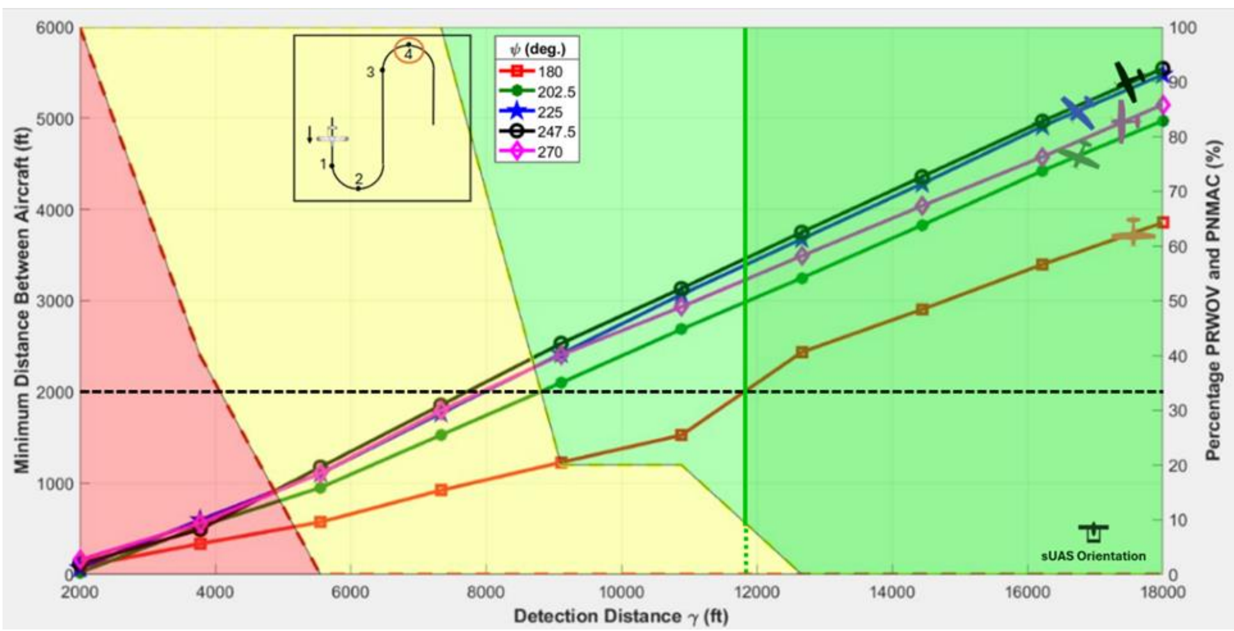


Figure 334. Cessna 172 Flying at 195 ft/s Encountering Multiple Survey sUAS Flying at 45 ft/s at Point 4.

I.8 Roll and Yaw Rates for Freeflight Single sUAS

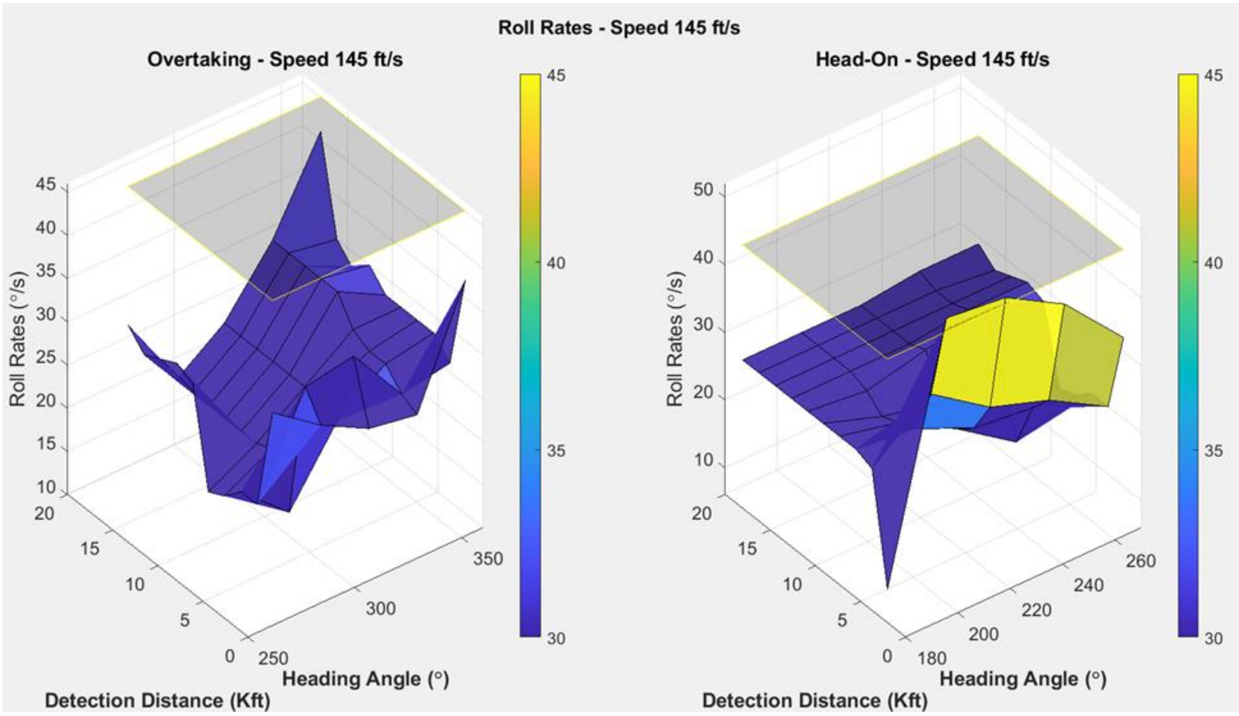


Figure 335. Roll Rates of Single sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 145 ft/s.

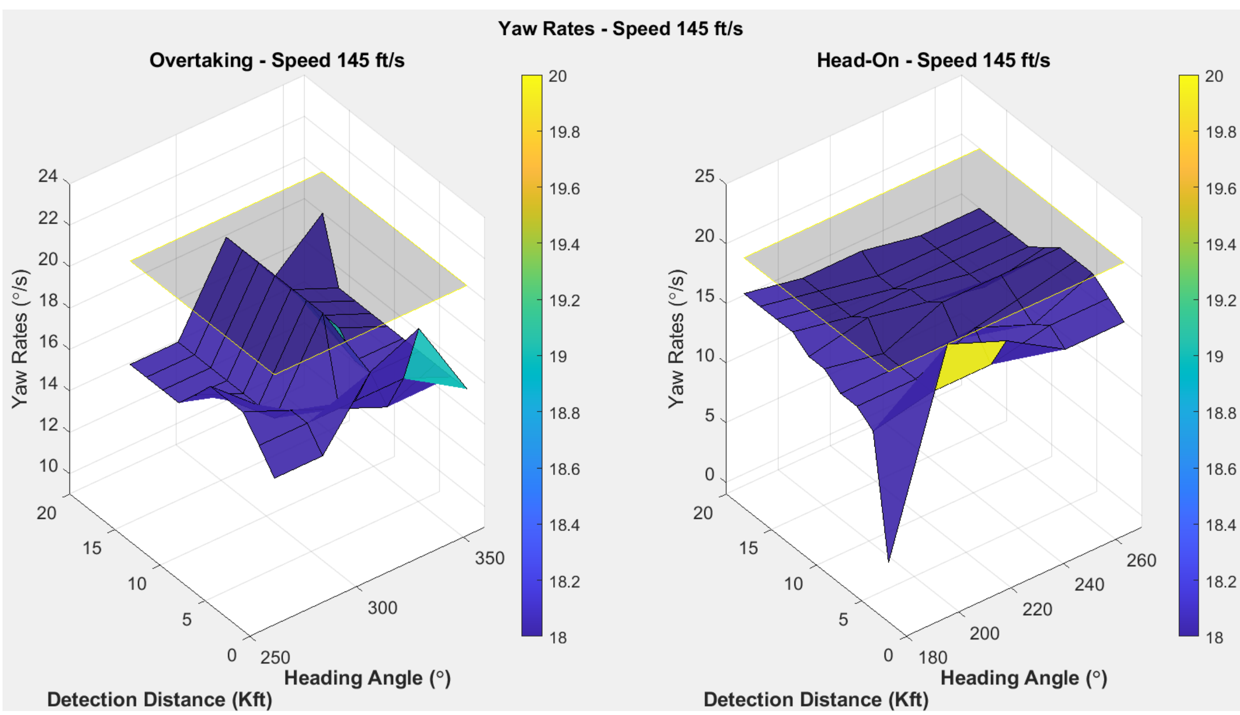


Figure 336. Yaw Rates of Single sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 145 ft/s.

Figure 337. Roll Rates of Single sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 170 ft/s.

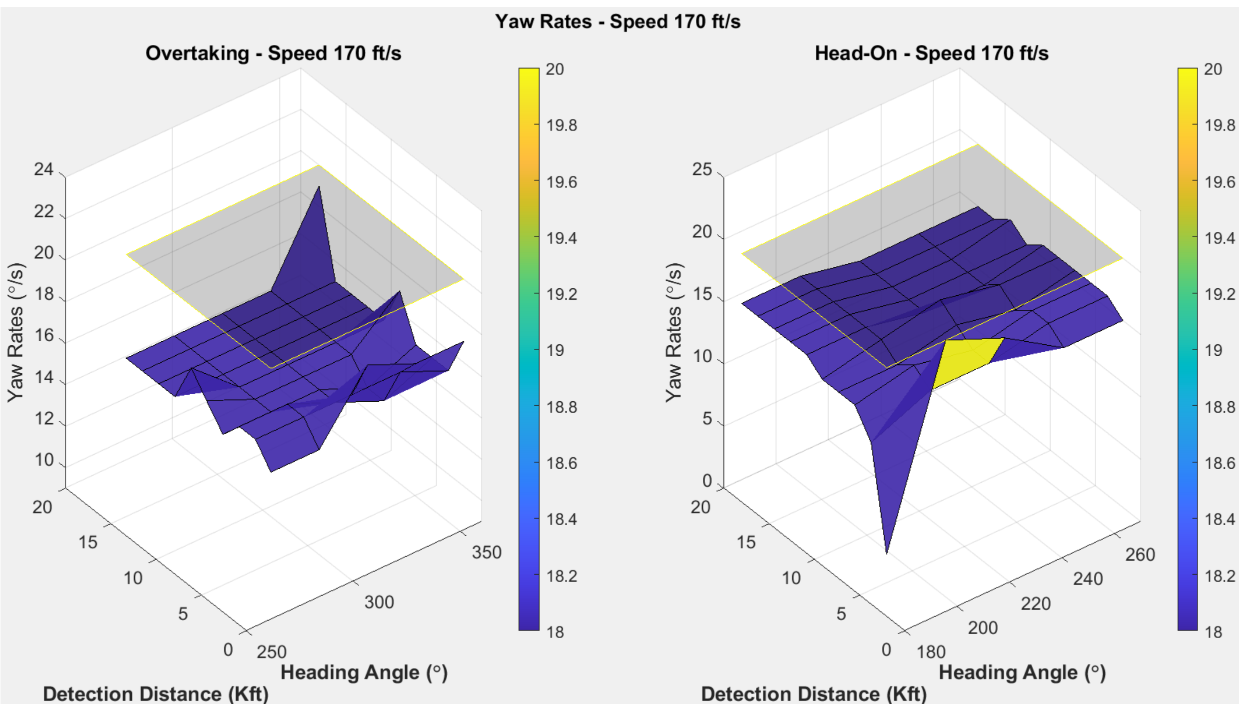


Figure 338. Yaw Rates of Single sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 170 ft/s.

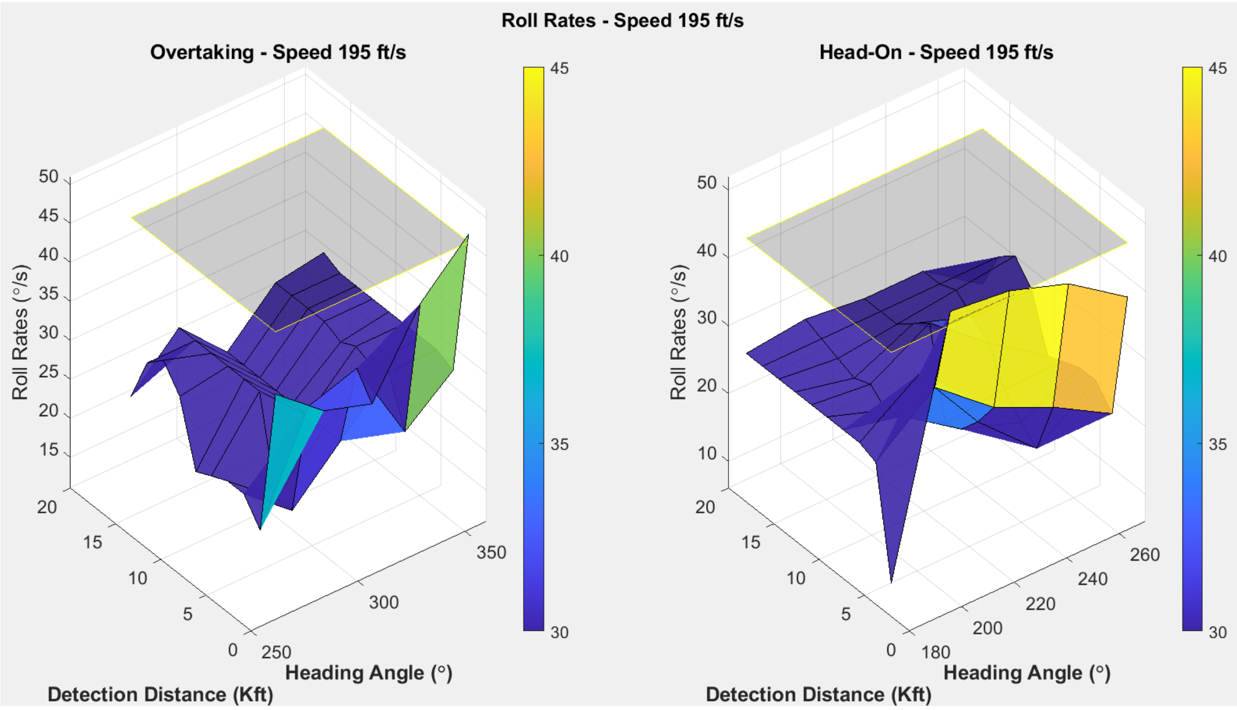


Figure 339. Roll Rates of Single sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 195 ft/s.

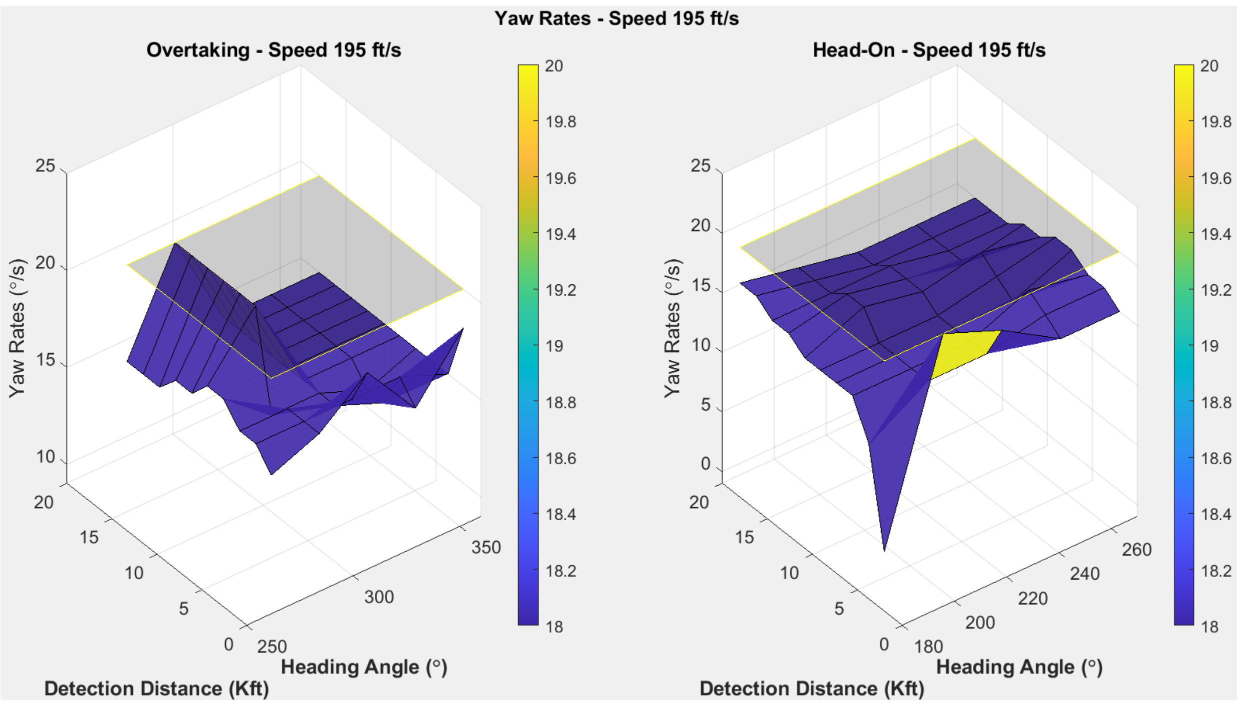


Figure 340. Yaw Rates of Single sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 195 ft/s.

I.9 Roll and Yaw rates for Freeflight Multiple sUAS

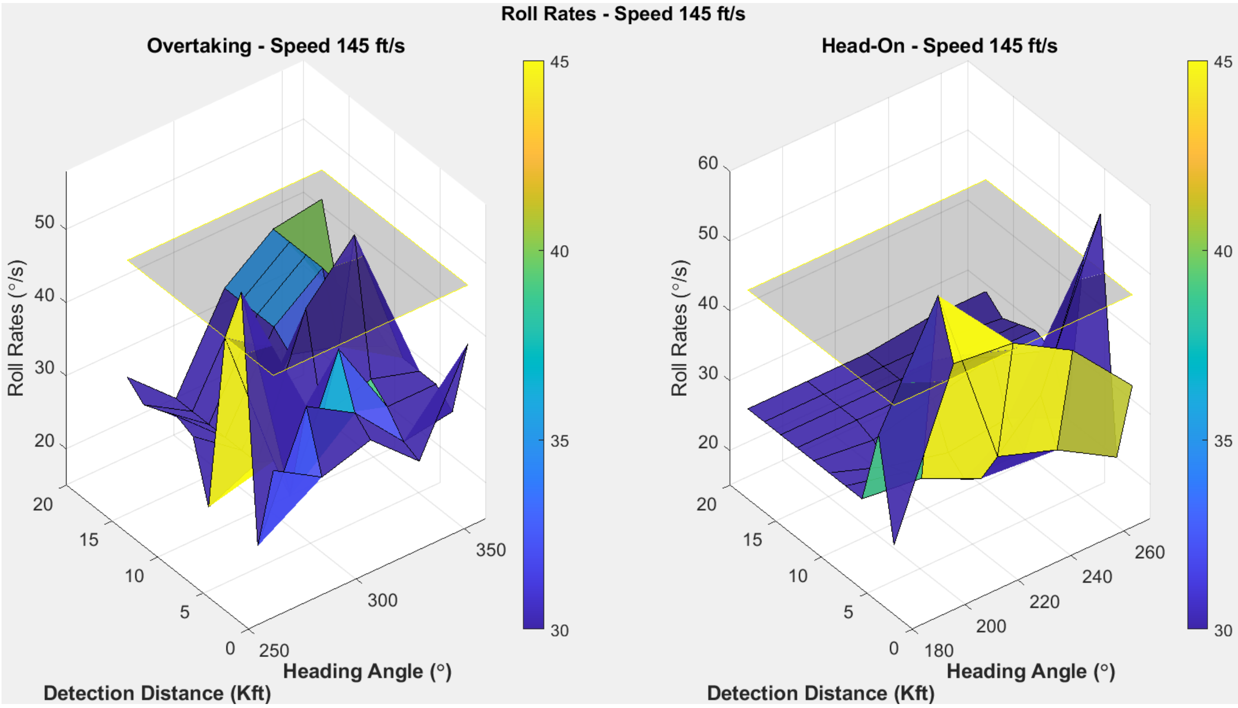


Figure 341. Roll Rates of Multiple sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 145 ft/s.

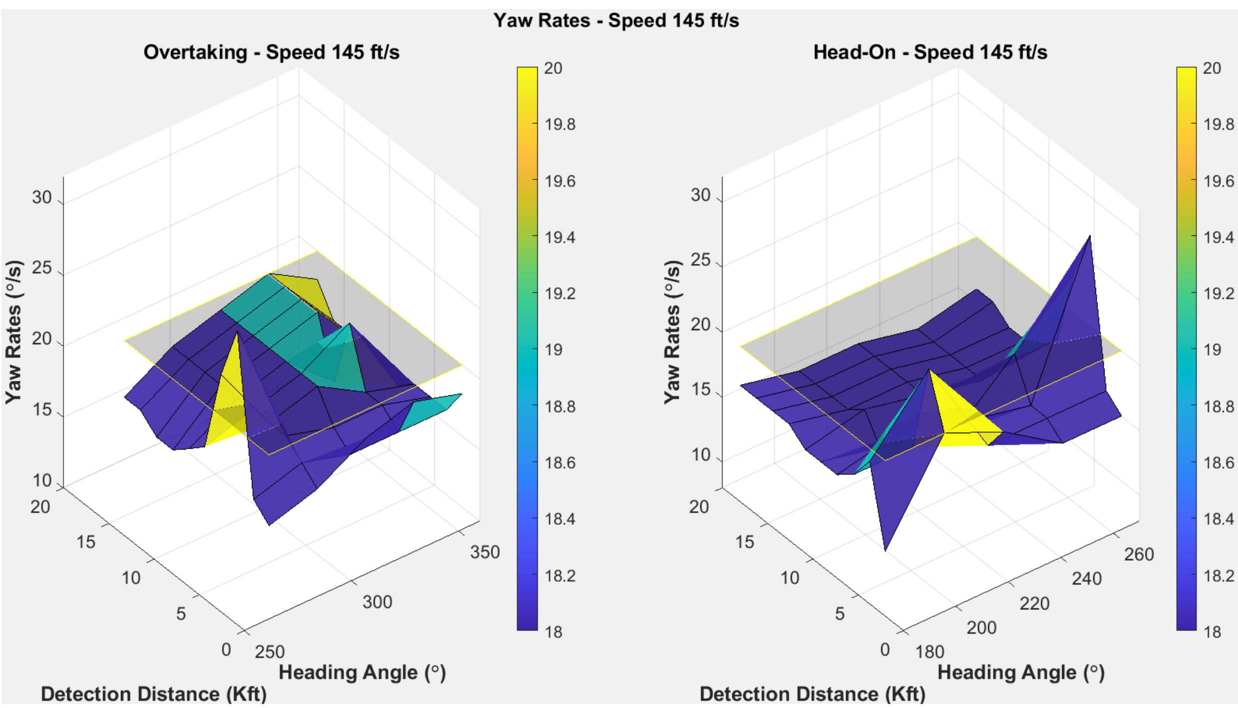


Figure 342. Yaw Rates of Multiple sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 145 ft/s.

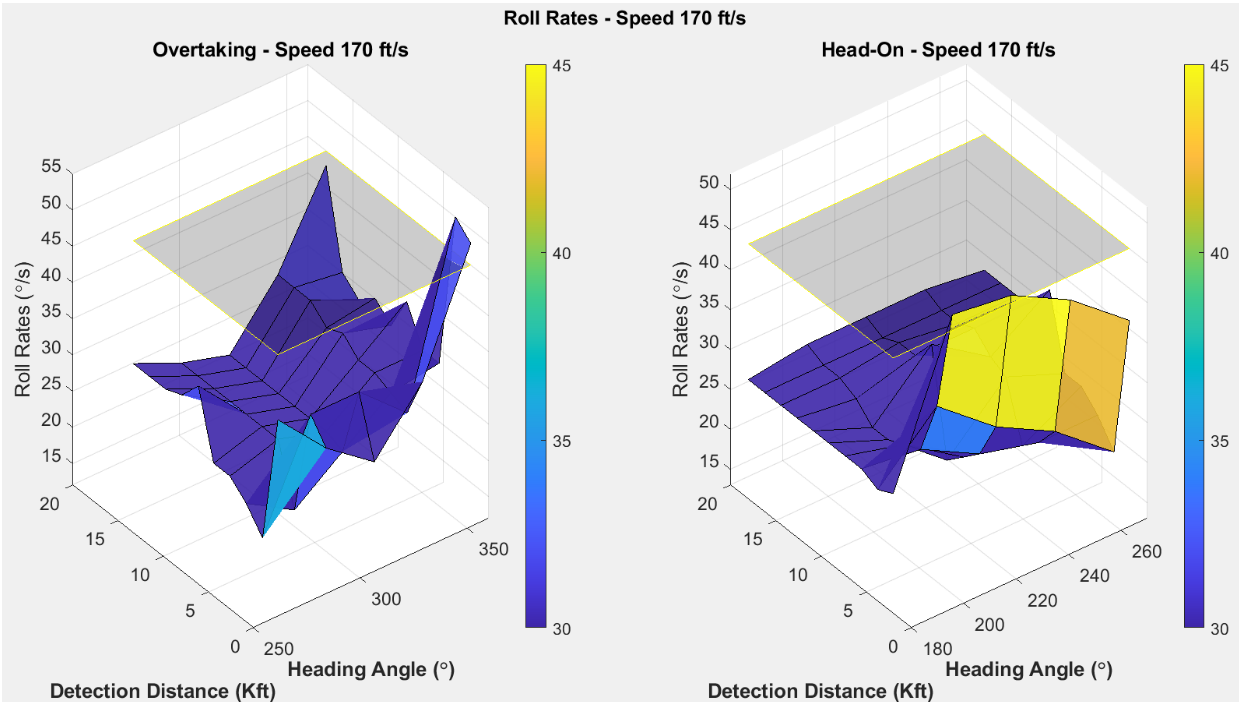


Figure 343. Roll Rates of Multiple sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 170 ft/s.

Figure 344. Yaw Rates of Multiple sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 170 ft/s.

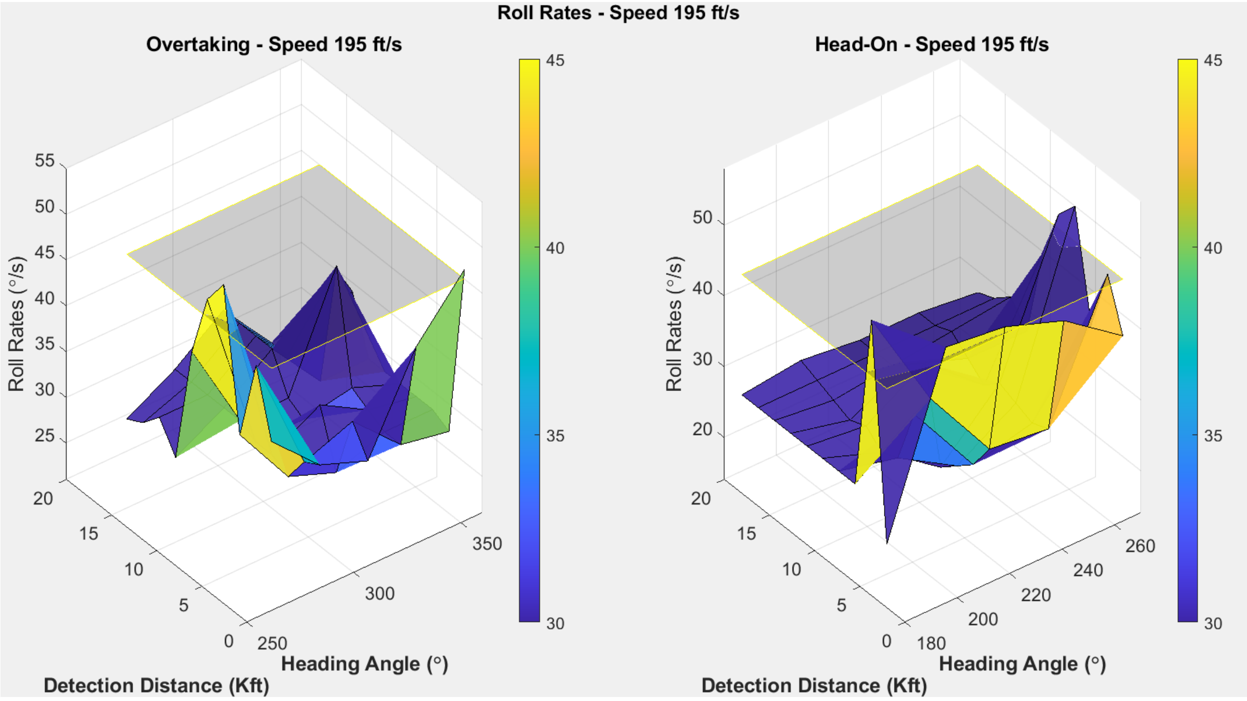


Figure 345. Roll Rates of Multiple sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 195 ft/s.

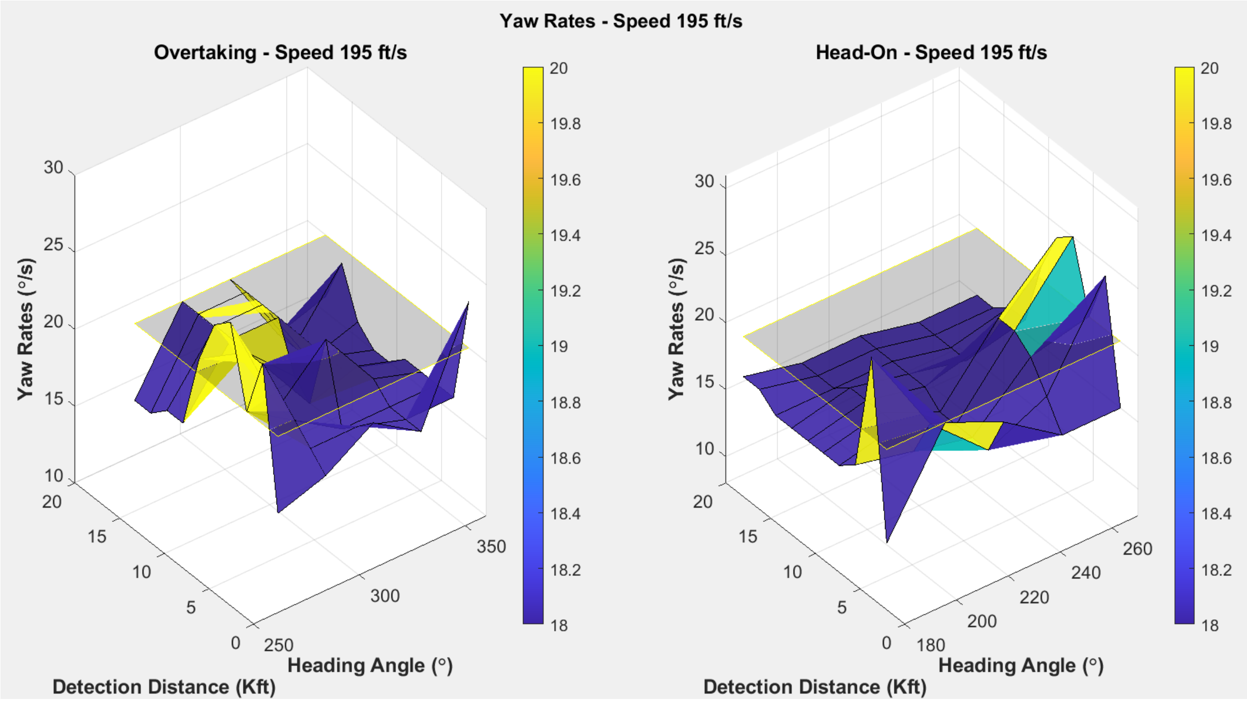


Figure 346. Yaw Rates of Multiple sUAS Flying at 45 ft/s Encountering Cessna 172 Flying at 195 ft/s.

I.10General Interactions Graphs Using Loiter Guidance Instead of Morphing Potential

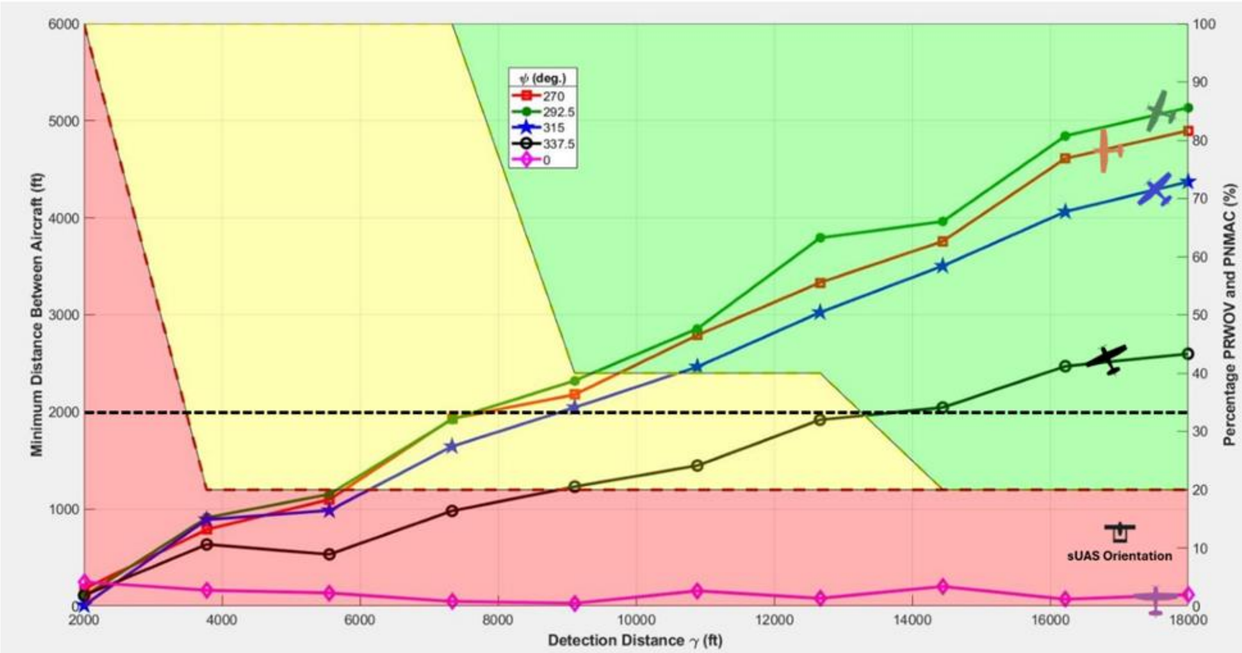


Figure 347. Cessna 172 Flying at 145 ft/s Overtaking Loiter Guidance sUAS Flying at 45 ft/s.

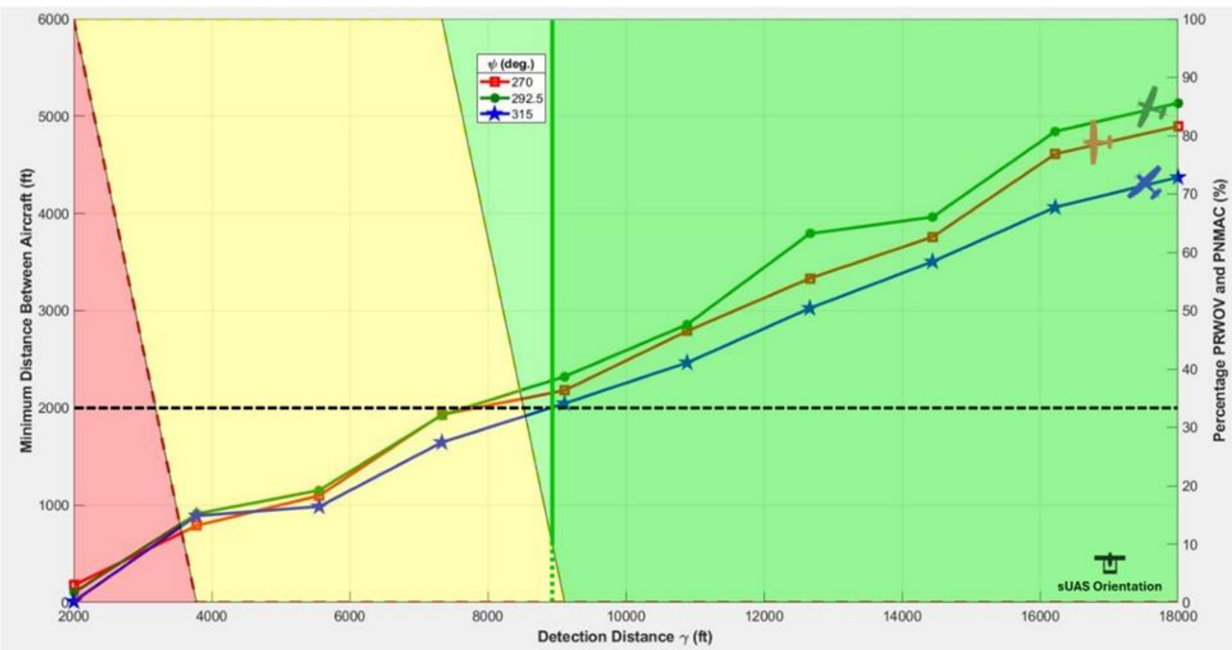


Figure 348. Cessna 172 Flying at 145 ft/s Overtaking Loiter Guidance with MPF sUAS Flying at 45 ft/s.

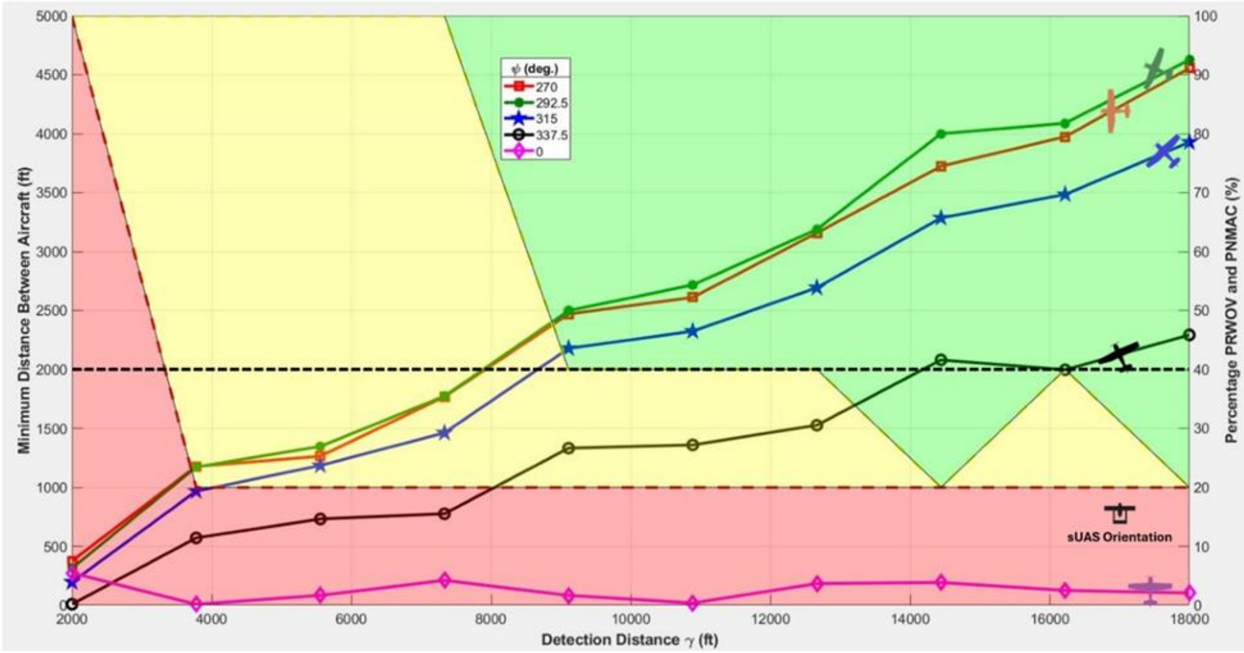


Figure 349. Cessna 172 Flying at 170 ft/s Overtaking Loiter Guidance sUAS Flying at 45 ft/s.

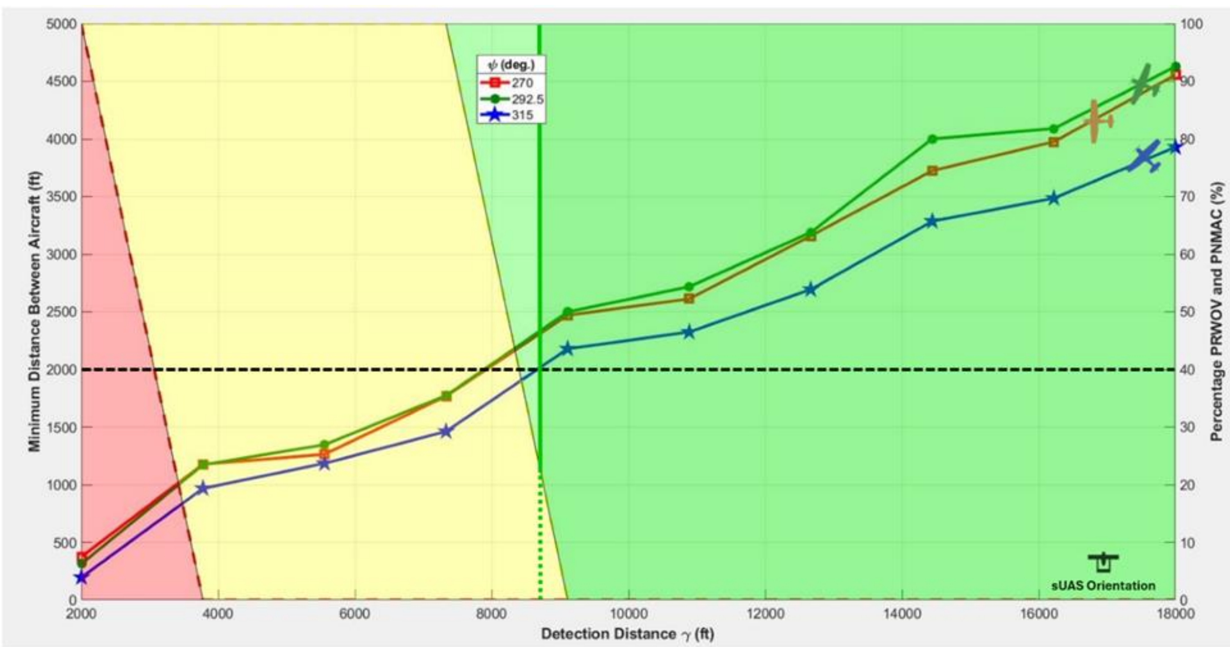


Figure 350. Cessna 172 Flying at 170 ft/s Overtaking Loiter Guidance with MPF sUAS Flying at 45 ft/s.

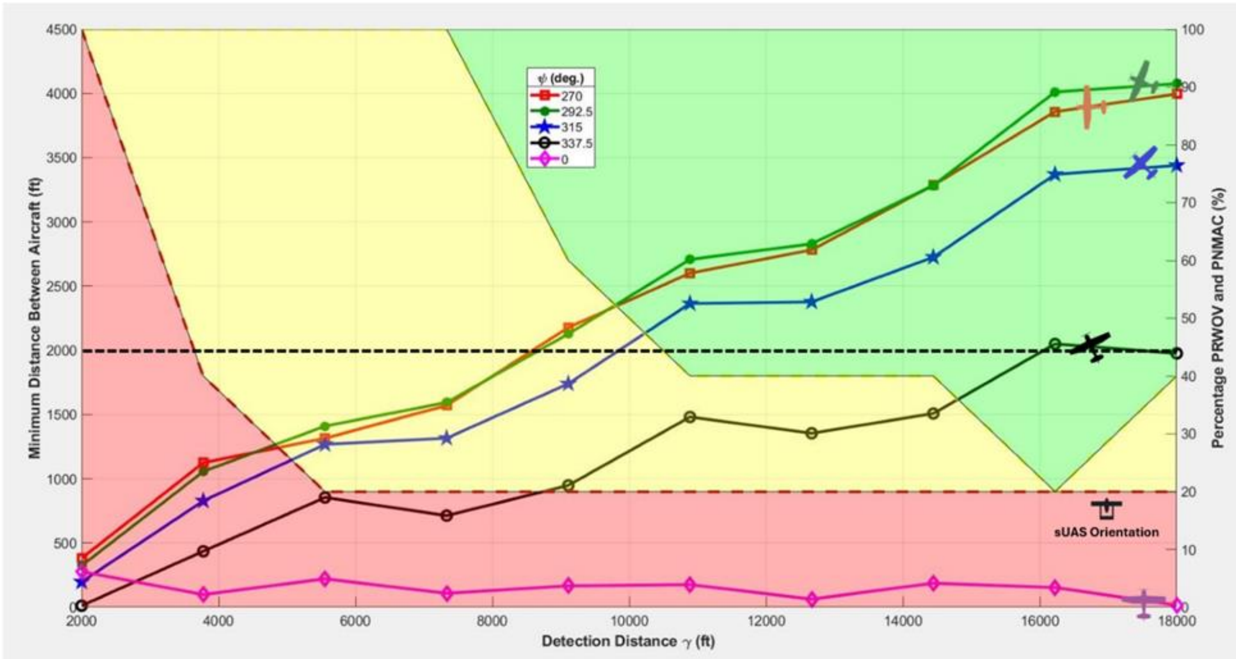


Figure 351. Cessna 172 Flying at 195 ft/s Overtaking Loiter Guidance sUAS Flying at 45 ft/s.

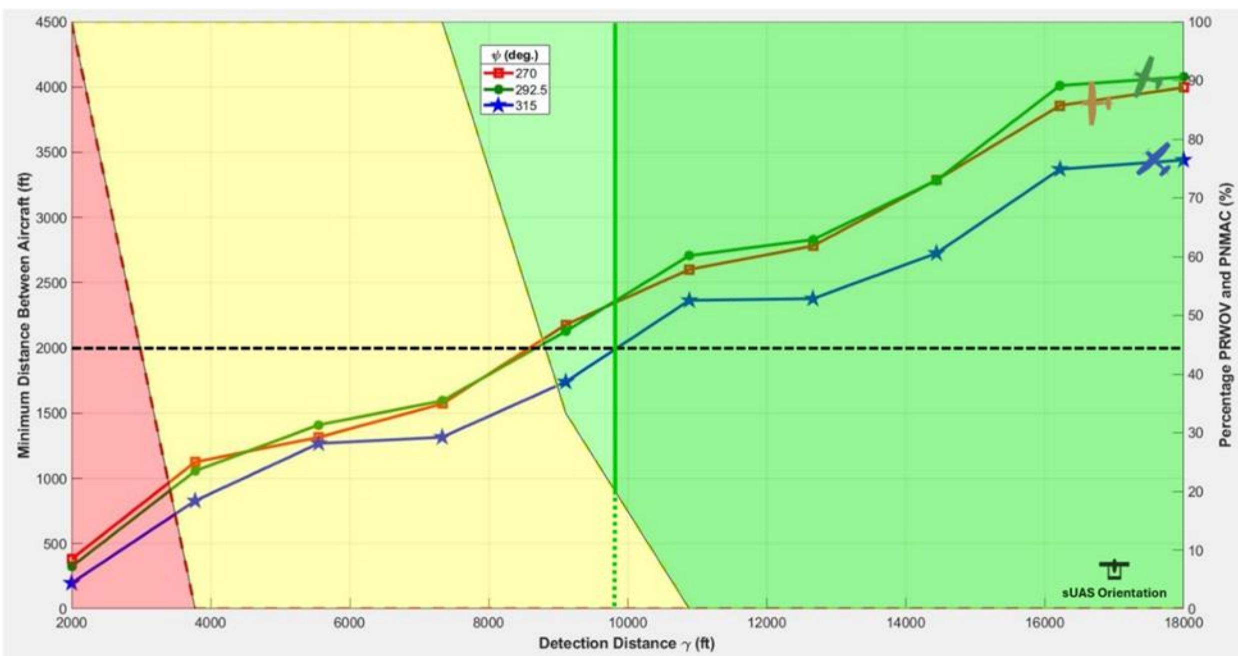


Figure 352. Cessna 172 Flying at 195 ft/s Overtaking Loiter Guidance with MPF sUAS Flying at 45 ft/s.

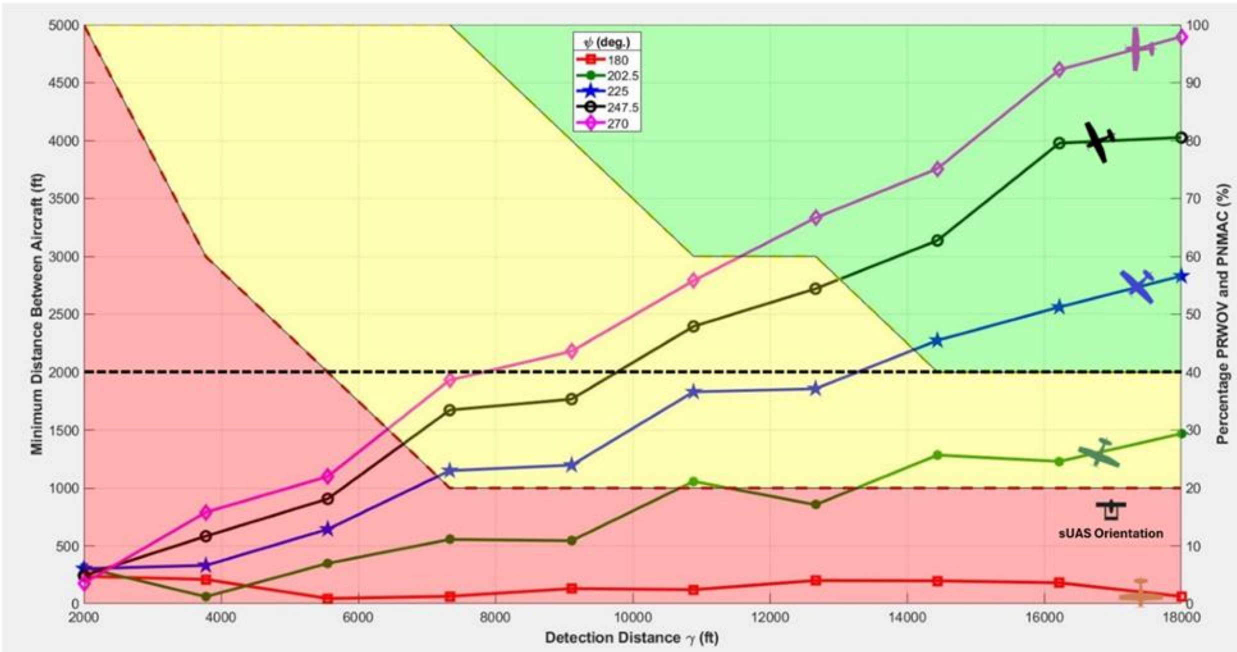


Figure 353. Cessna 172 Flying at 145 ft/s Head-On Converging Loiter Guidance sUAS Flying at 45 ft/s.

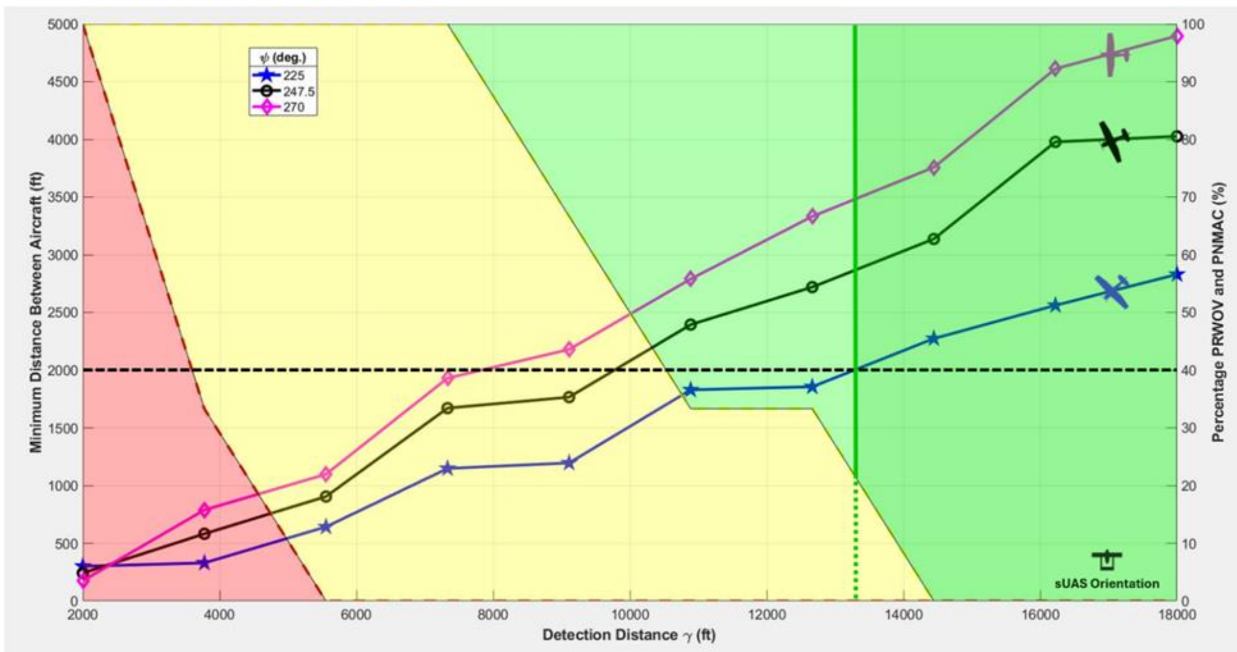


Figure 354. Cessna 172 Flying at 145 ft/s Head-On Converging Loiter Guidance With MPF sUAS Flying at 45 ft/s.

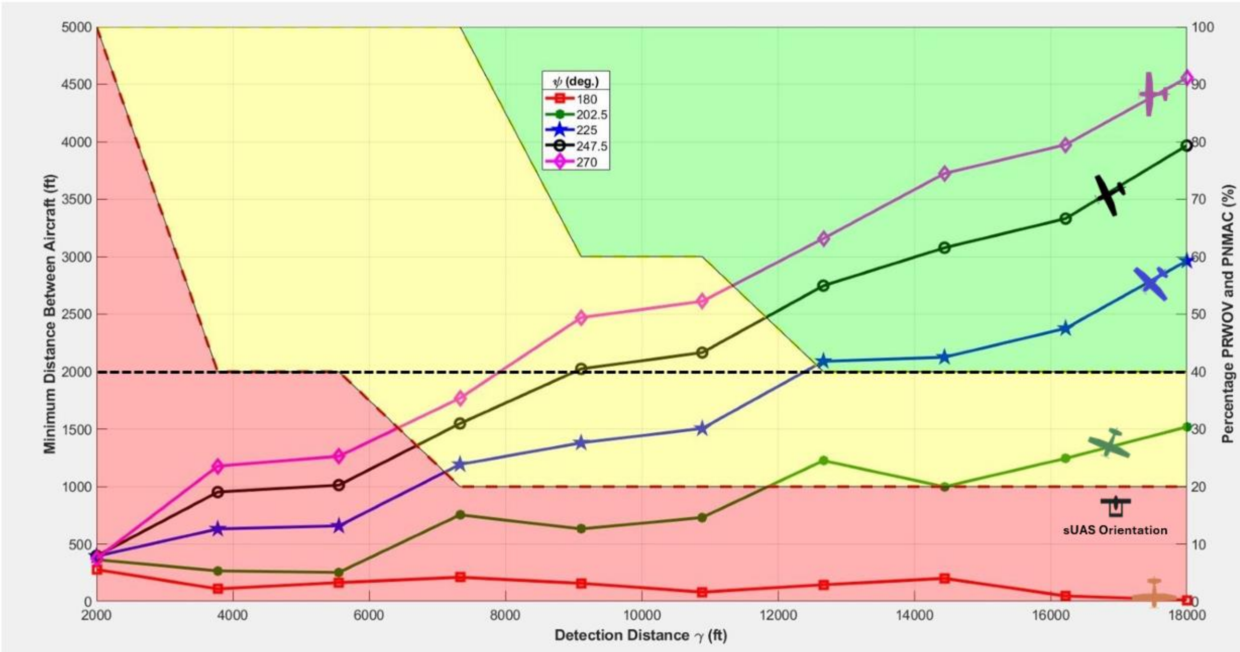


Figure 355. Cessna 172 Flying at 170 ft/s Head-On Converging Loiter Guidance sUAS Flying at 45 ft/s.

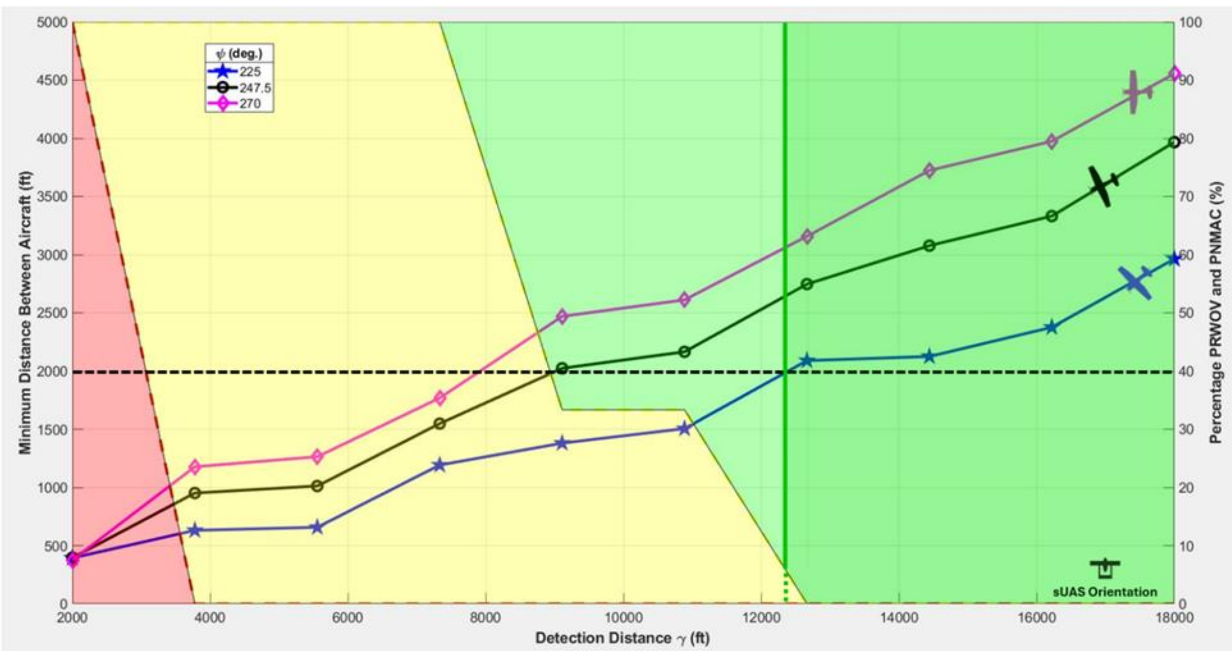


Figure 356. Cessna 172 Flying at 170 ft/s Head-On Converging Loiter Guidance with MPF sUAS Flying at 45 ft/s.

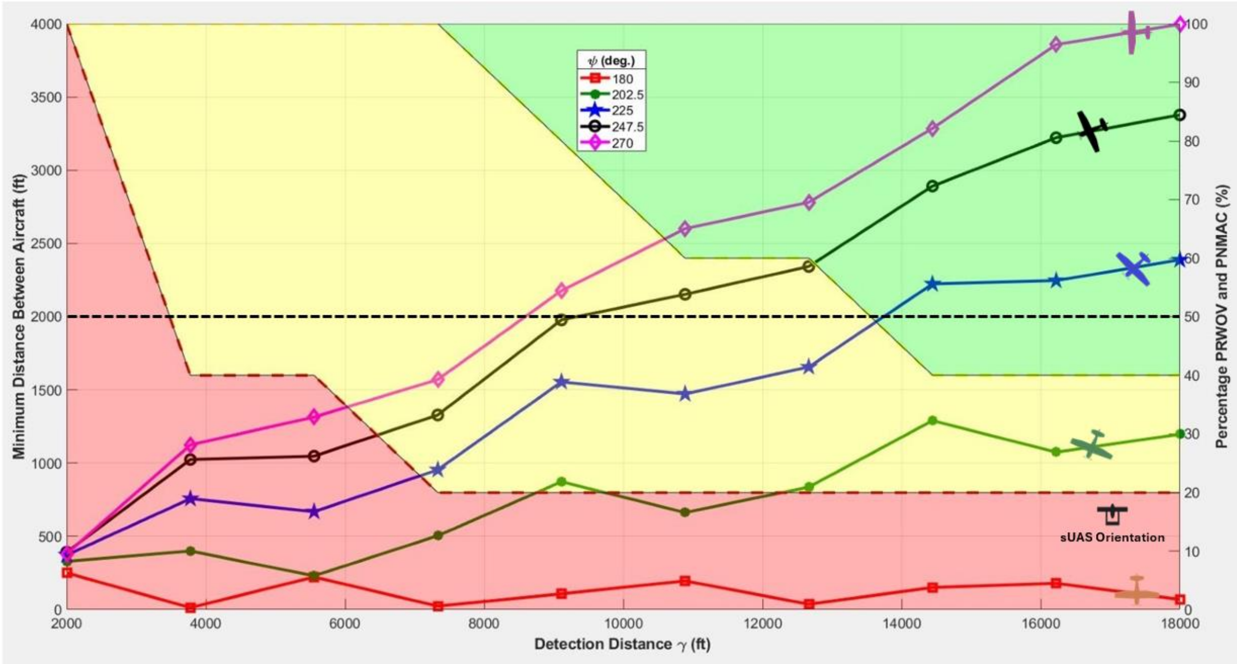


Figure 357. Cessna 172 Flying at 195 ft/s Head-On Converging Loiter Guidance sUAS Flying at 45 ft/s.

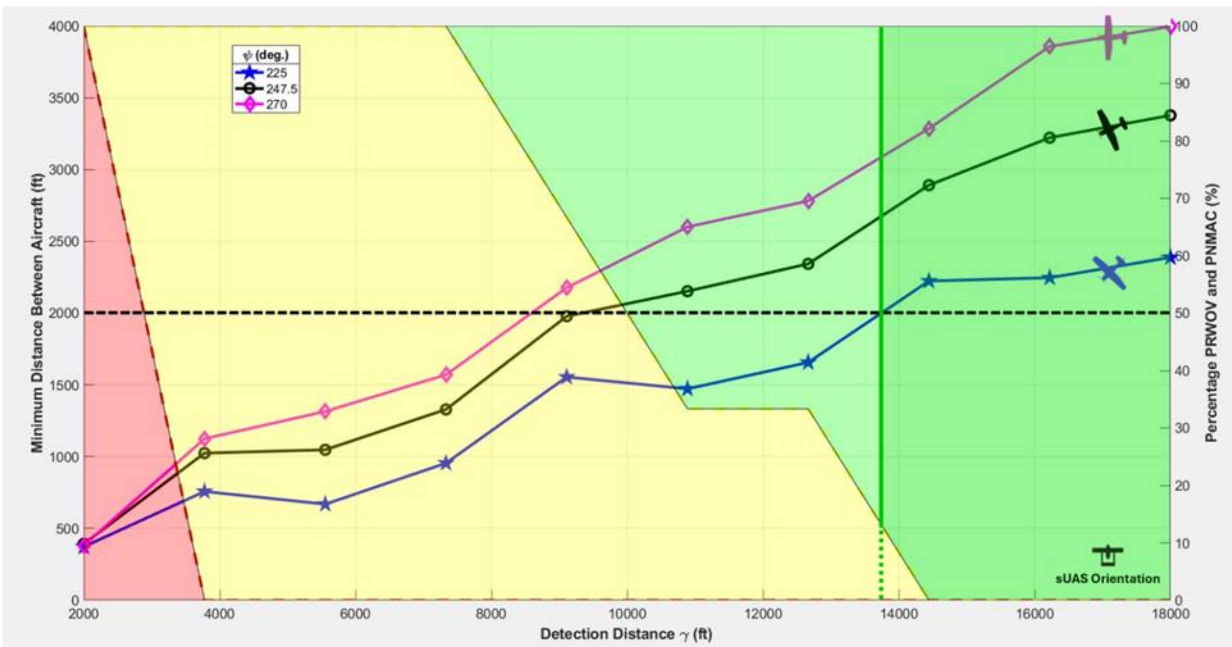


Figure 358. Cessna 172 Flying at 195 ft/s Head-On Converging Loiter Guidance with MPF sUAS Flying at 45 ft/s.