

RQ-7B Shadow Achieved  
Performance Model Verification  
Final Report

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## EXECUTIVE SUMMARY

In 2009, to support research in the area of Unmanned Aircraft Systems (UAS), the Federal Aviation Administration (FAA) formally engaged in Cooperative Research and Development Agreements with three industry partners: Textron/AAI Corporation, General Atomics – Aeronautical Systems Inc., and GE Aviation Systems LLC. This specific group of government and industry partners, commonly known as the UAS FAA and Industry Team (or UFIT), has planned a series of research and development (R&D) activities, using multiple platforms and methods, to provide data to support the integration of UAS into the National Airspace System (NAS). One such activity is the RQ-7B Achieved Performance Model Verification Exercise, also known as Demo 1S. This report presents the final results of the exercise.

The objectives of Demo 1S were:

- To independently assess and calibrate the 6 Degrees of Freedom aircraft model of the RQ-7B Shadow simulator against the performance of the RQ-7B Shadow aircraft. Once it is determined that the performance of the model adequately represents the actual aircraft, the human-in-the-loop (HITL) real-time simulator can be used to realistically represent the RQ-7B Shadow aircraft flying in the NAS and Next Generation Air Transportation System (NextGen) environments for R&D studies. These R&D studies support the broader set of goals identified in the FAA document entitled “Unmanned Aircraft Systems Integration Evaluation Plan.”
- To verify the successful integration of the RQ-7B Shadow simulator with the NextGen Integration and Evaluation Capability (NIEC), located at FAA William J. Hughes Technical Center.

This exercise was conducted in multiple phases:

- A July 14, 2009 field flight of a U.S. Army RQ-7B Shadow aircraft departing from Redstone Army Airfield (KHUA), in Huntsville, Alabama.
- A December 22, 2009 HITL simulation of the same flight using the RQ-7B Shadow simulator, which is part of the UAS Modeling and Simulation Capability in the NIEC.
- Data reduction and analysis of the parameters collected during the flight and the simulations and publication of the initial report on November 19, 2010.
- Refined analysis and publication of this final report in May 2011.

The data reduction and analysis in the initial report showed that several compared measurements did not meet the criteria defined in the exercise plan. However, the study also showed potential outliers in the data, possibly due to measurement errors and difficulties in exactly reproducing human actions and environmental conditions from the actual flight test. Furthermore, the criteria guidance provided in the exercise plan was established using standards for the evaluation of manned aircraft simulators, and UAS manufacturer and engineering guidance. The criteria applied conservatively in this study may be too restrictive for UAS simulators at this time and should be re-evaluated within the scope of future UFIT simulations.

Based on the initial results, the UFIT partners have agreed that the performance of the RQ-7B Shadow simulator integrated within the FAA’s laboratory suite is acceptable and

sufficient, as is, to run the currently planned simulations. The team unanimously decided to publish the initial results in an initial report and commence a follow-on refined analysis addressing the issues and concerns identified.

This final report confirms the conclusions of the initial report and concludes the exercise. It includes the results of the refined analysis, suggests improvement to the simulator, and provides recommendations to the future users of the simulator regarding some identified limitations. Because it includes data on proprietary and International Traffic in Arms Regulations regulated systems, the initial report remains approved for official use only. This final report exists in two versions: one complete version for official use only and one abridged version designed for public release.

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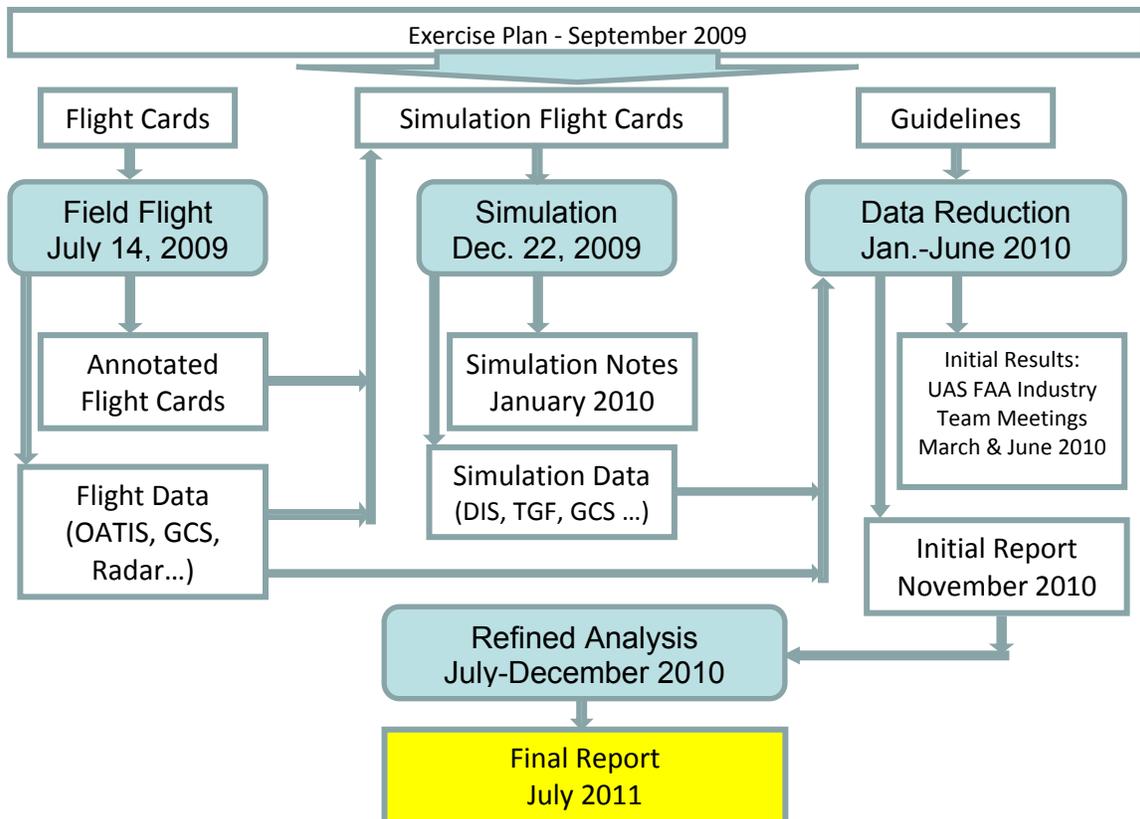
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## 1 Introduction

This document was developed by the Federal Aviation Administration's (FAA) Air Traffic Organization (ATO) Engineering Development Services Group, located at the William J. Hughes Technical Center (WJHTC), on behalf of a partnership of government and industry organizations. The industry partners involved are AAI Corporation, General Atomics – Aeronautical Systems Inc., and GE Aviation Systems LLC. Participating FAA organizations include the ATO Research Technology and Development Office, Aviation Safety (AVS) Unmanned Aircraft Program Office (UAPO), AVS Aircraft Certification Service, and ATO Unmanned Aircraft Systems Office. The U.S. Army also significantly supported this effort.

This report presents the data reduction, analysis, and results of the refined analysis that was started following the publication of the initial results of the RQ-7B Achieved Performance Model Verification Exercise. It concludes the exercise and completes the "RQ-7B Achieved Performance Model Verification Initial Report" [REF 4]. The study's objectives, background, methodology, and initial results are also briefly described. More detailed information on these aspects of the exercise is available in the FAA document entitled "RQ-7B Shadow Achieved Performance Model Verification Exercise Plan" [REF 1]. The exercise includes multiple phases that are represented in the following figure. This document is highlighted in yellow.

Figure 1 – RQ-7B Shadow Achieved Performance Exercise Overview



The other key documents of the exercise are:

- The UAPO's "Guidelines to Verify RQ-7B Shadow Performance with 6 Degree of Freedom Model" [REF 2], which provides guidance on the processing and presentation of the results
- The FAA's "Achieved Performance Demo 1S Simulation Notes" [REF 3], which reports on the conditions of the Achieved Performance simulation that was conducted on December 22, 2009
- The FAA Engineering Development Services' "RQ-7B Achieved Performance Model Verification Initial Report" [REF 4], dated November 19, 2010

The initial results were presented to the FAA and industry partners in March and June of 2010 and captured in detail in the initial report. A refined analysis to address issues identified during the initial phase followed. The analysis focused on the removal of outliers, the adjustment of data for explained biases, and errors associated with human response differences and environmental conditions.

The initial report contains aircraft data that is both proprietary and covered by the International Traffic in Arms Regulations (ITAR). As such, it is NOT FOR DISTRIBUTION and must be reserved for official use only. Because this final report also includes data on proprietary and ITAR regulated systems, it is published in two versions: one complete for official use only and one abridged version designed for public release.

## 1.1 Background

The increasing demand and interest in Unmanned Aircraft Systems (UAS) has made their integration into the National Airspace System (NAS) an FAA priority. Current access is restricted due to the lack of validated operational procedures, standards, and policies for UAS operations. As such, it is a growing imperative within the UAS community, including public and civil users, to reduce these restrictions in order to improve and advance integration of UAS into the NAS.

To standardize the certification processes and ultimately relax restrictions associated with UAS integration, the FAA is working to determine the parameters, operations, and procedures that define acceptable UAS operations while maintaining the highest level of safety. There are many challenges that must be overcome before the procedures for certification and operations of UAS are standardized and made routine. Extensive research is required to produce the safety case evidence.

To support these research needs, the FAA has joined resources with several industry partners under an alliance of Cooperative Research and Development Agreements and formed a team referred to as the UAS FAA and Industry Team (UFIT). The UFIT industry partners include AAI Corporation, General Atomics – Aeronautical Systems Inc., and GE Aviation Systems LLC.

The primary goals of the modeling, simulation, and flight demonstrations planned by UFIT include the following:

- Provide data to support the evaluation and integration of UAS into the NAS
- Provide data to support the development of a safety case for UAS
- Provide a platform for validation of RTCA SC-203 UAS performance requirements now under development
- Utilize the advanced capabilities of the UAS community to serve as a test bed for exploring future concepts, such as 4-dimensional trajectory based operations, a cornerstone of the Next Generation Air Transportation System (NextGen)

The FAA document “UAS Integration and Evaluation Plan (UASIEP)” [REF 5] unites several agency and industry partner efforts aimed at investigating UAS-NAS integration issues. An essential part of the overall initiative is characterizing the performance of existing UAS (such as the RQ-7B Shadow) and developing/verifying representative models for use in future simulation activities.

The RQ-7B Shadow Achieved Performance Model Verification exercise is a key initial activity supporting these goals. The achieved performance data and UAS models will be used to support further data collection activities to baseline and assess UAS performance in the NAS/NextGen using modeling and simulation techniques. In addition, this particular exercise is a building block demonstration that supports the UAS Demonstration Project (and therefore is also referred to as Demo 1S)<sup>1</sup>.

## 1.2 Exercise Objectives

The primary objective of the exercise is to independently assess and calibrate the 6 Degrees of Freedom (6 DoF) aircraft model of the RQ-7B Shadow simulator against the performance of the RQ-7B Shadow aircraft. Once it is determined that the performance of the model adequately represents the actual aircraft, the human-in-the-loop (HITL) real-time simulator can be used to realistically represent the RQ-7B Shadow flying in NAS/NextGen environments. In support of the broader set of goals identified in the UASIEP, the data will be used to make decisions, contribute to standards efforts, and serve as a foundation for additional research and development and performance data collection.

The secondary objective is to verify the integration of the RQ-7B Shadow simulator with the FAA’s Target Generation Facility (TGF), a suite of hardware and software located within the WJHTC that powers the HITL simulations conducted there.

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<sup>1</sup> The UAS Demonstration Project is part of the FY09 NextGen Portfolio for NextGen Demonstration and Infrastructure Development being sponsored by the FAA Research Technology and Development Office. The core activities of the UAS Demonstration Project are actually a subset of exercises described in the UASIEP that will demonstrate actual and evolving capabilities with corresponding risk assessments. To identify that this particular exercise is also affiliated with the NextGen Demonstration Portfolio, it is co-labeled Demo 1S. This demonstration project leverages, complements, and is fully coordinated with the broader set of activities described in the UASIEP.

### 1.3 Exercise Synopsis

The first phase of the exercise consisted of a single test flight of an RQ-7B Shadow UAS departing from Redstone Army Airfield (KHUA) and operating in restricted area R2104. A description of R2104 Restricted Airspace is presented in Appendix D.

During the test flight, three sets of maneuvers were performed to gather both straight and level flight characteristics and turning performance at two different airspeeds and three different altitudes. During these maneuvers, flight parameters were recorded using an independent set of equipment, installed onboard the aircraft, called the Open Architecture for Telemetry and Instrumentation Systems (OATIS). Details of the flight maneuvers, gathered data, and testing methods are available in the RQ-7B Shadow Achieved Performance Model Verification Exercise Plan [REF 1] and Achieved Performance Demo 1S Simulation Notes [REF 3].

The second phase of the exercise consisted of a duplication of the same maneuvers during an HITL real-time simulation using the AAI Corporation-built RQ-7B Shadow simulator, which is part of the UAS Modeling and Simulation Capability located within the WJHTC's NextGen Integration and Evaluation Capability (NIEC). Flight parameters were recorded by the simulator and the TGF, with which the simulator interfaces.

During the third phase, the performance data from the simulated flight was compared to the real world data to verify and calibrate the 6 DoF aircraft model, which is an integral part of the simulator.

The intent was to gather basic flight information for a wide range of flight parameters and capture sufficient data points to assess the performance of the simulated model against the performance of the aircraft.

### 1.4 Exercise Key Terms

The following terms will be used throughout the document:

- Field Flight: refers to the July 14, 2009 real world RQ-7B Shadow flight
- Simulated Flight or Simulation: refers to the December 22, 2009 RQ-7B Shadow simulator flight
- Flight profile: a series of maneuvers
- Run: each repetition of a flight profile being flown

## 2 Method

### 2.1 Participants

Participants for the field flight included one UAS pilot, one Mission Payload Operator (MPO), one Mission Commander (MC), one External Pilot, and a team of maintenance technicians. The operational support was provided by the U.S. Army. The flight crew was provided by AAI Corporation.

The participant for the simulated test flights included one UAS pilot provided by AAI Corporation.

## 2.2 Research team

The participating FAA organizations designed and implemented the research effort. In addition, FAA Aircraft Certification Service (AIR-130) provided support in flight plan development, criteria definition, and preliminary data analysis. All data was collected during both the field and simulated flights by members of the UAS team from the FAA's Research & Technology Development Office. Data from the July 14, 2009 field flight was pre-processed and provided by Dynetics Inc. Data reduction and analysis of all sets of data was performed at the WJHTC by the UAS team, with support from AAI Corporation. AIR-130 and the UAPO assisted in data collection, data reduction, and data analysis during and after the field flight as well as in coordinating flight logistics.

## 2.3 Assumptions and Limitations

During the course of the exercise, several limitations were observed that must be considered in the context of the results. These limitations include:

- The independent data collection system installed onboard the aircraft during the field flight was used as the source of independently collected “truth” reference data. Observations and analysis have shown that the data collected was itself subject to some degree of error.
- The data criteria tolerances provided in the exercise plan were applied conservatively because there are currently no standards or requirements for evaluating UAS simulators. Therefore, there are no formal criteria against which to evaluate.
- Winds aloft used in the simulated flights were entered using measured data from the field flight tests. Since the simulated effect of winds aloft cannot exactly replicate the calculated values from each flight, some error is expected in the simulated data due to variations in wind speed and direction.
- Similarly, the atmosphere model used in the simulator does not perfectly replicate the conditions present in the real world. Variations caused by local atmospheric fluctuations may result in some amount of error in the simulation data.
- The sampled data taken from the field flight and measured by the OATIS did not always have the same frequency as the sampled data taken from the simulated flight. In these cases, interpolation techniques were used to allow for direct data comparison at a common rate.
- During the field flight and simulation, flight maneuvers were manually initiated by the UAS pilot. This caused differences in the timing and sequencing of commands entered into the Ground Control Station (GCS). Whenever known and explained, these differences were corrected for during data reduction.
- The GCS software would not allow the UAS pilot to configure the commanded altitude with sufficient resolution. This was also adjusted during data reduction.
- Operational and airspace constraints could not be reproduced during the simulation.
- Some phases of the field flight required the use of an external pilot. Because this could not be reproduced during the simulated flight due to a limitation of the hardware-in-the-loop simulator (HILSIM), these phases of flight were excluded from the analysis.

- The current configuration HILSIM used in the study lacks the landing capability. Therefore, the landing phase of flight was excluded from the analysis.

## 2.4 Equipment

### 2.4.1 Unmanned Aircraft System

The UAS used in the field flight phase of the exercise was an RQ-7B Shadow owned by the U.S. Army. It was equipped with the OATIS system. The configuration of the aircraft was Full Rate Production IV, and the tail number was 2060. The transponder was set to operate in Mode 3A and Mode C.

**Figure 2 – AAI Corporation’s RQ-7B Shadow**



### 2.4.2 Laboratories and Equipment

The simulated phase of the exercise was conducted at the WJHTC. Detailed information on the integration of the RQ-7B Shadow simulator with the TGF and the NIEC, including computers, network, and interface configuration, is provided in the Achieved Performance Demo 1S Simulation Notes [REF 3].

#### 2.4.2.1 Unmanned Aircraft System Model

The RQ-7B Shadow simulator used was AAI’s HILSIM. It includes a 6 DoF aerodynamic model, aircraft avionics (i.e., the Avionics Computer Equipment [ACE] unit), and a GCS. The vehicle control software (VCS) was written by CDL Systems (an

AAI Corporation-contracted company). The HILSIM GCS consists of two stations, one used by the UAS pilot and one used by the MPO.

The HILSIM development has been a cooperative effort between AAI Corporation and the U.S. Army. Dynetics Inc., of Huntsville, Alabama, was contracted by the U.S. Army to develop a high fidelity 6 DoF simulator of the block 1B airframe. The block 1B simulator was tailored to interface with the ACE-II avionics. Dynetics Inc. has since been responsible for the development and configuration control of the 6 DoF aero model and support software on the simulation PC (developed by the Department of Defense's Joint Modeling and Simulation System). AAI Corporation has been similarly responsible for the avionics portion of the simulation code. The AAI Corporation portion of the HILSIM code was developed and is controlled using ISO 9000 standards and other approved software development procedures, including quality assurance reviews and peer level software reviews. Together, these separate pieces of code allow the RQ-7B Shadow to be test flown on the ground. For this exercise, a non-flight ACE-311 was integrated as part of the HILSIM.

#### 2.4.2.2 National Airspace System Model

For the simulated portion of this exercise, the Distributed Environment for Simulation, Rapid Engineering, and Experimentation (DESIREE) air traffic control (ATC) simulator, together with the TGF, were used to present the air traffic scenario on ATC workstations. The TGF allows researchers to capture information about aircraft trajectories, aircraft proximity, and other relevant data for use in subsequent analysis. DESIREE emulates both en route and terminal controller functions. It receives input from TGF that allows it to display information on the radar scope, including radar tracks, data blocks, and sector maps. It also allows controllers to perform the typical functions that they would perform in an operational environment (e.g., performing handoffs, entering data into the host computer). Like TGF, DESIREE has data collection capabilities and is equipped to collect information on all controller entries made during a scenario. DESIREE and TGF were developed by engineers at the WJHTC.

### 2.5 Materials

The sections below describe the operational environment and key components of the exercise.

#### 2.5.1 Airspace

The field flight portion of this exercise was performed under an existing Certificate of Waiver or Authorization (COA) issued by the FAA. This COA is valid for Shadow operations at KHUA into and out of restricted areas R2104 – A, C, D, and E. KHUA is located at Redstone Arsenal, near Huntsville, Alabama. Operations were only conducted when Redstone ATC was operational. Launch and recovery were from KHUA. The UAS flew directly into R2104 after launch and returned via the same route. Altitude was at or below 2500 ft. when the UAS was not in the restricted areas. For a detailed description of the airspace, including graphical representation and lat-long information, refer to Appendix D.

### 2.5.2 Scenario

The same scenario was used for the field and simulated flights. The scenario consisted of three runs of the same flight profile, all occurring within one continuous flight. The flight profile included a specific set of maneuvers that is listed in the initial report. The flight cards presented to the UAS pilot during the field flight and simulation are reproduced in the Achieved Performance Demo 1S Simulation Notes [REF 3].

### 2.6 Data Collection

All data collection was conducted by FAA research personnel, with support from the U.S. Army and AAI Corporation. The list of data and metrics collected for both the field and simulated flights for this exercise was defined by the UFIT data collection workgroup. The majority of all dynamic data required by the field flight testing was collected using the OATIS installed on the RQ-7B Shadow. The simulation data was collected by the GCS component of the RQ-7B Shadow simulator and the NIEC. Data collected for this exercise included all information on basic flight parameters, configuration of the RQ-7B Shadow, and existing weather conditions as described in the initial report.

## 3 Data Reduction and Analysis

All data analysis was conducted by FAA research personnel with support from AAI Corporation. In general, the analysis compared reference data captured during the field flight to simulated data captured during the HITL simulation. In addition to the achieved performance data from the aircraft that was used to verify and calibrate the 6 DoF model's performance, TGF position and speed data was captured to verify the integration of the simulator with the NIEC's NAS simulation capability.

### 3.1 Maneuvers

This section describes how the data was processed. It includes a definition of maneuvers, atmospheric conditions, and details on each of the processed parameters, together with the eventual corrections that were applied.

The data captured during the field and simulation flights were initially compared on a "per maneuver" basis. The refined analysis combined the results of these per maneuver comparisons in multiple categories, as follow:

- straight and level maneuvers
- turn and level maneuvers
- climbs and descents
- all maneuvers combined

A list of and definitions for the maneuvers are presented in tables 3 and 4 of the RQ-7B Achieved Performance Model Verification Initial Report [REF 4].

### 3.2 Atmospheric conditions

During the simulation flight, the altimeter setting, Outside Air Temperature (OAT), wind direction, and speed that had been recorded during the field flight were input into the HILSIM. However, the OAT and wind parameters were not updated every second during simulation. They were only updated once the maneuver level was reached (i.e., 3000 ft. Mean Sea Level [MSL], 7000 ft. MSL, and 11,000 ft. MSL) based on the values recorded by the flight crew during the field flight. These values are listed in the following table.

**Table 1 – Atmospheric Conditions Settings**

| Run | Altitude | OAT (°C) | Wind Dir/Speed | Alt. Setting (In. Hg) |
|-----|----------|----------|----------------|-----------------------|
| 1   | 3000     | 21.5     | 075/5kts       | 30.07                 |
| 1   | 7000     | 14.6     | 080/5kts       | 30.07                 |
| 1   | 11,000   | 9.8      | 330/10kts      | 30.07                 |
| 2   | 3000     | 21       | 075/10kts      | 30.07                 |
| 2   | 7000     | 15       | 080/4kts       | 30.07                 |
| 2   | 11,000   | 10       | 345/5kts       | 30.07                 |
| 3   | 3000     | 21       | 100/5kts       | 30.07                 |
| 3   | 7000     | 15       | -/0            | 30.07                 |
| 3   | 11,000   | 10       | 345/5kts       | 30.07                 |

The initial ground level conditions recorded by the crew during the July 14, 2009 field flight are presented in the following table.

**Table 2 – Initial Ground Level Conditions**

| Condition         | Ground Value |
|-------------------|--------------|
| Take off Heading  | 350 deg      |
| Dew Point         | 19° C        |
| Density Altitude  | 1700 ft.     |
| Temperature       | 24° C        |
| Altimeter setting | 30.07 In. Hg |
| Fuel              | 44 liters    |
| Take off altitude | 482 ft.      |

### 3.3 Human Resources

The crewmembers that flew the RQ-7B Shadow during the July 14, 2009 field flight and the pilot that flew the simulator on December 22, 2009 filled out questionnaires related to their qualifications and flight expertise. While the answers to these questionnaires were not used for this analysis, they are presented for completeness in Appendix E of the initial report.

### 3.4 Field Flight vs. Simulation Flight Parameters

To verify the performance of the RQ-7B Shadow simulator, select parameters were analyzed to compare the field flight to the simulation flight. The following table lists the parameters used in the Field Flight vs. Simulation Flight analysis.

**Table 3 – Field Flight vs. Simulation Flight Parameters**

| <b>Parameter</b>              | <b>Unit</b> |
|-------------------------------|-------------|
| Airspeed                      | Knots       |
| Altitude                      | Feet        |
| Density Altitude              | Feet        |
| Pitch                         | Degrees     |
| Yaw                           | Degrees     |
| Roll                          | Degrees     |
| Angle of Attack               | Degrees     |
| INS Position (Lat, Long, Alt) | Meters      |
| Fuel flow                     | Liters/hour |
| Engine RPM                    | RPM         |
| Lift Coefficient              | N/A         |

For each of the parameters, data from both sources was aligned and interpolated, if necessary. Two plots were generated for each maneuver and each run. They are presented in the appendices of the initial report. The first plot shows the value of the parameter from both sources on the same 2D plot. The second shows the absolute value of the difference between the two sources. If applicable, the criterion is also displayed on the difference plot. An embedded table displays the minimum, maximum, and average values of the difference and, if applicable, the percentage of points where the difference is above the criterion.

The refined analysis required plotting some of these parameters using different conditions. The new plots are provided in Appendix C.

### 3.4.1 Criteria

The RQ-7B Shadow Achieved Performance Model Verification Exercise Plan [REF 1] provided a list of criteria to guide the comparison of the field flight data to the simulation flight data. Some of the original criteria were not applicable (e.g., OAT, wind) and therefore not used during the data reduction process. The following table lists the criteria that were used for the statistical computations presented in the results section.

**Table 4 – Comparison Criteria**

| <b>Parameter</b>             | <b>Criteria</b> |
|------------------------------|-----------------|
| airspeed (knots)             | ± 3 knots       |
| altitude (feet MSL)          | ± 100 ft.       |
| pitch (degrees)              | ± 2°            |
| yaw (degrees)                | ± 2°            |
| roll (degrees)               | ± 2°            |
| engine revolution per minute | Assessment      |
| fuel flow                    | Assessment      |
| angle of attack              | Assessment      |
| coefficient of lift          | Assessment      |

### 3.4.2 Refined Analysis

The initial analysis had identified outstanding data points in the source data. For example, the altitude reported during the field flight in Run 3, maneuver 5.12 included two data points where the altitude changed by 1000 feet over a tenth of a second period of time. These erroneous measurements were eliminated during the interpolation process.

Other outliers were identified by comparing the deviation values to 150% of the Inter Quartile Range (IQR). This method was applied to the deviation data instead of the source data to account for cases where both sources would change significantly but still correlate.

For each set of data, the 25% quartile (Q1) and the 75% quartile (Q3) are computed. IQR is equal to  $Q3 - Q1$ . Outliers are data points above  $Q3 + 1.5 \times IQR$  or under  $Q1 - 1.5 \times IQR$ .

Most data points identified by the 1.5 IQR method were located at the beginning and end of maneuvers but did not deviate from the trend line. Probable causes include:

- Inaccuracy of the simulator model during transient states
- Imprecision regarding the appreciation of the start and stop times for each maneuver
- Differences in the pilot's technique and timing when entering and leaving a maneuver

In the absence of a definitive conclusion, the values identified by the 1.5 IQR method were not removed from the statistical pool. For future model evaluations, it is recommended to leave the pilot out of the loop as much as possible, and, for example, create automated missions that include the sequences of required maneuvers.

Some biases were also identified and taken into account during the analysis. The following sections describe how each parameter was processed and how the differences were interpreted by the analysis team.

### 3.4.3 Airspeed

The plots of the various maneuvers consistently show a bias between the field flight and the simulation flight data points. This difference is also present when comparing the airspeed values provided by the aircraft system and the values provided by the independent data collection system, which were both onboard. This bias could be caused by differences in the position of the Pitot tubes and of the static ports or the calibration of the instruments. It was also confirmed by users of the aircraft that this bias value is typical.

The average deviation between the simulated flight and the field flight is very close to the estimated value of the bias. The maximum deviations are located at the beginning and end of the maneuvers, which suggests that they could also be caused by transient error, pilot technique, maneuvers not being completely established, or inaccurate appreciation of start time.

For future exercises, it is suggested that a series of data samples from all the installed systems be collected at the same time prior to the flight. This would help identify calibration differences between the instruments and remove associated biases in the data.

### 3.4.4 Altitude

The three requested maneuver altitudes were 3000, 7000, and 11,000 ft. MSL. However, the pilots did not always command these exact values during the field and simulation flights. Accordingly, the actual altitudes entered by the pilots were recorded and the data was corrected according to the following table. These corrections were only applied to level maneuvers.

**Table 5 – Altitude Corrections**

| <b>Run</b> | <b>Flight card altitude</b> | <b>Altitude entered by pilot during field flight</b> | <b>Correction applied to field flight data</b> | <b>Altitude entered by pilot during simulation flight</b> | <b>Correction applied to simulation field data</b> |
|------------|-----------------------------|--|--|---|--|
| 1          | 3000                        | 3000   | 0  | 3010  | -10  |
| 1          | 7000                        | 7000   | 0  | 7010  | -10  |
| 1          | 11,000                      | 11,000   | 0  | 11,020  | -20  |
| 2          | 3000                        | 3000   | 0  | 3010  | -10  |
| 2          | 7000                        | 6990   | 10   | 7090  | -90  |
| 2          | 11,000                      | 11,000   | 0  | 11,010  | -10  |
| 3          | 3000                        | 3010   | -10  | 3040  | -40  |
| 3          | 7000                        | 7010   | -10  | 7000  | 0  |
| 3          | 11,000                      | 11,010   | -10  | 11,090  | -90  |

*Altitudes and corrections in feet*

The reference altimeter setting on the day of the field flight was 30.07. The same value was input by the pilot in the simulator's VCS interface during the simulation flight. In an attempt to remove any bias due to altimeter settings, the altitude comparison was done by comparing the OATIS barometric altitude with the simulator's pressure altitude. OATIS is calibrated with an altimeter setting of 29.92 In. Hg and pressure altitude is the altitude indicated when using a 29.92 altimeter setting.

Even after correction for pilot input error, approximately half of the data points are above the 100 ft. criterion, while the average values are relatively close to that limit. Therefore, the following two tests were run on the HILSIM simulator:

Test #1 (Standard atmospheric pressure): With a VCS altimeter setting of 29.92 In. Hg and the aircraft flying at 3000 ft. MSL, the following altitudes were reported:

- Simulator log files (AltMSL field in tle.txt): 3002 ft.
- Simulator log files (PressureAlt field in target.txt): 2996 ft.
- TGF log files: 3000 ft.

Test #2 (Field Flight atmospheric pressure): With a VCS altimeter setting of 30.06 In. Hg (rounded by VCS from 30.07) and the aircraft flying at 3000 ft. MSL, the following altitudes were reported:

- Simulator log files (AltMSL field in tle.txt): 2871 ft.
- Simulator log files (PressureAlt field in target.txt): 3001 ft.
- TGF log files: 2869 ft.

Test #1 results were acceptable but the values for test #2 should have been close to:

- Simulator log files (AltMSL field in tle.txt): 3001 ft.
- Simulator log files (PressureAlt field in target.txt): 3132 ft.
- TGF log files: 3132 ft.

Note: TGF is internally using Pressure Altitudes only.

Test #1 and test #2 clearly demonstrate that there is a problem with the simulator's altitude data output when not flying in standard atmospheric pressure conditions.

In light of these findings, altitude comparisons were recomputed after correcting the simulator's Pressure Altitude data points by 131 ft.

While the maximal deviation values are still very high, the average differences are now under the criterion limit for all maneuvers.

It appears that the atmospheric model incorporated into the simulation capability can only simulate standard atmospheric pressure conditions or that the altimeter settings entered into the VCS interface are not properly used by the HILSIM's 6 DoF model.

Until this is corrected by the manufacturer, the HILSIM simulator should only be used within a standard pressure atmosphere.

### 3.4.5 Density Altitude

Density Altitude for the field flight was provided in the OATIS log files. However, no information was provided on the calculation used by that system to generate these values.

There is no density altitude value in the log files generated by the simulator, so this parameter was originally estimated using the following formula:

$$DA = PA + (120 * (OATC - ISA))$$

↓

*Where:*

$$OATC = ((OAT-32)*(5/9))$$

$$ISA = 15 - ((1.98/1000) * Alt\_AGL)$$

*DA:* Density Altitude (in feet)

*PA:* Pressure Altitude (in feet)

*OAT:* Outside Air Temperature

*ISA:* International Standard Atmosphere

*Alt\\_AGL:* Ground Level Altitude

The results and plots were presented in the RQ-7B Achieved Performance Model Verification Initial Report [REF4].

In order to obtain a better estimate of the temperature at the altitude of the aircraft, the pressure altitude was used instead of ground level altitude. The pressure altitude was also corrected by 131 feet as described in Section 3.4.4.

The new comparison using the Pressure Altitude corrected by 131 ft. showed no improvement regarding the results, but this is not conclusive for the following reasons:

- OAT has a strong influence on the computed Density Altitude (1 deg => 120 ft.)
- The OATIS uses directly measured OAT while it is estimated for the simulator
- The OAT in the simulator was only entered at the beginning of the level maneuver and was not updated during climbs or descents
- The algorithm used to compute the Density Altitude in the OATIS is not known and might be different from the one used for the simulator

### 3.4.6 Pitch, Yaw, Roll

The pitch comparison showed good results with all the averages under the criterion and only 10% of the data points above. In particular, once a climb was established, there was an excellent match.

However, some straight and level legs showed higher than expected differences. For example, during Run 2 Man 5.03 (a straight and level leg at 3000 ft. MSL), the field flight data shows a relatively constant pitch, which was expected for a straight and level maneuver. For the same maneuver, the simulated flight data shows higher variations of the pitch. This suggests inaccuracies generated by the simulator's airplane dynamics model and stability mode. Generally, it appears that the simulator's stability model may have more dynamic oscillatory behavior than that of the actual performance of the aircraft.

The roll and yaw parameters were collected and plotted for each maneuver during the field and simulation flights. During climbs and descents, the pilots initiated turns. The exact timing and sequence of turns could not be reproduced during the simulation flight. Therefore, the statistical results only relate to the level maneuvers.

The results show that for 80% of the data points, the yaw deviation is greater than the 2 degree criterion. However, the yaw comparison was done using data fields labeled "Heading" (true heading for the field flight and magnetic for the simulation flight, which adds a 3 degree magnetic declination bias to the results). Furthermore, the data is significantly influenced by the way the maneuvers were executed by the different pilots and the rudimentary model for the winds. One can also question how the relationship between heading and yaw was established within the simulator model.

A better comparison of the yaw would require an automated flight with preprogrammed maneuvers and a more advanced wind modeling capability within the HILSIM.

The results show that for more than 97% of the data points, the roll deviation was smaller than the criterion. The fact that the pilot did not actually have to fly the bank in/out but only entered the turn commands using the VCS graphical interface contributed to these results. Some small variations were noted in the plots; these were probably caused by the aircraft performing automated wind corrections during the field flight, corrections that were not needed during the simulation flight (where the wind was constant).

#### 3.4.7 Angle of Attack

The Angle of Attack (AOA) is not recorded by the RQ-7B Shadow simulator and could not be calculated from available parameters. Only the flight AOA versus time could be plotted for the field flight. Plots are provided in the initial report.

#### 3.4.8 Inertial Navigation System Position

The aircraft position during the field flight was recorded by the OATIS Inertial Navigation System. The RQ-7B simulator provides the aircraft position to TGF using the Distributed Interactive Simulation (DIS) standard. The messages sent by the RQ-7B simulator include WGS-84 earth-centered aircraft positions (X, Y, Z) updated at a 50 Hz rate. X, Y, and Z were converted to lat, long, and ellipsoid height.

The altitudes were also corrected for the pilot input error, as described in Section 3.4.4.

The following three plots were generated for each maneuver:

- The east/north plot shows the 2D position of the aircraft (lat/long) from both the field flight and the simulation flight. The first point of the maneuver was translated to the (0, 0) coordinate. There was no rotation applied.
- The ellipsoid height from both sources is plotted versus time. The corrections listed in “Table 5 – Altitude Corrections” were applied.
- The absolute difference of the ellipsoid heights. This plot also shows the criterion 100 ft. (30.48 m) and provides the statistical values: min, max, average, and % above criterion.

The conclusions are similar to the ones for the altitude parameter in Section 3.4.4. This parameter was not required by the test plan. This was an attempt at using a comparison parameter based on GPS and that would not be dependant on atmospheric conditions and settings. However, the team has limited confidence in the validity of the results due to the significant assumptions that were made regarding the accuracy of GPS measurements during the field and simulation flights and the accuracy of the algorithm generating the X, Y, Z position during the simulation.

#### 3.4.9 Fuel Flow & Engine RPM

Fuel flow and RPM are consistent throughout the maneuvers, meaning that Fuel Flow and RPM vs. time plot mimic each other, but the simulation flight data show unexpected variations — particularly in the level maneuvers (e.g., Maneuver 5.02). This could be caused by deficiencies of the simulator’s fuel flow and RPM model, assuming that the aircraft’s control logic is the same in the simulator as in the real system.

Fuel flow and RPM are not used in our currently planned HITL simulations. Still, one can further speculate that the actual fuel flow and RPM model’s inaccuracies could have a notable effect on the entire simulator performance (i.e., climbs, descents, accelerations, performance maneuvers, etc.).

#### 3.4.10 Lift Coefficient

Specific data sets, correlating to the “wings-level” maneuvers, were subjected to an aerodynamic analysis to determine the lift coefficient while in the achieved “straight-and-level-flight” state. This analysis was comprised of 18 maneuvers, each 60 seconds in duration, that captured endurance airspeed and cruise airspeed. While in this state, the data parameters that contribute to the derivation of the lift coefficient are the airspeed, OAT, fuel weight, total weight and all initial ground atmospheric conditions (i.e., barometric pressure, OAT, density). Based upon the assumption of ideal atmospheric conditions, an algorithm utilizing the above mentioned data parameters as inputs is then employed to determine the lift coefficient.

To begin quantifying the lift coefficient algorithm, a list of defined parameters and associated notations is provided below:

**Table 6 – Lift Coefficient Parameters and Associated Notations**

| <b>Notation</b> | <b>Parameter</b>                                 |
|-----------------|--|
| $W_t$           | Total Weight (N)                                 |
| $W_f$           | Current Fuel Weight (N)                          |
| $W_{fi}$        | Take Off Fuel Weight (N)                         |
| $W_i$           | Initial Weight (N)                               |
| $T_0$           | Sea Level OAT (K)                                |
| $\rho_0$        | Sea Level Density (kg/m <sup>3</sup> )           |
| $P_0$           | Sea Level Pressure (Pa)                          |
| $a$             | Lapse Rate (constant = -6.5E-03 K/m)             |
| $g$             | Gravity (constant = 9.81 m/s <sup>2</sup> )      |
| $S$             | Planform Area (constant = 2.601 m <sup>2</sup> ) |
| $R$             | Gas Constant (constant = 287 J/kg-K)             |
| $V$             | Indicated Airspeed (m/s)                         |
| $T$             | Local OAT (K)                                    |
| $\rho$          | Local Density (kg/m <sup>3</sup> )               |
| $C_L$           | Lift Coefficient                                 |

Due to the aircraft state (e.g., straight and level), the relationship where “lift is equal to weight” can be established. This first step in determining the lift coefficient is to identify the aircraft’s total weight at the beginning of the interval of interest. This is done using the following equations:

$$W_t = W_i - (W_{fi} - W_f)$$

$$L = W_t$$

It is also important to define the sea level density using the previously mentioned assumption that atmospheric conditions are ideal. Hence, the ideal gas law applies:

$$\rho_0 = \frac{P_0}{RT_0}$$

Once these initial conditions have been quantified, the next step is determining the local air density. This is expressed in the following relationship:

$$\rho = \rho_0 \left( \frac{T}{T_0} \right)^{-\frac{g}{Ra} - 1}$$

Given all the previously determined parameters, the lift coefficient is thus determined according to the following expression:

$$C_L = \frac{W_t}{\frac{1}{2}\rho V^2 S}$$

The lift coefficient is ideally plotted against AOA. However, due to the unavailability of AOA within the data sets, the lift coefficient was plotted against the associated time interval.

Overall consistency is maintained between the lift performance of the actual and simulated aircraft. Although there were no established criteria for evaluation, based upon the speed at which the aircraft were flying as well as their overall size and weight, the observed results are within tolerable and expected ranges. One notable consideration is that the lift coefficient is predominantly influenced by the airspeed, and thus all associated errors and deviations with respect to velocity will affect the determination of the lift coefficient parameter. The results clearly indicate that the lift profile of the simulator models the performance of the actual aircraft with reasonable accuracy.

### 3.5 Simulator vs. TGF Parameters

The Simulator vs. TGF comparison was completed during the initial analysis. This section provides a summary of the initial report’s relevant sections.

To verify the integration of the RQ-7B Shadow simulator with the TGF, a comparison of select parameters for both sources was conducted. The following table lists the parameters used in the “Simulator vs. TGF” analysis.

**Table 7 – Simulator vs. TGF Parameters**

| <b>Parameter</b> | <b>Unit</b> |
|------------------|-------------|
| Latitude         | Degrees     |
| Longitude        | Degrees     |
| Altitude         | Ft. MSL     |
| Ground Speed     | Knots       |

For each of the parameters, data from both sources was aligned and interpolated, if necessary, to obtain data points for the same times. After an update of the simulator’s DIS interface and configuration of TGF’s software as described in the initial report, the following plots were generated. They are presented in Appendix D of the initial report.

- Position (lat/long) of the aircraft, as recorded by the GCS and TGF
- Altitude of the aircraft vs. time, as recorded by the GCS and TGF
- Ground speed of the aircraft vs. time, as recorded by the GCS and TGF
- Difference of altitude vs. time
- Difference of ground speed

The following table presents summarized results of the comparison of positions and ground speed between the data recorded from the RQ-7B Shadow simulator and the data captured from TGF. The metrics represent the observed difference between the two data sources. These results were computed from the 2 ½ hour supplemental data collection simulation conducted on May 3, 2010.

**Table 8 – Simulation vs. TGF Results**

|                           | <b>Min</b> | <b>Max</b> | <b>Average</b> | <b>Standard Deviation</b> |
|---------------------------|------------|------------|----------------|---------------------------|
| Horizontal Position (ft.) | 85         | 269        | 170            | 39                        |
| Altitude (ft.)            | 0          | 46         | 3              | 4                         |
| Ground Speed (kts.)       | 0          | 5          | 1              | 1                         |

These deviations are very likely due to the multiple conversions that occur between the 6 DoF computed position and the TGF logged positions and to the interpolations required because of the different update frequencies of both systems. However, the values are considered low and the partners of the team agreed that the objective of verifying the integration of the RQ-7B Shadow and the TGF/DESIREE/NIEC suite was satisfied.

#### **4 Conclusions and Recommendations**

The initial results of the RQ-7B Shadow Achieved Performance Model Verification were presented at the UFIT meeting in June of 2010. The partners of the team agreed that the objective of verifying the integration of the RQ-7B Shadow and the TGF/DESIREE/NIEC suite was satisfied.

Furthermore, the performance of the RQ-7B Shadow simulator was considered acceptable, and sufficient as it stands, to run the currently planned simulations. However, a refined analysis was initiated to research the effect of additional corrections for biases and environmental conditions.

The criteria guidance provided in the exercise plan was established using standards for evaluation of manned aircraft simulators and manufacturer and engineering guidance. As such, the criteria were applied conservatively both in the initial as well as in the refined analysis. The research team suggests that the criteria applied in this study may be too restrictive for UAS simulators at this time and should be reevaluated within the scope of the UFIT simulations. The research team also suggests that this information be forwarded to the FAA office responsible for establishing simulator standards.

The refined analysis described in this document showed that:

- An airspeed bias was present but this is typical of using an independent collection system.
- The altitude deviations were for the most part within the criterion once corrections for altimeter settings were taken into account.
- Density altitude is a calculated parameter in which OAT has a strong effect. Since OAT can not be accurately configured in the simulator, the results were inconclusive.

- The unexpected variations of fuel flow and RPM during straight and level maneuvers suggest that the simulator's engine model could be improved.
- The larger differences between field and simulation parameters occurred mostly at the beginning and end of maneuvers and while they could be due to the simulator's model inaccuracies they could also have been caused by pilot technique and timing.
- The current version of the simulator does not report altitude correctly in non-standard atmospheric pressure conditions.
- The large pitch variations during straight and level maneuvers suggest that the simulator's stability model may have more dynamic oscillatory behavior than that of the performance of the actual aircraft.

These findings were sent to the manufacturer of the simulator for consideration. The following recommendations were developed for users of the current system:

- Do not use the current version of the simulator within a non-standard atmosphere.
- Take into account the deviations identified by the analysis when using the simulator for studies.

Recommendations for future Achieved Performance Model Evaluation Exercises:

- Obtain experience on the aircraft, the simulator, and their limitations to ensure that the required sequences of maneuvers and their mode of execution can be reproduced accurately.
- Maximize the use of automation. Leave the pilot out of the loop as much as possible by using missions and a preprogrammed series of maneuvers.
- Calibrate the sensors before the field flight, particularly if multiple or independent sensors are going to be used.
- Precisely define the criteria and how they should be applied.
- Collect all available data, verifying that time stamps and conversion elements are available.
- During the flights, record (i.e., audio/video & via written notes taken by observers) the pilot's actions for future review and analysis.
- Minimize the timeline between field flight and simulation flight and, if possible, use the same pilot for both flights.

## 5 References

[REF 1]

RQ-7B Shadow Achieved Performance Model Verification Exercise Plan,  
FAA Research and Technology Development Office, Final: September 2, 2009

[REF 2]

Guidelines to Verify RQ-7B Shadow Performance with 6 Degree of Freedom Model,  
FAA Unmanned Aircraft Program Office, September 1, 2009

[REF 3]

Achieved Performance Demo 1S Simulation Notes V1.0, FAA ATO Engineering  
Development Services, January 11, 2010

[REF 4]

RQ-7B Achieved Performance Model Verification Initial Report V2.4, FAA ATO  
Engineering Development Services, November 19, 2010

[REF 5]

UAS Integration: Evaluation and Demonstration Plan, Federal Aviation Administration  
January 29, 2010

## Acronyms

|         |  |
|---------|--|
| 6 DoF   | 6 Degrees of Freedom   |
| ACE     | Avionics Computer Equipment  |
| AOA     | Angle of Attack  |
| ATC     | Air Traffic Control  |
| AVS     | Aviation Safety  |
| COA     | Certificate of Waiver or Authorization   |
| DESIREE | Distributed Environment for Simulation, Rapid Engineering, and Experimentation |
| DIS     | Distributed Interactive Simulation   |
| FAA     | Federal Aviation Administration  |
| GCS     | Ground Control Station   |
| HITL    | Human-in-the-Loop  |
| HILSIM  | Hardware-in-the-Loop Simulator   |
| ITAR    | International Traffic in Arms Regulations                                      |
| KHUA    | Redstone Army Airfield   |
| IQR     | Inter Quartile Range   |
| MSL     | Mean Sea Level   |
| NAS     | National Airspace System   |
| NextGen | Next Generation Air Transportation System                                      |
| NIEC    | NextGen Integration and Evaluation Capability                                  |
| OAT     | Outside Air Temperature  |
| OATIS   | Open Architecture for Telemetry and Instrumentation Systems                    |
| R&D     | Research and Development   |
| TGF     | Target Generation Facility   |
| UAPO    | Unmanned Aircraft Program Office   |
| UAS     | Unmanned Aircraft System   |
| UFIT    | UAS FAA and Industry Team  |
| VCS     | Vehicle Control Software   |
| WJHTC   | William J. Hughes Technical Center   |

## APPENDIX A – R2104 Restricted Area Details

### DESCRIPTION

The description of the following restricted areas is from FAA Order 7400.8K and is only provided as general information. The legal descriptions are published in the Federal Register.

**R2104A Huntsville, AL:** Boundaries. Beginning at lat. 34°38'40"N., long. 86°43'00"W.; to lat. 34°38'40"N., long. 86°41'00"W.; to lat. 34°38'00"N., long. 86°40'53"W.; to lat. 34°37'35"N., long. 86°37'40"W.; to lat. 34°37'00"N., long. 86°37'00"W.; to lat. 34°36'27"N., long. 86°36'38"W.; to lat. 34°34'50"N., long. 86°36'38"W.; thence west along the Tennessee River to lat. 34°35'02"N., long. 86°43'25"W.; to lat. 34°37'19"N., long. 86°43'20"W.; to lat. 34°37'19"N., long. 86°43'05"W.; thence to the point of beginning.  
Designated altitudes. Surface to 12,000 feet MSL. Time of designation. Intermittent, 0600-2000 local, Monday-Saturday; other times by NOTAM 6 hours in advance  
Controlling agency. FAA, Memphis ARTCC Using agency. Commanding General, U.S. Army Aviation and Missile Command, Redstone Arsenal, AL.

**R2104C Huntsville, AL:** Boundaries. Beginning at lat. 34°41'25"N., long. 86°42'57"W.; to lat. 34°42'00"N., long. 86°41'35"W.; to lat. 34°38'40"N., long. 86°41'00"W.; to lat. 34°38'40"N., long. 86°43'00"W., thence to the point of beginning.  
Designated altitudes. Surface to 12,000 feet MSL. Time of designation. Intermittent, 0600-2000 local, Monday-Saturday; other times by NOTAM 6 hours in advance  
Controlling agency. FAA, Memphis ARTCC Using agency. Commanding General, U.S. Army Aviation and Missile Command, Redstone Arsenal, AL.

**R2104D Huntsville, AL:** Boundaries. Beginning at lat. 34°38'40"N., long. 86°43'00"W.; to lat. 34°38'40"N., long. 86°41'00"W.; to lat. 34°38'00"N., long. 86°40'53"W.; to lat. 34°37'35"N., long. 86°37'40"W.; to lat. 34°37'00"N., long. 86°37'00"W.; to lat. 34°36'27"N., long. 86°36'38"W.; to lat. 34°34'50"N., long. 86°36'38"W.; thence west along the Tennessee River to lat. 34°35'02"N., long. 86°43'25"W.; to lat. 34°37'19"N., long. 86°43'20"W.; to lat. 34°37'19"N., long. 86°43'05"W.; thence to the point of beginning.  
Designated altitudes. 12,000 feet MSL to FL300 Time of designation. By NOTAM 6 hours in advance  
Controlling agency. FAA, Memphis ARTCC Using agency. Commanding General, U.S. Army Aviation and Missile Command, Redstone Arsenal, AL.

**R2104E Huntsville, AL:** Boundaries. Beginning at lat. 34°41'25"N., long. 86°42'57"W.; to lat. 34°42'00"N., long. 86°41'35"W.; to lat. 34°38'40"N., long. 86°41'00"W.; to lat. 34°38'40"N., long. 86°43'00"W., thence to the point of beginning.  
Designated altitudes. 12,000 feet MSL to FL300 Time of designation. By NOTAM 6 hours in advance  
Controlling agency. FAA, Memphis ARTCC Using agency. Commanding General, U.S. Army Aviation and Missile Command, Redstone Arsenal, AL.

# Graphical Depiction of R2104 Restricted Airspace

