

Ground-Based Sense and Avoid: Enabling Local Area Integration of Unmanned Aircraft Systems into the National Airspace System

Sarah K. Yenson, MIT Lincoln Laboratory

Rodney E. Cole, MIT Lincoln Laboratory

M. Sage Jessee, JHU Applied Physics Laboratory

Chris Crowder, SRC

John Innes, US Army

Distribution A: Public Release

Abstract

As unmanned aircraft systems (UAS) become more important to the US military and other users, the pressure to allow them to fly in the national airspace increases. The greatest impediment to this is the lack of an alternative means of compliance with federal “see and avoid” regulations to provide the capability to avoid airborne conflicts between the UAS and manned aircraft. To provide this alternative means of compliance, the US Army is leading the development of a Ground-Based Sense and Avoid System (GBSAA). The system uses ground-based radars, threat detection and alerting logic, and decision support display aids to provide an air picture of the UAS’s operating environment and follows the DO-254 and DO-178C standards for safety critical avionics hardware and software, respectively. This system will allow greater airspace access and lower cost operations by replacing ground observers in the field with a centralized system, thus consolidating the observer function. The first GBSAA deployment site is expected to go live in 2016 at Fort Hood Army Air Field, Fort Hood, TX, operating under the FAA’s Certificate of Authorization process. This paper provides an overview of the system and of a human-in-the-loop simulation-based test exercise which is a key component of the certification of the system. During this test exercise, 19 self-separation violations and no near-mid-air collisions (NMACs) occurred during 195 hours of simulation, including many stressing multi-intruder scenarios, during which reported workload was low and situation awareness was high throughout. All participants ultimately stated that the GBSAA system was appropriate for UAS operations within the National Airspace System (NAS).

1 Introduction

The Department of Defense (DoD) and other government agencies, as well as universities and commercial companies, have a strong interest in flying unmanned aircraft systems (UAS) in the National

Airspace System (NAS). In particular, all branches of the US military have unmet UAS crew training needs. Currently, UAS training is conducted in special use airspace, but the UAS must transit the NAS to reach this airspace. In operational scenarios, UAS often must transit to Class A airspace where air traffic control (ATC) will provide separation. When not under ATC separation, aircraft operators must meet federal regulations that require the operator of an aircraft to see-and-avoid other aircraft. Unmanned aircraft, having no pilot in the air to provide this function, must instead provide an alternative method of compliance with these regulations [CFR, 2004].

Permission to operate within the NAS requires Federal Aviation Administration (FAA) approval of the alternative means of compliance and other aspects of the proposed flight operations. Once approval is granted by the FAA, the agency receives a Certificate of Authorization allowing operators to perform specific UAS activities. Today, two alternative means of compliance are available: the use of a chase airplane to accompany the UAS on its flight, or a series of ground observers in contact with the aircraft operator who can warn of approaching air traffic. The Army is developing a technology-based alternative means of complying with these “see-and-avoid” regulations called Ground-Based Sense and Avoid (GBSAA). The development of this technology follows a spiral approach where software releases, known as blocks, of increasing capability are deployed after extensive testing and validation. Each new block includes increasingly sophisticated decision aids that are incrementally integrated into the UAS ground control station (GCS) and into the operator’s (known in Army parlance as the Aircraft Operator, or AO) workflow.

The GBSAA system replaces the human’s visual acquisition of traffic with ground-based radars that sense nearby traffic. The radar data are then provided to operators of the GBSAA system or, in future blocks, directly to the AO, along with other information to help human operators maintain the desired separation of 1 nmi in the horizontal or 1000 ft in the vertical. In the first deployment of the system, known as GBSAA Block 0, this information is provided to a Ground-Based Operator (GBO) who, much like the ground observers currently employed, provides warnings and guidance to the AO. In addition, the system includes decision support logic to enable the GBO (or AO, in future blocks) to rapidly prioritize which aircraft represent a potential future conflict and to take action in a timely manner to maintain adequate separation from all aircraft. Future blocks will provide explicit maneuver guidance.

The GBSAA system will initially employ two types of radars: FAA airport surveillance radars such as ASR-9 and ASR-11, and LSTAR (Lightweight Surveillance and Target Acquisition Radar, SRC Inc.) radars. The FAA radars provide two-dimensional locations on all aircraft with sufficiently strong radar returns, and when an aircraft provides its altitude they provide a full three-dimensional location estimate. The LSTAR radars provide three-dimensional position data on all aircraft with sufficient radar returns. The data from these radars is fused using a Kalman filter tracker to improve track accuracy and the fused tracks are passed through a track classifier to remove false tracks such as those caused by birds. Figure 1 shows the GBSAA Block 0 system architecture.

Once a clean air picture is produced, each aircraft is evaluated by the Assess algorithm to determine if it poses a threat to the UAS and if so, its relative priority among all threat aircraft. If an aircraft is assessed as a threat, a prioritized alert is issued. There are two levels of alerts: proximate and warning. A

proximate alert lets the GBO know there is an aircraft that must be watched, and the operator may or may not take action. A threat alert, in contrast, is provided when a developing situation necessitates operator action. In addition, the Assess algorithm makes a maneuver recommendation based on the behavior of current intruders. Initially this recommendation will not be displayed to the operator and will only be recorded for post-mission analysis. Once the maneuver logic is sufficiently robust it will be enabled as a display product in future blocks.

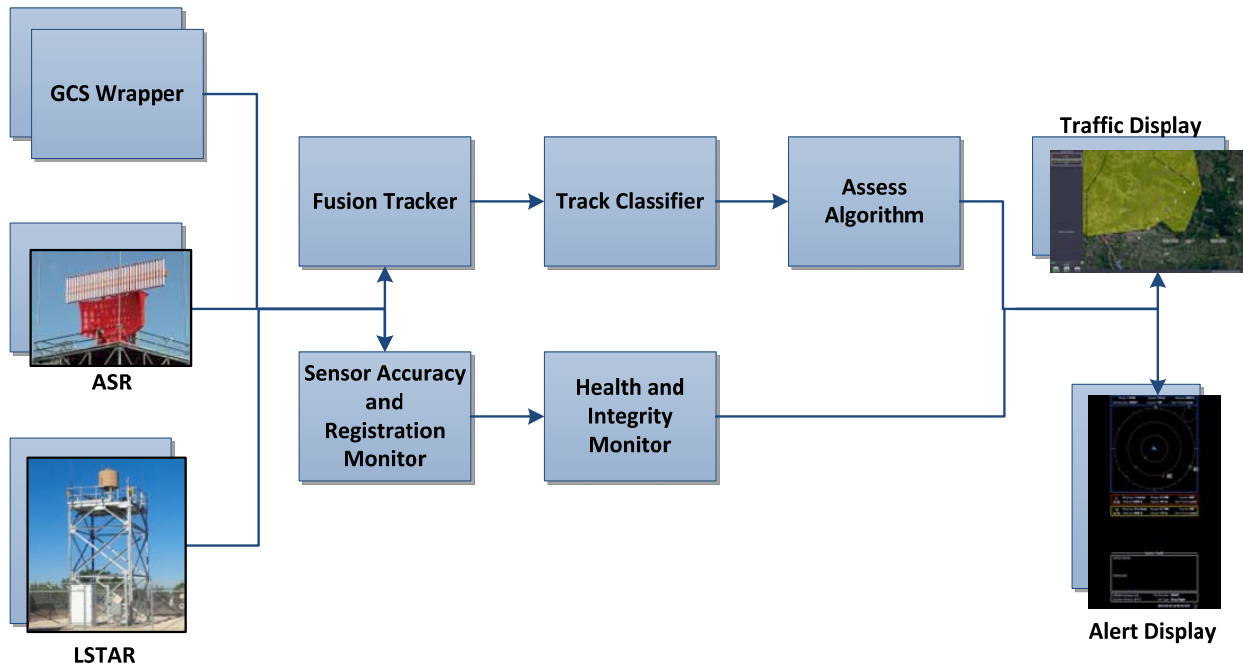


Figure 1: GBSAA Block 0 system architecture

Lastly, the GBSAA system is a dual-display system. A traffic display shows the overall air picture and basic information on intruder prioritization and system status. An alert display provides a streamlined air picture of only traffic; it also includes more detailed information about the alerting intruders.

The Army is in the final stages of transitioning the GBSAA system from development to production and deployment. The software is written to DO-178C standards, the hardware meets DO-254 standards, and the Army Engineering Directorate is providing the airworthiness certification. As part of the certification process, the Army requires a safety analysis of the full GBSAA system. This safety case includes, but is not limited to, analyses of the GBSAA subsystems, potential failure modes, risk ratios, and requirements. It also requires a demonstration of the usability of the GBSAA system by the UAS operators; in this case, the AO and GBO working together as a team. An important component of this requirement was a human-in-the-loop (HITL) laboratory simulation called the Operational Effectiveness (OE) evaluation and is the focus of this discussion. In this simulation the production code for the Assess algorithm and the Traffic and Alert displays were run on production hardware; synthetic intruder aircraft tracks were injected into the testbed system in which the UAS was simulated and the GCS controls emulated.

Although the OE evaluation is included as part of the Army's safety case for the GBSAA system, a discussion of the majority of the safety case is outside of the scope of this work. Additionally, although data informing the safety case's risk ratio analysis were collected during this evaluation, the analysis was performed by US Army analysts and is not included herein.

The GBSAA OE evaluation for Block 0 took place at the Massachusetts Institute of Technology – Lincoln Laboratory (MIT LL) from 22 March through 10 April 2015. This evaluation focused on the GBSAA GBO's ability to successfully utilize the GBSAA system as measured by user surveys and by an analysis of the ability of GBOs to maintain separation from other air traffic. The OE test was conducted as a HITL evaluation that examined GBO utilization of the system across three different scenario types:

1. Use Case: 14 synthetic flights representative of end-to-end missions based at Robert Gray Army Airfield (KGRK) at Fort Hood, TX (each 20 – 25 minutes in duration).
2. Envelope Case: 125 very challenging traffic encounters involving multiple intruders in unstructured airspace (each 4-5 minutes in duration) designed to help define the outer performance envelope of GBSAA operations.
3. Risk Ratio: 66 short, multi-intruder vignettes designed to support the human effectiveness component of the safety case for the GBSAA system.

In all scenarios, ownship performance and speeds were based on those of a Gray Eagle aircraft. Intruder speeds and altitudes were representative of those of helicopters and general aviation aircraft.

A total of eight individuals with pilot and/or ATC backgrounds participated in the OE evaluation as GBOs. All selected GBOs were familiar with the system's basic concept of operations and functionality. The test environment was established to replicate a GBO workstation that will be used at each fielded site. Surrogate AOs were included in the use case and risk ratio cases to simulate the crew coordination required under normal operating constraints. In preparation for runs for record, GBOs participated in a two-hour training period, designed as a refresher course for the display symbology definitions and test-specific standard operating procedures. Afterwards, the GBOs were provided approximately two hours of hands-on simulation time in order to familiarize themselves with the GBSAA displays and test procedures conducted throughout the runs for record.

The OE evaluation was designed to verify that the GBSAA system meets the human performance requirement outlined in the GBSAA System Level Requirement SRP2B0-340. This requirement states that the GBSAA system controls and displays shall be arranged and located so they are functionally visible. Additionally, this evaluation intended to assess that the GBSAA system is safe, usable, and useful from the perspective of the intended user and to evaluate if the system is capable of safely operating within its intended area of operation. The final goal of OE testing was to capture HITL data necessary to calculate the GBO logic ratio as part of the GBSAA safety case. Similar human performance evaluations were conducted for the Traffic Alert and Collision Avoidance System (TCAS) [Chappell, 1988] and for a flight data management tool for tower air traffic controllers [Reynolds et al., 2013].

Five key organizations participated in the development, integration, and runs for record (RFR) for the OE test event. The Army sponsored the OE evaluation and is the system integrator. MIT LL and Johns

Hopkins University Advanced Physics Laboratory shared responsibility for planning and executing the OE evaluation. SRC, Ensco, and Kutta Technologies participated in system architecture, subsystem, and code development and testing.

2 OE Evaluation Design and Method

2.1 Test Needs and Purpose

To evaluate the OE test goals, three types of tests were used: envelope tests, use case tests, and risk ratio tests. The envelope tests were designed as stressing cases, while the use case tests were designed to verify that the system is usable in simulated scenarios similar to the context in which the system will be deployed. Finally, risk ratio tests were conducted to capture critical data needed for the safety case. Further details of each test are provided below.

2.1.1 Envelope Test Scenarios

The envelope tests were designed to stress the human-inclusive system's ability to maintain self-separation in an unstructured airspace with multiple unpredictable intruders in the vicinity of the ownship. This was accomplished by presenting a GBO with a series of trials that lasted four to five minutes each. Each trial began with up to four potential intruders located within ten nmi of an eastbound ownship. As the trial progressed, the intruder aircraft flew predefined flight paths in the vicinity of the ownship. These flight paths were designed to produce proximate or warning alerts that would motivate the GBO to make a maneuver decision. The GBO initiated each maneuver decision by using a command interface shown in Figure 2.



Figure 2: GBO/AO command input widget

Of the 420 total intruders seen throughout the envelope tests, 209 were designed to produce a proximate alert, while 211 were designed to produce warning alerts. However, it is important to note that the expected alert status of each pre-defined intruder track may not have consistently developed into an alert because of the variability in GBO maneuver responses. In addition to the alert status of

each intruder, the test team designed the intruders so that they captured the full range of the following parameters.

- Intruder count – One, two, three, or four intruders
- Intruder approach geometry relative to ownship – Head on, overtaking, 90 degree intrusion, front oblique, or back oblique
- Speed relative to ownship – Greater than, less than, or the same
- Altitude relative to ownship—Greater than, less than, or the same
- Acceleration parameters – Accelerating, decelerating, or none
- Altitude trend – Climbing, descending, or level
- Predictability – Heading change of intruder, or no heading change of intruder

The closest point of approach (CPA) was then evaluated for each intruder across each trial in order to determine if the GBO was able to maintain self-separation throughout the very difficult, if not worst-case, situations. In addition to CPA, workload and situational awareness ratings were captured at the end of each trial in order to determine relationships between performance, intruder characteristics, and subjective assessments under varying conditions.

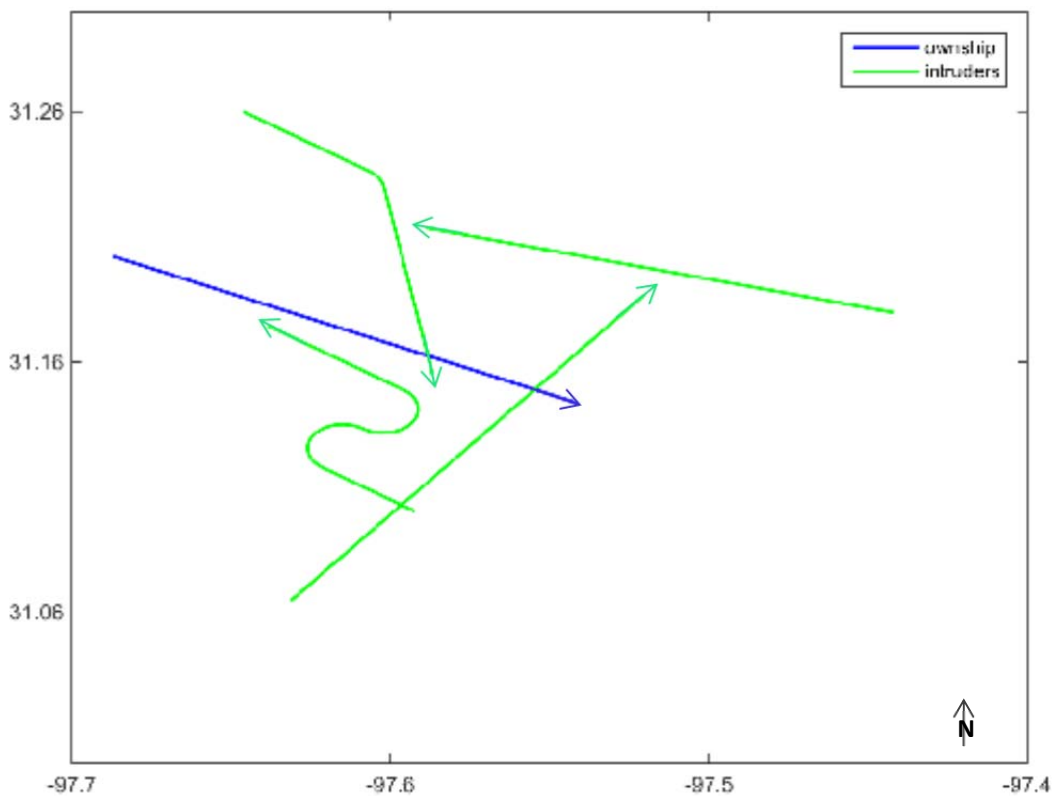


Figure 3: Example of 4-intruder envelope scenario

Figure 3 shows an example of an envelope scenario. In this scenario there are two westbound head-on intruders, one southeast-bound oblique intruder, and one northeast-bound 90-degree intruder. All intruders are shown in green, while the ownship is shown in blue. For all scenarios, the ownship

maintained a constant speed and altitude throughout the scenario. These speeds ranged from 85 to 110 kn and altitudes ranged from 3000 to 10,000'. The intruder altitudes varied through the same altitude range, with speeds ranging from 90 to 150 kn. Intruder turn rates varied between two and 3.5 degrees per second and vertical rates varied between 300 and 1000 fpm.

2.1.2 Use Case Test Scenarios

In contrast to the envelope tests, the use case tests were designed to mimic a real-life mission for an unmanned aircraft operating out of Robert Gray Army Air Field (KGRK) at Fort Hood, Texas. These scenarios, lasting 20 to 25 minutes each, began with a takeoff from KGRK. The ownship then proceeded to the restricted area near Fort Hood (R-6302) via a prescribed corridor. Once in the restricted area, the ownship performed some simple maneuvers in the restricted area, followed by a return to KGRK via the corridor. Throughout the scenario, the operator identified potential traffic threats and communicated maneuver recommendations to a confederate AO located in a separate room, who would then input the maneuver via the same command interface used in the envelope tests. Communication with the AO was achieved through an open telephone line; the GBO and AO both wore headsets to reduce environmental distraction. The GBO's communications were recorded using a lapel microphone to facilitate an analysis of communication latency.

Fourteen use case scenarios were used in the OE evaluation. Traffic levels and patterns seen in these scenarios were based on an airspace analysis of the Fort Hood region and included military helicopters and civilian fixed-wing aircraft operating outside the restricted area, and military aircraft operating within the restricted area. Four missions had low density traffic, with the number of intruders ranging from two to four intruders. The remaining ten missions were split between medium density traffic, with eight to ten intruders, and high density traffic, with 16 to 20 intruders. Figure 4 illustrates an example of a low density use case scenario. Note that the track shown in blue indicates the ownship track. The remaining tracks are all intruder tracks.

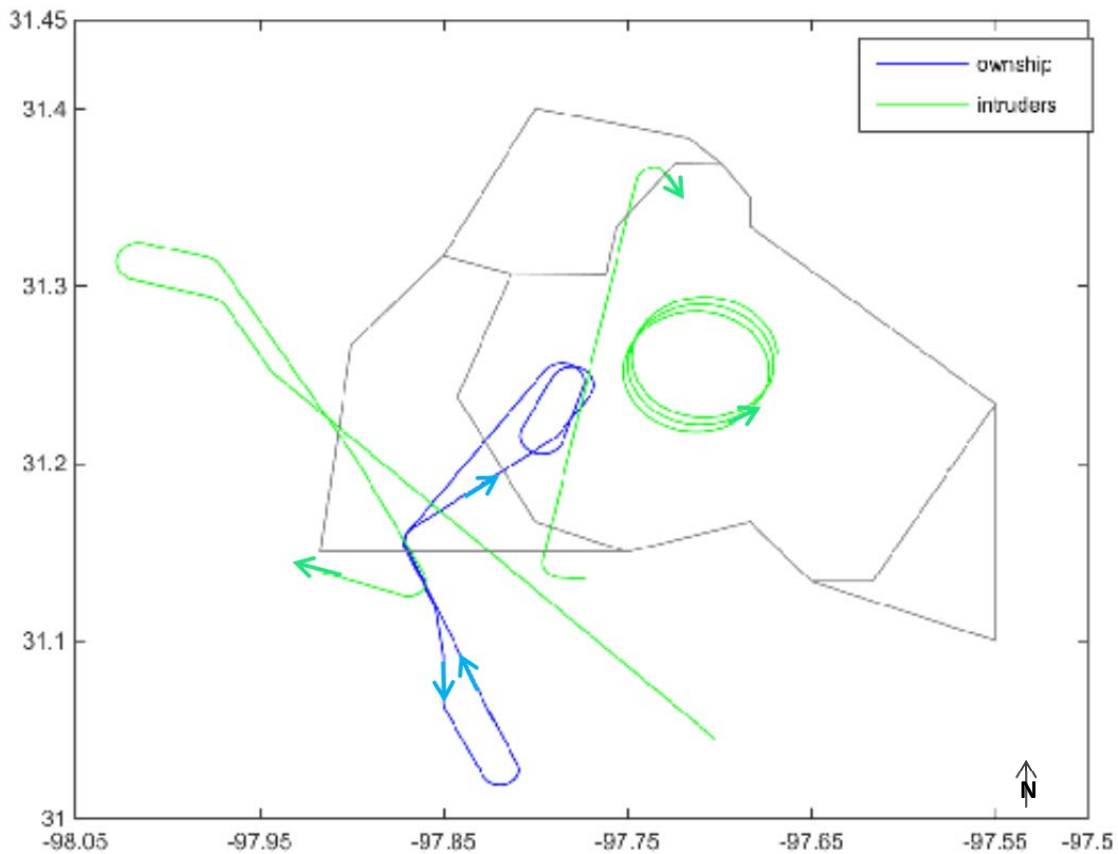


Figure 4: Example of low-density use case scenario

In designing the intruders' flight paths, various Fort Hood flight rules and procedures informed traffic placement and timing. For example, at KGRK manned aircraft fly on the east side of the runway, while unmanned aircraft operate on the west side. Additionally, military helicopters are authorized to fly at specific altitudes in a corridor between KGRK and R-6302.

With these rules in mind, a collection of intruder flight paths and a collection of ownship mission paths were created and used to develop the 14 missions. For each mission, these common flight paths were modified for location, timing, altitude, and speed to facilitate reasonable potential encounters throughout the mission. However, it must be noted that the encounters assumed no deconfliction efforts from either ATC or the intruder pilot, both of whom would typically prevent such encounters – for example, operators noted that ATC would never allow another aircraft to take off from GRK when an unmanned aircraft was inside the transit corridor returning to the airfield.

Unlike the envelope tests, test parameters other than traffic density were not controlled, since a main goal of the use case tests was to imitate a realistic mission to the extent possible within the confines of an experimental testbed. To accomplish this goal of reasonable realism, the use case scenarios were

reviewed by an ATC subject matter expert at MIT LL and were presented to subject matter experts associated with the Army for review.

As for the envelope tests, for each trial the CPA was evaluated to determine if self-separation was maintained, and workload and situation awareness ratings were collected.

2.1.3 Risk Ratio Test Scenarios

The risk ratio tests were designed to test GBO responses to intruder events that occur in unstructured airspace. As compared to the envelope tests, risk ratio trials had slightly fewer intruders, but were still highly stressing and in some cases beyond what would normally be expected in typical operations in the NAS. As in the use cases, the risk ratio tests required communication between the GBO and AO for recommended maneuvers. These data were collected in support of the GBO logic ratio calculation that is included in the GBSAA safety case documentation.

In designing the risk ratio scenarios, several criteria were taken into account. First, the encounters were designed with a primary intruder that would trigger a threat alert if no action was taken. Though additional intruders were present and potentially causing alerts, these intruders were secondary targets. Additionally, the encounters occurred over a range of angles, similar to the approach geometry classifications used in the envelope scenarios. The encounters also were designed using standard rate turns and approximately 500 fpm altitude changes. Finally, the scenarios were designed so that with no GBO intervention the CPA would fall within 0.5 to 1 nmi horizontally and less than 1000' vertically.

Many of the envelope scenarios already met these criteria, so they were reviewed and modified by a subject matter expert for reuse as risk ratio scenarios. The modifications primarily involved adjustments to the ownship and intruders' paths and altitudes in order to better fulfill the specified criteria. Of the 65 risk ratio scenarios, 19 scenarios were unique to the risk ratio scenarios while the remaining 46 were modified envelope scenarios. Figure 5 provides an example of a risk ratio scenario. As the majority of these scenarios were repurposed from existing envelope scenarios, the intruder and ownship performance characteristics are the same as those for the envelope scenarios.

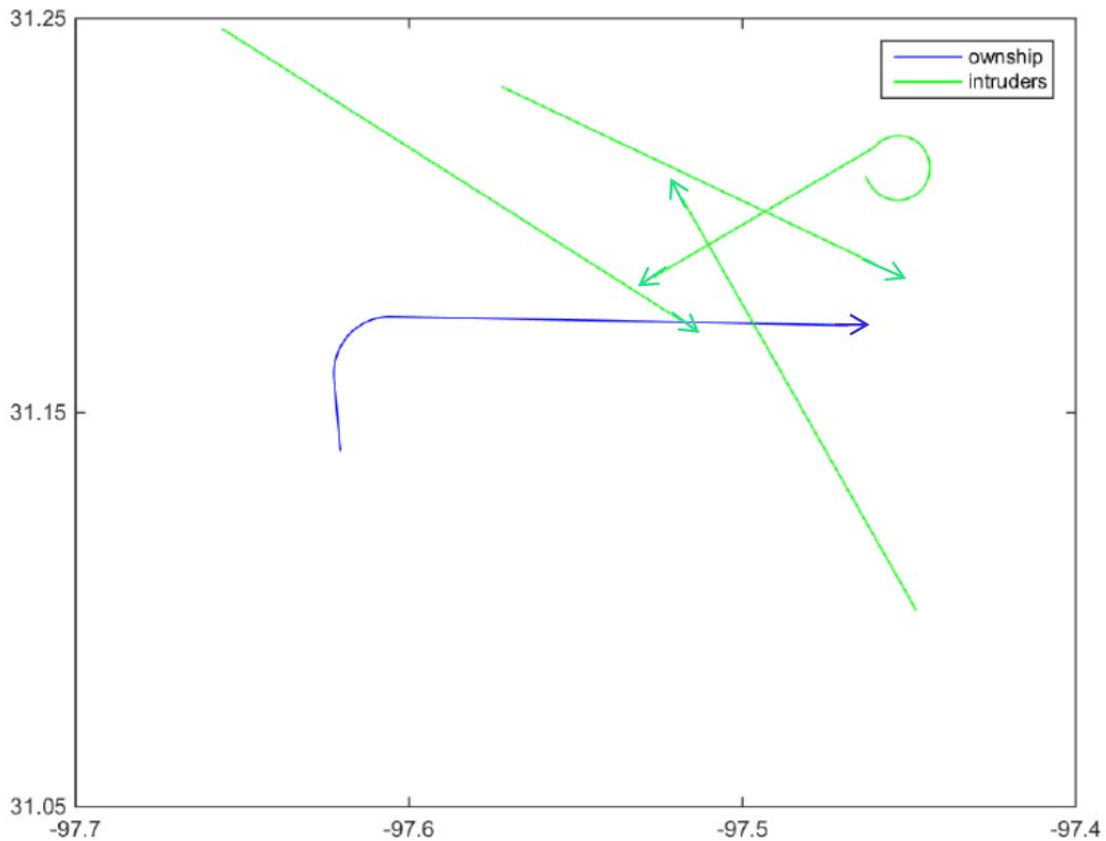


Figure 5: Example of 4-intruder risk ratio scenario

3 GBO Selection and Schedule

3.1 GBO Qualifications

Eight GBOs were selected from a consortium of government and contractor organizations from the ATC, pilot, and UAS operator communities. The selected GBOs were required to meet minimum qualifications needed to perform the GBO functions. These minimum requirements included 500 hours as pilot-in-command of manned aircraft or one year as a facility-rated air traffic controller. All selected GBOs were familiar with the system’s concept of operations and functionality. GBOs were required to travel to MIT LL for a one-week period from either March 29th to April 3rd or April 5th to April 10th, 2015. In lieu of the 80-hour qualification training required for qualification as an official GBO, GBO operators went through an abbreviated GBSAA GBO familiarization session that included a classroom training session and a hands-on simulation session.

Five of the GBOs had ATC experience only, while the remaining three were pilots. Of the three pilots, one GBO had experience as a pilot and air traffic controller and one GBO had experience as a small UAV operator and pilot. The controllers reported experience ranging from three to 20 years, with the

average being 13.8 years, and the pilots' reported flight time ranged from 2,500 to 4,500 flight hours, with an average of 3,167 flight hours.

Most operators reported familiarity with the GBSAA concept and a general working knowledge of the flight rules and airspace in and around Fort Hood. Operator familiarity with the GBSAA concept averaged 4.4 on a 5-point scale, where 5 corresponded to "very familiar"; the lowest rating was a 1 and highest was a 5. They were similarly familiar with the Fort Hood flight procedures, averaging 4.1 on the same 5-point scale; the lowest score was a 3 and highest was 5.

3.2 Operational Effectiveness GBO Training Session

There were two primary components of the GBO training session. First, the previously mentioned classroom portion provided an overview of the GBSAA displays, test procedures, and other test information. This briefing covered logistics associated with test conduct, differences in the GBO input between different test types, guidelines for interpreting the assessment algorithm alerts, a review of the operating area characteristics associated with each test type, and phraseology guidance for traffic communications between the GBO and AO. GBOs received the following guidance on how to respond to the alerts.

- Proximate alert: GBO may use discretion in providing traffic information and/or maneuver information to AO
- Warning alert: GBO must provide traffic information and maneuver information to AO if outside the 3.4 nmi area surrounding the airport, known as the Terminal Area Alert Zone (TAAZ)

One of the key areas within this two-hour training session were the voice communication procedures used to recommend maneuvers to a confederate acting as an air vehicle operator. In order to optimize crew coordination, the following phraseology guidance was provided for maneuver recommendations.

- Recommend <right/left> turn to <heading>. Traffic is <bearing>, <range>, <course>, <altitude>, <trend>
 - Example: "Recommend right turn to heading 030 degrees, intruder 2 o'clock, 2.2 miles, eastbound, 4,300 ft, 170 knots, level"

In addition to the briefing, the GBOs received an operator packet that included an overview of the display symbology, criteria for maintaining self-separation, and phraseology examples. The packet also provided maps with an overview of the operating area for the use case test, including manned and unmanned corridors within the operational area. This operator packet could be used by the GBOs at any time during the runs for record.

Once the classroom training session was complete, GBOs began the second portion of training in which they utilized the GBSAA system in the simulated environment. During this two-hour period, GBOs completed training trials for each of the test types. This allowed them to gain hands-on experience with the GBSAA system and the specifics of how it would be utilized in each test type. For example, during the risk ratio and use case trials the GBOs focused on applying their knowledge of the system symbology and algorithms for conducting operationally relevant procedures with an AO. In the envelope test training the GBOs provided their own maneuver inputs to avoid oncoming traffic. Here it was important

for GBOs to familiarize themselves with the maneuver input software. In all cases the GBOs gained familiarity with the pace and structure of each test type.

3.3 Operational Effectiveness Daily Test Schedule

Run for Record test days began at approximately 7:30 am with a quick overview of the day's activities and test station and test block assignments. Participants then proceeded to the test lab for runs for record. On an average day, they completed four to five test blocks before breaking for an hour-long lunch. Operators had the option of taking a 10-minute break between each block.

After the lunch break, operators received new test station and test block assignments. They completed another four to five test blocks, again with discretionary 10-minute breaks between each block. At the end of the day's runs, a short after-action review was conducted, where the day's activities were reviewed, any issues with the system were noted, and operators provided brief feedback on the day's activities. Operators were dismissed between 5 and 6 pm.

4 Simulation Test Environment

The simulation test environment was located in MIT LL's Air Traffic Management (ATM) and Ground Control Station (GCS) labs. Figure 6 illustrates the physical layout for the two labs.

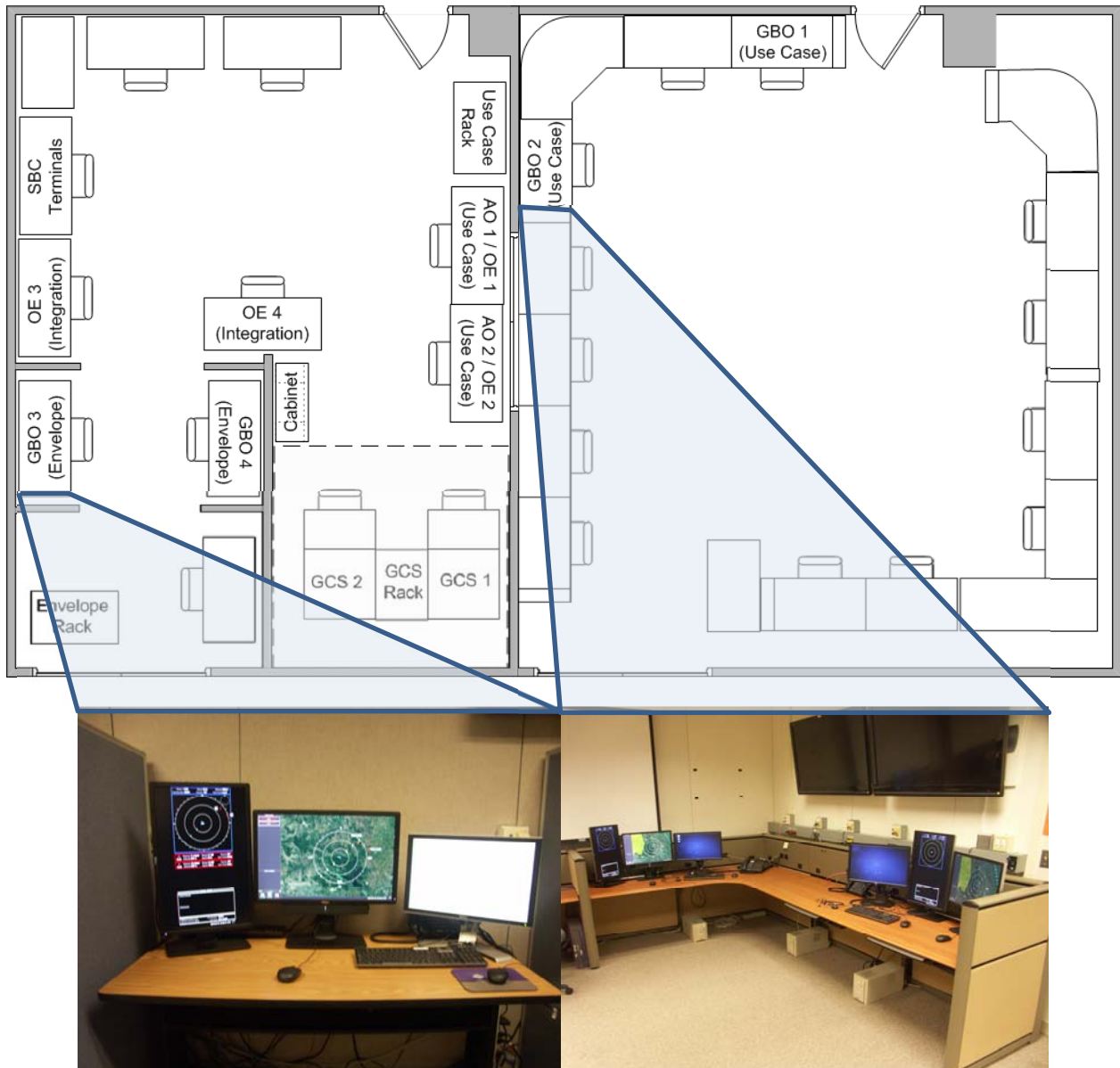


Figure 6: GBSAA OE lab layout and test stations

The GCS lab, located on the left, housed the two envelope test stations. It also contained the two AO stations and the supporting hardware necessary to run the OE testbed. The test stations used for the use case and risk ratio scenarios were located in the ATM lab, shown on the right side of Figure 6. This physical separation was designed to simulate the distributed nature of the GBO and AO coordination that would be observed *in situ*, which requires voice communications over a headset. The use case stations were converted to risk ratio stations after all use cases were complete. These test stations were utilized for the risk ratio test instead of the envelope stations because of the GBO to AO coordination requirement.

During the envelope trials the GBOs were required to wear headsets in order to ensure that audible alerts were presented in a similar manner to a live situation. This also ensured that ambient noise did not serve as a significant distractor.



Figure 7: Alert Display (left) and Traffic Display (right)

For all three test types, participants used the Alert Display, located on the left side of the workstation, and the Traffic Display, located in the center of the workstation. The right-hand monitor provided the scenario start-up and delivery graphical user interface, and in the case of the envelope tests, the heading command widget shown in Figure 1. The Alert and Traffic Displays are shown in Figure 7.

In this study, since only the Assess algorithm and the Traffic and Alert Displays were evaluated, MIT LL developed software designed to facilitate scenario delivery, data recording, and data emulation so that a realistic simulation of the GBSAA system could be evaluated. Figure 8 details the system architecture used for the OE evaluation and how the data is supplied, shared, and recorded in the system testbed. Tools developed for this evaluation include software to deliver scenarios and surveys to the operator. Running these delivery tools initiated data recording tools that record ownship and intruder position, altitude, and alert data. Additional software was written to emulate GBSAA health and status, and a final tool was developed to monitor the status of the OE tool suite described here.

In Figure 8, red blocks represent production software. Blue blocks denote software tools developed for the OE testbed system, including tools designed for data emulation and recording. Software tools written to enable scenario delivery and operator control of the ownship for the OE evaluation are shown in orange, and green indicates tools that were developed to enable the development of the synthetic scenarios used during OE testing.

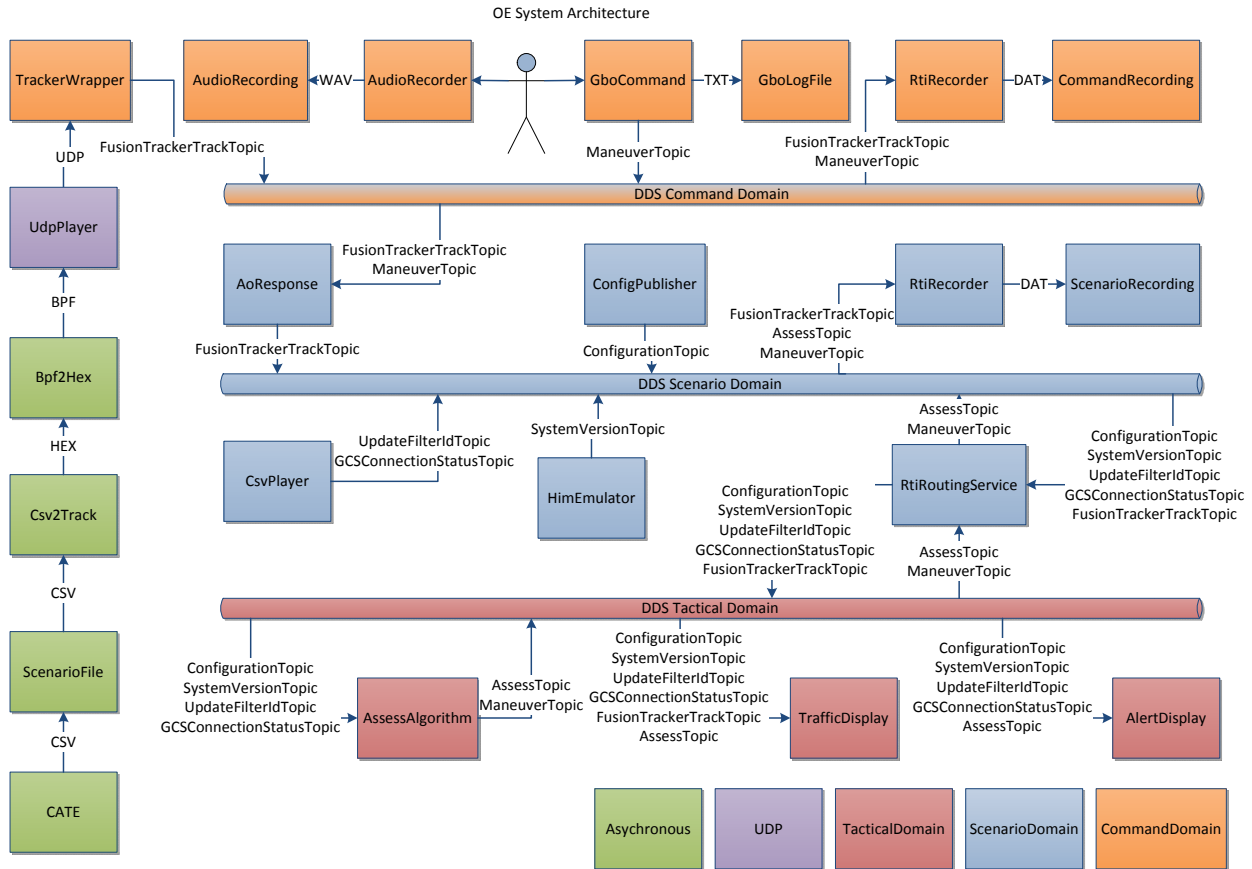


Figure 8: OE technical system architecture

5 Operational Effectiveness Test Results

5.1 Results

Two key criteria used in the separation analysis were the TCAS definition of a near-mid-air collision (NMAC) and the self-separation standard designed into the GBSAA system.

- NMAC – As defined by TCAS standards, an NMAC is when separation between the ownship and an intruder aircraft is less than 100ft’ vertically and 500ft’ horizontally [RTCA, 2013].
- Self-separation – For the GBSAA system, a self-separation violation is defined as when separation between the ownship and an intruder aircraft is less than 1000ft’ vertically and 1 nmi horizontally. This definition was developed prior to the existence of the emerging RTCA well-clear definition and is based on the Army’s investigation of several self-separation criteria [Hendrickson, 2015a, 2015b].

Overall, the operators and the GBSAA system performed well during the OE evaluation. The two week RFR resulted in the 1,608 trials for use in the separation analysis, with 5,856 intruders encountered. Across these encounters, no NMACs and 19 self-separation violations were recorded.

5.1.1 Total Trials and Intruders

During the runs for record testing, a total of 1,640 trials of 205 unique scenarios were completed, with the eight GBOs encountering 5,960 intruders. However, during the test conduct four scenarios were

identified by the GBOs and other test personnel as being inappropriate for use in assessing the usability of the GBSAA system by the GBOs, and were marked for closer review. These trials each utilized the same core intruder set—namely two overtaking intruders rapidly accelerating from 70 knots up to 140 knots with one of them turning directly towards the ownship. These intruders accelerated very quickly towards the ownship in a way that was specifically disadvantageous to maintaining separation. Test personnel and GBOs agreed that when faced with these intruders, successful maintenance of the self-separation standard would be beyond the capability of any SAA system. It is important to note that an SAA system itself cannot necessarily avoid more maneuverable and potentially hostile intruders that can in essence hunt down the UAS.

These trials—four envelope and one risk ratio—were subsequently eliminated from the test data and subsequent analysis. After removing these four scenarios, the data set for analysis consists of 201 unique scenarios, 1608 trials, and 5,856 intruders. All reported results in this report use this dataset which is summarized in Table 1. Additionally, the total number of test blocks and trials completed are presented to illustrate the breadth of the human in the loop data that were collected. Here, a test block is defined as a set of trials that usually lasted 60 minutes. The envelope test had a total of 12 blocks consisting of 10 or 11 trials depending on the specific block. The use case test had a total of seven blocks, each with 2 trials, while the risk ratio test had 6 blocks, each with 11 distinct trials. Note that each block did not contain the same number of trials across each test type. For example, the use case blocks were fewer in number but greater in duration compared to the envelope or risk ratio trials. Table 2 provides a breakdown of the total trials, blocks, and intruder encounter frequency for each of the test types.

Overall OE Intruder/Trial Count	
Total # of Intruders	5856
Blocks Completed	200
Trials Completed	1608

Table 1: Total trials, blocks and intruder encounter frequency

Envelope Test Status		Use Case Test Status		Risk Ratio Status	
Total # of Intruders	3272	Total # of Intruders	1176	Total # of Intruders	1408
Blocks Completed	96	Blocks Completed	56	Blocks Completed	48
Trials Completed	976	Trials Completed	112	Trials Completed	520

Table 2: Total trials, blocks, and intruder encounter frequency per scenario type

5.1.1.1 Total Number of Intruders

Of the 5,856 intruders, 4,354 of them produced at least one alert. These intruders break down as follows:

- Envelope trials: 2,463 alerting intruders
- Use case trials: 844 alerting intruders
- Risk ratio trials: 1,047 alerting intruders

5.1.2 Total Number of Self-Separation Violations

Self-separation violations were defined as when an intruder is closer than 1 nmi laterally and 1000' vertically to the ownship. Intruders that are 1 nmi or farther laterally, or 1000' or more vertically from the ownship will not incur a self-separation violation. Both conditions must be met to result in a self-separation violation, so an intruder 1 nmi laterally and 999' vertically from the ownship will not result in a violation, while an intruder 0.99 nmi laterally and 999' vertically from the ownship will.

Out of 1,608 trials and 5,856 intruders, a total of 19 self-separation violations occurred. The 19 violations were spread across 18 trials, with one use case experiencing two self-separation violations in a single trial. **Error! Reference source not found.** The small fraction of intruders and alerts, including the stressing cases in the envelope test, resulting in separation violations provides evidence that the GBSAA system is capable of safely providing the sense-and-avoid function for unmanned aircraft. This is further reinforced in the NMAC analysis below.

5.1.3 Total Number of NMACs

A near-mid-air collision is defined as when an intruder is closer than 500' laterally and 100' vertically to the ownship. As in the definition for self-separation, intruders that are 500' or farther laterally or 100' or more vertically from the ownship will not incur a NMAC violation.

Over the duration of the OE evaluation, no NMACs occurred in any of the test types. The lack of any NMACs across 1,608 trials and 5,856 intruders, including the stressing cases in the envelope test, provides evidence that the GBSAA system is capable of safely providing the sense-and-avoid function for unmanned aircraft.

5.1.4 Minimum Separation Distances

In addition to quantifying the number of NMACs and self-separation violations, the OE evaluation analysis looked at the CPA for each trial. For this analysis, a weighted slant range for each intruder report was calculated by $R = \sqrt{h^2 + (5z)^2}$, where h = horizontal range and z = vertical range; in each trial, the minimum value for R was then used as that trial's CPA. This weighted slant range provides normalized input from both the horizontal and vertical miss distances in a ratio equal to that of an NMAC (500' horizontal:100' vertical) and accounts for the difference in the level of safety provided by vertical vs horizontal separation distances. For all trial types, the average minimum slant range separation for each trial was 2.87 nmi, with a standard deviation of 1.05 nmi. The minimum weighted slant range separation was 0.66 nmi and the maximum was 7.74 nmi. Horizontal separation distances were similar, with an average minimum horizontal separation distance of 2.69 nmi and a standard deviation of 1.17 nmi for all trials. iFigure 9 provides a histogram of minimum weighted slant range binned by 1-nmi increments up to 10 nmi, with subdivisions for 0.1 and 0.5 nmi.

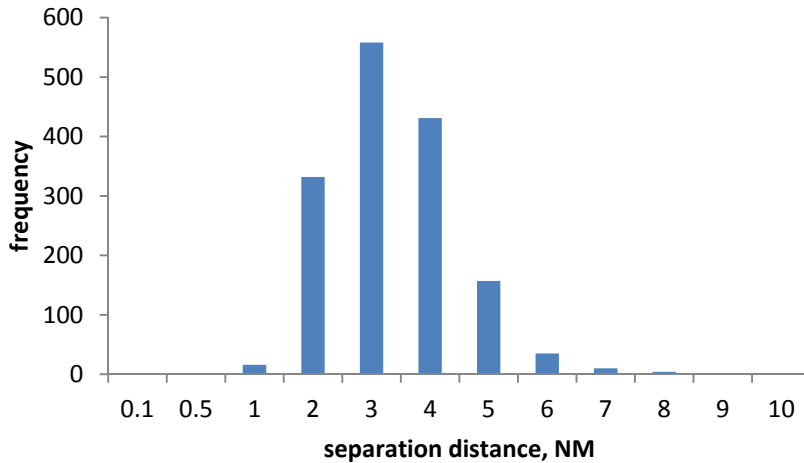


Figure 9: Minimum weighted slant range separation

The analysis also looked at differences in minimum separation distances for each trial type. Minimum slant range separation distances for envelope and risk ratio tests were similar, averaging 2.89 nmi (σ : 1.04 nmi) and 3.06 nmi (σ : 1.02 nmi), respectively. Minima for these test types were also similar (0.75 nmi, 0.76 nmi respectively) but the maximum value for the closest intruder for envelope trials was lower than that for risk ratio trials (7.49 nmi, 7.74 nmi respectively). This similarity also applied for horizontal separation distances (2.73NM, 2.90 nmi respectively) and standard deviations (1.11 nmi, 1.10 nmi respectively).

Slant range separation distances for the use case trials were lower than those for the envelope and risk ratio trials, averaging 2.01 nmi with a 0.79 nmi standard deviation and a range of 0.66 nmi to 3.88 nmi. These results are shown in Figure 10.

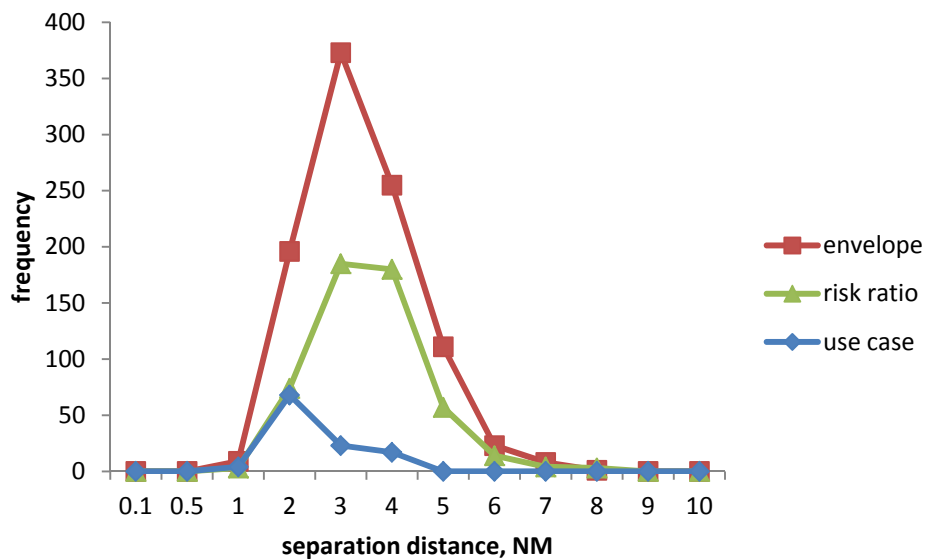


Figure 10: Minimum weighted slant range separation by trial type

Since the use case trials were designed for a different purpose and in a different manner than the envelope and risk ratio tests, it is not surprising that the average separation distances differ. When the use case trials are separated by traffic density, the average separation distance for the low density use cases is greater than those for the medium and high density use cases, as shown in Figure 11. The medium and high density cases have similar average slant range separation distances (1.08 nmi, 1.05 nmi respectively) and standard deviations (0.49 nmi, 0.47 nmi respectively).

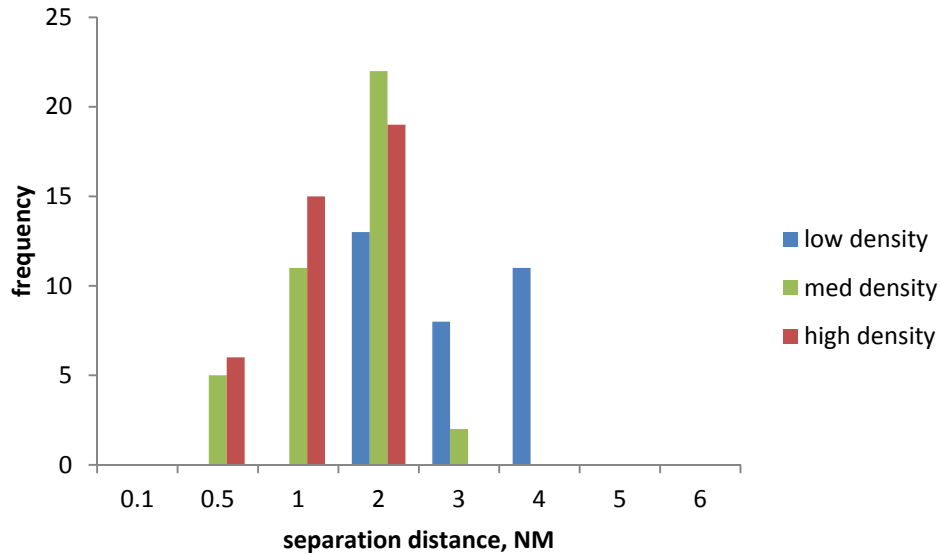


Figure 11: Minimum slant range separation for use case trials by traffic density level

Of the 112 use case trials, 32 had low traffic density: two to four intruders, with an average of three intruders per trial. The remaining 80 trials were evenly split between medium and high traffic density. The medium density trials had eight to 10 intruders and averaged 8.8 intruders per trial, while high density trials each had 16 to 20 intruders and averaged 18 intruders per trial.

Figure 12 shows the minimum horizontal and vertical separation distances for a subset of the OE trials. Also shown on this figure are the horizontal and vertical boundaries for NMAC and self-separation violation parameters. From this figure it can be seen that many of the self-separation violations occurred on the edge of the defined self-separation boundary; similarly, the violations that were within the self-separation bounds did not approach the bounds defined for an NMAC.

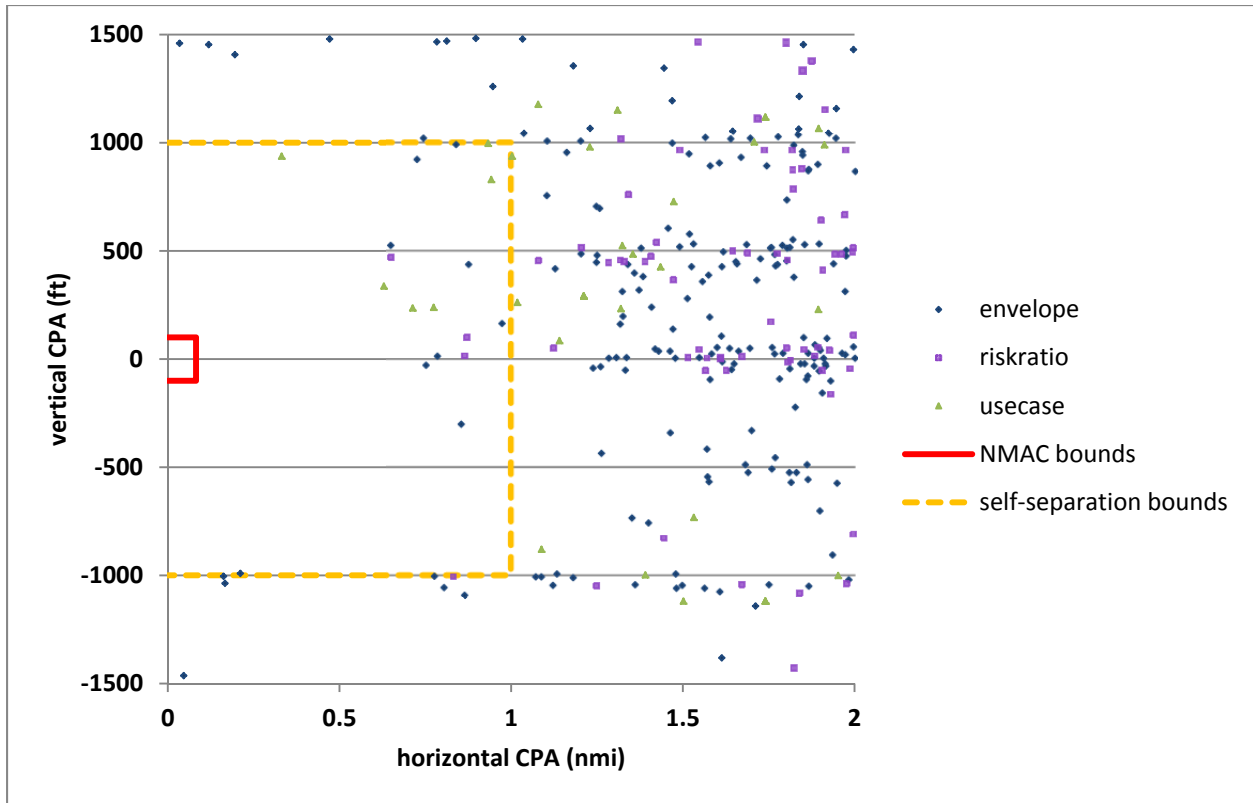


Figure 12: Horizontal and vertical separation distances for all trial types, 2NM and 1500' range, with GBSAA operator input

In comparison, Figure 13 shows the horizontal and vertical minimum separation distances for the same scenarios when no GBO input was provided. These unmitigated trials resulted in a total of 1672 self-separation violations and 56 NMACs. Note that when GBSAA is not used each of the eight runs of each scenario would result in an identical plot in Figure 13. To make these eight identical points visible as eight distinct points in the figure to aid in comparison to Figure 12, they were artificially spread out slightly by adding a small amount of noise.

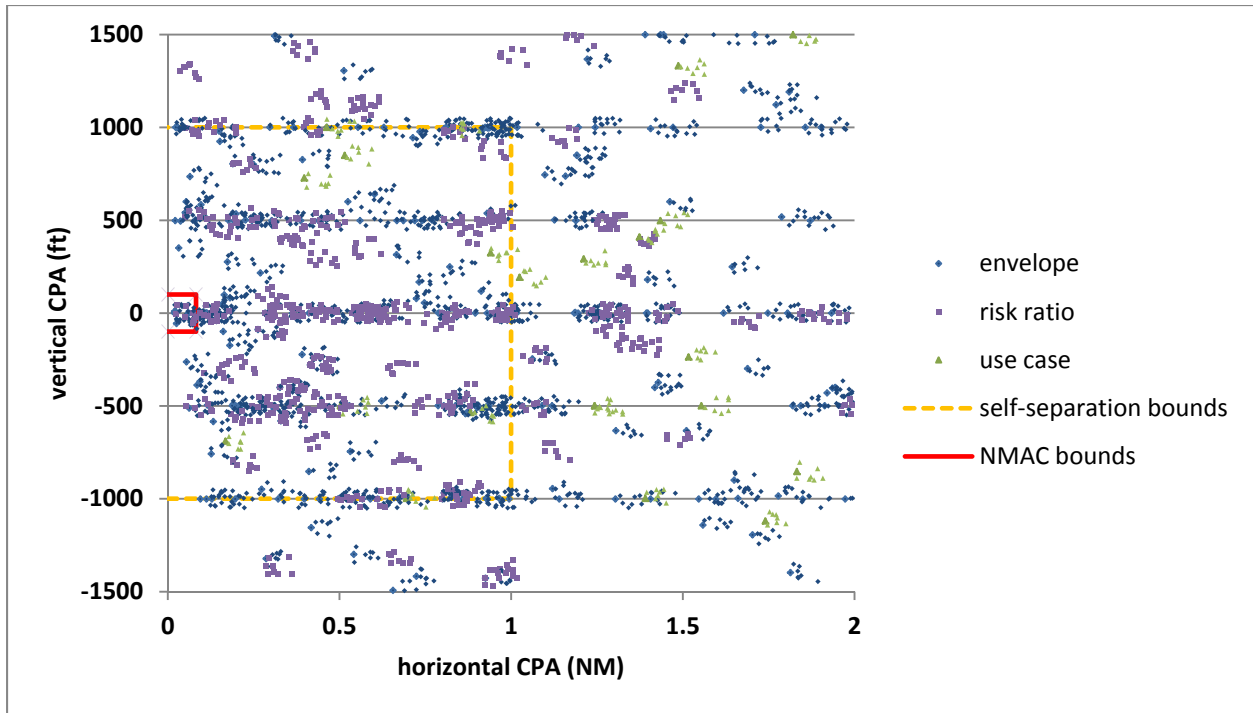


Figure 13: Horizontal and vertical separation distances for all trial types, 2 nmi and 1500' range, without GBSAA operator input

5.1.5 Subjective Operator Responses

In addition to collecting quantitative data on operator performance, the OE evaluation also collected survey data regarding operator workload, performance, and factors that motivated maneuver recommendation. Both workload and situation awareness were measured on a five-point scale, where 1 was equivalent to *very low* and 5 was equivalent to *very high*. Overall, operator workload was very low (mean: 1.62; σ : 0.92), even when the most difficult scenarios were encountered, and situation awareness was very high (mean: 4.71; σ : 0.75).

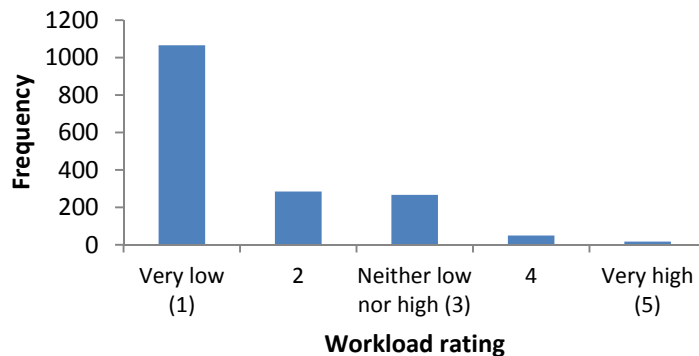


Figure 14: Operator workload, all test types

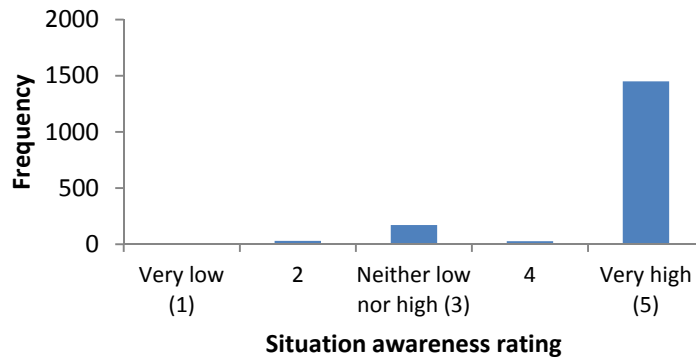


Figure 15: Operator situation awareness, all test types

Participants also found it easy to use the displays to perform the GBO tasks. The ease of use questions were also rated on a five-point scale; this time, a 1 was equivalent to *very easy* and a 5 was equivalent to *very difficult*. Operators thought it was slightly easier to perform general GBO tasks with the Threat Display (mean 1.21; σ 0.51) than the Alert Display (mean: 1.29; σ : 0.62); when asked about identifying threat traffic, the opposite was true (Threat Display: mean 1.33, σ 0.56; Alert Display: mean 1.29, σ 0.62). However, these differences are not significant.

5.1.6 Key AAR Qualitative Insights and Observations

At the end of each weekly session an open discussion was held among the test stakeholders and GBOs. This after-action review was designed to gather qualitative feedback from the operators based on their experience with the system. During these sessions, operators provided comments on display improvements and enhancements and evaluation feedback. The observations provided in this section were generally observed by more than one GBO.

The GBOs indicated that they had received ample training time and adequate materials to perform successfully on the GBSAA system. Overall, hands-on familiarization time was reported as the most beneficial training event.

The information and its presentation on the displays were positively received by the GBOs, who found the system easy to use. However, a few suggestions were made. Many operators suggested that course information be included in the traffic data block. Similarly, they wanted access to more information about non-alerting traffic. Certain information that was provided about threat traffic, such as vertical trend information, was less visible for non-alerting traffic. Though the datablocks expanded when operators clicked on them, this feature was not apparently obvious; additionally, the operators thought that some of the information shown in the expanded datablock should be available in the smaller datablock.

Some operators expressed interest in consolidating the information onto a single display to reduce the division of attention, and many operators commented that rapid changes to intruder prioritization made it very difficult for them to process the information provided in the prioritization list. One operator

stated that he would start to provide a traffic call-out but before he could complete it, the prioritization would change and another intruder became the priority intruder.

As RFR weeks progressed, GBOs became more familiar with the GBSAA displays. Initially, GBOs reported that they most frequently relied on the traffic display for situational awareness. As they became more familiar with the system they incorporated information presented on the alert display into their scan pattern; one operator commented that she originally eschewed using the alert display since she was unfamiliar with it, but as the testing progressed, she realized its value to her scan.

Operators also provided feedback on the evaluation design. They noted that some of the scenarios were less predictable than what might be seen in an operational context, stating that some of them felt “unwinnable”. They began to anticipate unexpected maneuvers from intruder traffic and responded more cautiously as the evaluation progressed. Operators also commented that in a realistic use case, they would have been included in a mission brief and had access to a mission flight plan. Having this information would have influenced their recommended maneuvers and would have allowed them to prioritize the mission to a greater degree. Finally, though the test duration was similar to the on-task hours for real-life operations, operators reported slight fatigue as a result of the number and challenging nature of the encounters presented each day.

Finally, all operators recommended that the GBSAA system should be fielded.

6 Conclusions and Future Work

Operator performance throughout all three test types indicated that the GBSAA system elements under test as part of the OE evaluation provide acceptable levels of performance in both simulated structured and unstructured airspace. Over the entire OE duration, the facts that no NMACs were observed and that, relative to the number of encounters experienced, 19 self-separation violations occurred, with a minimum slant range distance of 0.66 nmi, provide evidence that the GBSAA system is likely to be safe and effective in supporting the SAA function in a real-life deployment. This performance supports the operators’ belief that the GBSAA system will warn them of potential NMAC and self-separation violations with enough time to respond and avoid such situations.

In addition to providing adequate self-separation, the GBSAA system proved easy to learn and to use. Operators stated that the training time and materials they received were sufficient for OE test purposes, and their responses to the survey questions showed that system use did not incur much workload, even during the most stressing scenarios. The GBOs also thought that the system provided adequate situation awareness in all of the scenarios. All operators believed that GBSAA would be well-received in the UAS community and had high opinions of the system at the end of the OE evaluation.

The results of the OE evaluation indicate that the GBSAA system has the potential to be a sufficient replacement for the current SAA solution of ground observers and chase planes. Both operator performance and feedback suggest that the system is able to meet the OE goals of safety, usability, and usefulness, and that it is able to operate within both structured airspace representative of a deployment site and within unstructured, challenging airspace.

Further evaluation of the use of the production GBSAA system as a replacement for the current SAA capability will occur during flight tests at Dugway Proving Grounds, Utah, in the winter of 2015/2016. Field operations are currently planned to begin in 2016 at five Army and two Air Force sites after the conclusion of these flight tests. Additionally, development for Block 1 of the GBSAA system will continue; this next block will supply operators with automated maneuver guidance provided by the Assess algorithm.

7 Acknowledgements

This work is sponsored by the United States Army under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.

8 Acronyms

AO	Aircraft Operator
ATC	Air Traffic Control
CPA	Closest Point of Approach
DoD	Department of Defense
FAA	Federal Aviation Administration
GBO	Ground-Based Operator
GCS	Ground Control Station
GBSAA	Ground-Based Sense and Avoid
HITL	Human-in-the-Loop
KGRK	Robert Gray Army Airfield, Fort Hood, TX
kn	Knots
LSTAR	Lightweight Surveillance and Target Acquisition Radar
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
NAS	National Airspace System
nmi	Nautical miles
NMAC	Near Mid-Air Collision
OE	Operational Effectiveness
RFR	Runs for Record
SAA	Sense and Avoid
TAAZ	Terminal Area Alert Zone
TCAS	Traffic Alert and Collision Avoidance System
UAS	Unmanned Aircraft System

References

Chappell, S. (1988), "TCAS from a Human Factors Point of View," *SAE Technical Paper Series*.

Code of Federal Regulations. (2004), "Right of Way Rules: Except Water Operations," Title 14, Section 113, Washington, DC.

Hendrickson, A. (2015a), *Top Level Sense and Avoid Performance Requirements Based on See and Avoid Efficacy*, US15-Hendrickson, US Army Unmanned Aircraft Systems Common Systems Integration Product Office, Huntsville, AL.

Hendrickson, A. (2015b), *Systems Engineering of SAA Systems, US Army Unmanned Aircraft Systems*, US Army Unmanned Aircraft Systems Common Systems Integration Product Office, Huntsville, AL.

Reynolds, H., Lokhande, K., Kuffner, M., & Yenson, S. (2012), "Human-Systems Integration Design Process of the Air Traffic Control Tower Flight Data Manager," *Journal of Cognitive Engineering and Decision Making*, 273-293.

RTCA, Inc. (2015), *Detect and Avoid (DAA) Minimum Operational Performance Standards (MOPS) for Verification and Validation*, RTCA Paper 261-15/PMC-1400, Washington, DC.

RTCA, Inc. (2013), *Minimum Operational Performance Standards (MOPS) for Traffic Alert and Collision Avoidance System II (TCAS II) Hybrid Surveillance*, DO-300A, Washington, DC.

RTCA, Inc. (2011), *Software Considerations in Airborne Systems and Equipment Certification*, DO-178C, Washington, DC.

RTCA, Inc. (2000), *Design Assurance Guidance for Airborne Electronic Hardware*, DO-254, Washington, DC.

Biographies

Sarah K. Yenson is the human factors lead for the GBSAA Operational Effectiveness evaluations at MIT Lincoln Laboratory. She received a B.S. in aeronautical and astronautical engineering from MIT and an M.S. in civil engineering with a focus on aviation and transportation from the University of California, Berkeley. Her work includes the development and assessment of complex human-machine systems, particularly in the area of aviation. She is an instrument-rated private pilot.

Rodney E. Cole is the Assistant Leader of the Surveillance Systems Group leading the Laboratory's portfolio of UAS Airspace Integration programs and other aviation safety programs. He received a B.S. with a double major in physics and mathematics from VA Tech, a M.S. in mathematics from VA Tech, and a Ph.D. in mathematics from the University of Colorado. He developed a number of operational aviation safety and efficiency systems over the past 25 years.

M. Sage Jessee is a Human Factors Engineer with The Johns Hopkins University Applied Physics Laboratory. He received his M.A. in Experimental Psychology from the University of Alabama in Huntsville, in May 2009, and has served in multiple positions on the committee of the Tennessee Valley chapter of the Human Factors and Ergonomics Society. He specializes in human-in-the-loop simulation testing across a variety of warfighter domains. His expertise in the field has allowed him to become instrumental in bridging the gap between warfighter requirements and material development. Currently, Mr. Jessee focuses on multi-modal input technology for novel computing environments, process instrumentation technology in support of complex training, and operator monitoring technology. Throughout his career he has been featured in the Discovery Channel's documentary "The

Science of War” as an eye tracking specialist and received several team achievement awards at the Pentagon’s Hall of Heroes for his contributions to coalition command and control.

Chris Crowder

John Innes is a retired Army Infantry Colonel. He retired after 26 years as an army infantry ranger master parachutist and assignments teaching at West Point, Long Island University, the U.S. Naval War College and University of Alabama Huntsville and currently works as the Test Lead for the Ground Based Sense and Avoid System in the PM Unmanned Aircraft Systems in Huntsville, AL.