Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

Integrated Test and Evaluation
Flight Testing Overview
Integrated Test and Evaluation (IT&E) Goals

- Conduct simulations and integrated flight tests in a relevant environment to collect required research data

- Develop and adapt the test environment infrastructure to conduct UAS research
IT&E Objectives

- Provide an adaptable test infrastructure for simulation and flight test research
  - Leverage existing and/or modify aircraft
  - Leverage airspace
  - Leverage and build upon existing NASA Live Virtual Constructive (LVC) system
  - We are not building a prototype operational system

- Execute simulations and flight tests
  - Concept development
  - Verification and validation (V&V)

- Technology integration

- Maintain data collection archive
**Live Virtual Constructive (LVC) Objectives**

### Distributed
- To support asset usage where they exist
- External partner support

### Adaptable
- Support for dynamic research requirements
- Utilize inputs from multiple surveillance sources (air and ground)
- Emulate data sources and features

### Extensible
- Use for simulation and live flight testing
  - Reduces risk moving between simulation and flight
- Across NASA centers
- Tie in UAS collaborators
IT&E Capabilities

**Encounter Design and Range Coordination**

Airspace Planning
- Primarily Mercury Spin, 4 Corners and Buckhorn Military Operating Area (MOA) (red outline)
- 1,000 feet AGL (4.2K feet) to 20K feet MSL
- Extensions (west/north) may be requested real time for encounters that need the additional airspace
- Operations outside of test area (blue shaded areas) are planned to be performed early (before 0800) when airspace is relatively empty
- Operations between 0600 and 0700 are under Joshua control and have less geographical constraints

Coordination with Edwards Range
- Coordination of range/operating area borders and UAS keep out zones
- Ikhana must remain within Range (R)-2515 at all times
- Intruder aircraft can use Buckhorn MOA, plus areas shaded in blue

Encounter design accomplished by operations working group with researchers and partners
- Encounter requirements coordinated with System Safety Working Group to ensure flight safety
- Mitigations designed into flight test planning (safe separation, training, testing, offsets, procedures, etc.)

Airspace Extensions (Blue Shaded Areas)
- Conducted early 0600-0800 preferably
- Pre-coordinated 24-48 hours in advance
- Requested real-time with SPORT (after 0700)
Completed Flight Tests
Completed Flight Tests

Risk Reduction Approach to Integrated Test Flow

- Each test built upon the previous and reduced future risk
- Lessons learned applied from one test to the next

Timeline Not to Scale

<table>
<thead>
<tr>
<th>Integrated Human-in-the-Loop Sim</th>
<th>ACAS Xu/Self-Separation</th>
<th>Flight Test 3</th>
<th>Flight Test 4</th>
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Timeline Not to Scale

- Level 1 Milestone
- Reviews
- Development Milestones

Armstrong Flight Research Center
Ownship – Ikhana

- Build-up of detect and avoid (DAA) system (air-to-air [A/A] radar/Automatic Dependent Surveillance-Broadcast (ADS-B)/traffic alert and collision avoidance system [TCAS]) to meet researcher requirements
- Ikhana logged more than 190 hours flight time for airborne collision avoidance system (ACAS) Xu, Flight Test (FT)3, and FT4 data collection

Intruder Aircraft (seven total aircraft)

- Met researcher objectives to represent many classes of aircraft
  - Low-speed, mid-speed, high-speed
  - Cooperative versus non-cooperative
  - Small, medium, large radar cross section
- Equipped four aircraft with required surveillance systems
- Coordinated 25 crew members from three organizations
  - NASA, U.S. Air Force, Honeywell

Flight Test Stats

- **ACAS Xu**: 9 flights, 170 encounters flown (one intruder)
- **FT3**: 11 flights, 212 encounters flown (multiple intruders)
- **FT4**: 19 flights, 321 encounters flown (up to four intruders)
FT4 Flight Test Card

1. TC announces COMEX time.
2. Announce "<Callsign>, IP inbound, altitude & special procedure review" crossing IP.
3. On condition at IP.
4. TC calls "terminate" when run complete.
5. TC announces next Card Number.

FT4 DAA Scripted
A/C: NASA 870  S/N: 270  VERSION 4

**CARD#** 270-Sc-S3M **OWNSHIP**

**ABORT PROCEDURE**
- NAV TO LL WPT
- 9000

**COMEX TIME:**

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<th>LATITUDE</th>
<th>LONGITUDE</th>
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**NOTES:**
- Ownership maneuver. Follow CPDS Guidance. Or, follow TCAS RA if generated.
- Maneuver Guidance moves WTR/TA/TCAS.
- TOLERANCE: ±8 sec ±5 kts

FT4 DAA Scripted
A/C: NASA 865  S/N: 270  VERSION 4

**CARD#** 270-Sc-S3M **INTRUDER**

**ABORT PROCEDURE**
- RIGHT 123

**COMEX TIME:**

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**NOTES:**
- Expect Ownership maneuver. Intruder standard rate turn. Turn to maintain sight.
- TOLERANCE: ±8 sec ±5 kts
In Progress/Upcoming Flight Tests
IT&E Integrated Test Flow – ACAS Xu FT2

ACAS Xu FT2 (TC: DAA)

- **Purpose**
  - Validate modeling and simulations
  - Demonstrate system behavior integrated on prototype avionics and UAS
  - Collect flight test data for performance evaluations and future research and development (R&D)

- **Approach**
  - Increased functionality
    - Combined horizontal and vertical maneuvers against multiple intruders
    - Resolution advisory (RA) logic accounts for sensor quality and ownship performance limitations

- **Test Duration**
  - June-July 2017: 10-12 flights (~150 encounters)

- **Tech Transfer**
  - Contribute to ACAS Xu minimum operational performance standards (MOPS) development

- **Project Benefit**
  - Continued collaboration with the Federal Aviation Administration (FAA) to mature the ACAS Xu software in support of the ACAS Xu MOPS development

**Well clear and collision avoidance functions integrated into one algorithm**
<table>
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<tr>
<th>Card #</th>
<th>HCHK-09</th>
<th>Ikhana Ownship</th>
<th>Card #</th>
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No Chase Certificate of Authorization (COA)

FY17

FY18

FY19

No Chase COA

Obj Peer
Rev

FAA COA
K/O

Status Rev

NASA COA Rev
(Pre-Tech Brief)

NCC Tech Brief

Gap Analysis

Safety Case/COA Application Prep

FAA Assessment of COA Application

NCC Demo Flts

Development Activities

Flight Tests

Aircraft Mods

Review/Tech Brief

Purpose

- Obtain COA from FAA to fly Ikhana UAS without safety chase in multiple classes of airspace, including Class A, D, and E
- Demonstrate UA transitioning to/from Class A or special use airspace (SUA) to Class E and Class D employing the Phase 1 detect and avoid (DAA) and A/A radar MOPS systems as alternate compliance for 14CFR 91.113b

Approach

- Complete gap analysis and safety case analysis justifying alternative method of compliance with Federal Aviation Regulation (FAR) Part 91.113
- Work in partnership with General Atomics Aeronautical Systems Inc. (GA-ASI) to secure use of GA-ASI DAA system as primary airborne de-conflicting tool

Test Duration

- February 2018: 2-3 flights

Tech Transfer

- Demonstrate Phase 1 DAA and radar MOPS research findings through a “Capstone” event

Project Benefit

- Demonstration of UAS-NAS Phase 1 DAA technologies
No Chase Aircraft COA Flight Demonstration

Concept of Operations (CONOPS)

**Objective:** Demonstrate UA transitioning to/from Class A or SUA to Class E and Class D employing the Phase 1 DAA and air-to-air radar MOPS systems as alternate means of compliance for 14 CFR 91.113b

The Operational Environment for Ph 1 DAA MOPS is the transitioning of a UAS to/from Class A or special use airspace, traversing Class D, E, and G airspace.

- Exit R-2515 at 20k ft MSL
- Transit at 20k ft MSL ARTCC Handoff (ZLA <--> ZOA)
- Detect and Avoid (as required) Coop and Non-Coop VFR Traffic Enroute to/from KVCV
- Execute approach into KVCV traffic pattern
- Non-cooperative VFR Traffic
- Cooperative IFR/VFR Traffic
- Cooperative IFR Traffic

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No Chase Aircraft COA Flight Demonstration

Mission Profile

1. Exit R-2515 at 20k ft MSL (Point Rosie)
2. Transit Class A at 20k ft MSL
3. ARTCC Handoff (ZLA ↔ ZOA)
4. Start Descent into Class E 11k ft MSL
5. Transit Class E at 11k ft MSL
6. ARTCC Handoff (ZOA ↔ ZLA)
7. Start Descent to 9k ft MSL
8. Detect and Avoid (as required) Coop and Non-Coop VFR Traffic Enroute to KVCV (Joshua App)
9. Execute approach into KVCV Class D and traffic pattern
10. RTB Enter R-2515 at 8.5k ft MSL (Point Grizzly)
Phase 2 DAA MOPS Development and Validation

Phase 2 DAA and A/A Radar MOPS

- Shifting focus to medium-sized (group 2/3) UAS equipped with a low size, weight and power (SWaP) non-cooperative A/A sensor
  - Cooperative Agreement Notice (CAN) to partner/cost-share with low SWaP A/A sensor manufacturer
  - NASA Ames Systems Integration Evaluation Remote Research Aircraft (SIERRA)-B UAS selected as medium-sized UAS ownship
Flight Test Series 5

Purpose
- Initial flight testing of low-cost size, weight and power (C-SWaP) airborne non-cooperative surveillance sensor integrated on group 2/3 UAS

Approach
- Equip NASA SIERRA-B UAS with low C-SWaP sensor and perform DAA encounters with manned intruder(s)
- Downlink sensor tracks to ground control station (GCS) and LVC Gateway (GW) for processing by DAA algorithm
- DAA well clear (DWC) alerts and maneuver guidance provided to Vigilant Spirit Control Station (VSCS)
- UAS pilot employs VSCS display to meet test objectives

Test Duration
August-September 2018: ~100 encounters

Tech Transfer
- Inform development of Phase 2 MOPS

Project Benefit
- Collection of data used by researchers to inform contributions to MOPS
Flight Test Series 6

**Purpose**
- Operationally representative scenarios and increased emphasis on pilot performance data collection with integration of a NASA research GCS capability.

**Approach**
- NASA SIERRA UAS and potential Partner Group 2/3 UAS equipped with low C-SWaP sensor(s) performing DAA encounters with manned intruder(s).
- Sensor tracks downlinked for processing by DAA algorithm.
- SIERRA-B equipped with non-coop and coop (ADS-B In) sensors and a tracker to correlate multiple sensor tracks.
- DWC alerts/Maneuver guidance provided to DAA display.
- UAS pilot employs integrated DAA display to meet encounter test objectives.
- Pilot response data collected using subject pilots.

**Test Duration**
- July-August 2019: ~100 encounters

**Tech Transfer**
- Inform development of final Phase 2 MOPS.

**Project Benefit**
- Collection of data used by researchers to inform contributions to MOPS.
Purpose

- Evaluate three DAA algorithms using sensor data for ability to inform UAS pilot of traffic/potential well clear violations in order to resolve conflicts
- Evaluate performance of ACAS Xu collision avoidance (CA) algorithms against coop intruders with ADS-B surveillance and non-coop intruders with A/A radar
- Demonstrate DAA CONOPS in real-world scenarios
- Demonstrate LVC distributed test environment

Approach

- Ikhana UAS modified with proof of concept DAA system (prototype A/A radar, sense and avoid (SAA) processor, TCAS, ADS-B, sensor fusion)
- Multiple encounter geometries (CA and SS)

Test Duration

- November 2014-December 2014 (9 flights)
  - November 2014: ACAS Xu CA (UAS versus manned)
  - December 2014: ACAS Xu CA (UAS versus UAS)
  - December 2014: Self-Separation (UAS versus manned)

Tech Transfer

- DAA CONOPS and algorithm flight demonstration
- Data for validation of sensor models, well clear definition, and SS/CA interop

Project Benefit

- Conduct flight test risk reduction activities for FT3 and FT4
- First live flight test for DAA algorithms and pilot guidance displays for real sensor data/uncertainties, real environmental factors
- LVC-Distributed Environment (DE) connectivity to Ikhana GCS established
Four unmanned versus manned CA flights conducted
- **Ownship**: Ikhana UAS
- **Intruders**: FAA Convair 580, Honeywell King Air C90, NASA T-34C
- Single intruder at a time
- 85 encounters, 20 hours flight time/data collection
- First CA system for UAS tested without artificial horizontal or vertical offsets
- Flight test encounters flown in exact conflict conditions

Two unmanned versus unmanned CA flights conducted
- **Ownship**: Ikhana UAS
- **Intruder**: GA-ASI Predator-B
- 30 encounters, 10 hours of flight time/data collection
- First CA flight test employing UAS versus UAS encounters

Three unmanned versus manned initial SS flights conducted
- **Ownship**: Ikhana UAS
- **Intruders**: Honeywell King Air C90, NASA T-34C
- Single intruder at a time
- 55 encounters, 12 hours flight time/data collection
- Three self-separation algorithms evaluated
  - **VSCS – Autoresolver**: NASA/AFRL, UAS-NAS
  - **Stratway+**: NASA, UAS-NAS
  - **Conflict Prediction and Display System (CPDS)**: GA-ASI
**Flight Test 3 Overview**

**Flight Systems**

- **Aircraft Radar**
- **ADS-B**
- **TCAS II**

**SAA Processor**
- Surveillance & Tracking Module (STM) / Honeywell Tracker

**Digital Flight Control System (DFCS)**

**Pilot Input**

**ADS-B 1090ES**

**TCAS II Active 1030 MHz Surveillance**

- **EDM**
  - Due Regard Radar

**LOS or BLOS Datalink**

**TCAS II RA**

**Ground Control Station**

**Heads-Up Display (HUD)**

**Self-Separation Maneuvers with VSCS:**
- Pilot-in-the-Loop
- TCAS II:
  - Automatic with Pilot Override

**Transponder Equipped (No TCAS)**

**Non-Cooperative**
Flight Test 3 Summary

FT3 Flight Operations

- June 17-July 24, 2015
  - Ikhana versus manned intruder(s)
  - 11 flights completed
    - More than 200 A/A encounters
    - DAA maneuver guidance and alerting logic checks
    - Auto TCAS II maneuvers
    - Engineering development model (EDM) radar performance near scan volume limits
    - EDM radar low-altitude performance tests
    - Higher closure rate encounters with F/A-18
    - Stressing multi-intruder encounters

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<th>ADS-B</th>
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Armstrong Flight Research Center
Flight Test 4 Overview

Flight Systems

- Pilot-in-the-Loop
- Well clear recovery
- Interoperable with TCAS II resolution advisories (RAs)
- Auto-response with pilot override

Detect and Avoid Alerts and Maneuver Guidance:
- Pilot-in-the-Loop
- Well clear recovery
- Interoperable with TCAS II resolution advisories (RAs)
- Auto-response with pilot override
Flight Test 4 Summary

- **Research Objectives:**
  - Conduct FT4 integrating the latest Separation Assurance/Sense and Avoid Interoperability (SSI) algorithms, Human Systems Integration (HSI) displays, and LVC test environment to support validation of Phase 1 DAA MOPS
  - Document the performance of the test infrastructure in meeting the flight test requirements

- **Results, Conclusions, and Recommendations:**
  - FT4 successfully completed June 30, 2016
    - Leveraged lessons learned and risk reduction from technology refinements to support Phase 1 MOPS validation
    - Two system checkout and 19 data collection flight tests
    - 11 weeks (April 12-June 30)
    - 321 A/A encounters
      - 98.1 flight hours on Ikhana
      - 25 pilots and six different intruder aircraft
    - Excellent collaboration between partners
      - GA-ASI, Special Committee (SC)-228 DAA Working Group, Honeywell
  - Nearly 500 gigabytes of data collected
    - Data products provided in an accurate and timely manner to researchers (close of business day of flight test, differential Global Positioning System [DGPS] data next day)
  - In concert with project simulation activities, FT4 contributed significantly to the validation of DAA MOPS; it identified some key performance requirements that needed additional refinement
    - Well clear recovery
    - DAA/TCAS interoperability
  - Flight test report completed
  - Lessons learned documented
ACAS Xu Flight Test 2

- Flight Test Objectives:
  - Validate modeling and simulations
  - Demonstrate system behavior integrated on prototype avionics and UAS
  - Collect flight test data for performance evaluations and future R&D

- Flight Test Overview:
  - Continue collaboration with the FAA TCAS Program
  - Office-led partnership to mature the ACAS Xu software in support of ACAS Xu MOPS development (draft FY18, final FY20)
    - FY17 flight tests (mid June-early August)
    - About 220 encounters/ ~13-14 flights (Ikhana as ownship)
    - Intruders provided by Honeywell and Aviation Surveillance & Communications Systems (ACSS)
  - More capable functionality
  - Horizontal and vertical maneuvers against multiple intruders
  - RA logic accounts for sensor quality and ownership performance limitations
  - Includes DAA or SS functionality (Phase 1 DAA MOPS)
  - ACAS processors are representative production units (Honeywell and ACSS)
  - Performance against ACAS Xa (mature system in operational evaluation that will directly replace TCAS II)
  - Ownship low approach operations (data collection only during mission)
ACAS Xu FT2 Overview

- ACAS Xu FT2 leverages off of ACAS Xu 2014 (plus FT3/4)
- ACAS scripted encounters
- Data collection for system under test (SUT):
  - CPDS
  - Honeywell ACAS Xu unit
  - ACSS ACAS Xu unit
  - EDM radar
- Sensor evaluation
  - ACAS Xa/Xu
  - EDM A/A radar
  - Mode C
  - Mode S
  - TCAS II
  - ADS-B
- Multi-intruder requirements
  - King Air C90 (2)
Detect and Avoid Function

- FAA TCAS PO
- NASA SSI
- GA-ASI

Honeywell

Well Clear Threshold (WCT)

Collision Avoidance Threshold (CAT)

SA Interop. Timeframe

Loss of separation

Detect and Avoid

ATC Provided Separation Function

Self Separation

Self Separation Threshold (SST)

Collision Avoidance

0 to ~30 sec to NMAC

Avoid WCT; ~60-120 sec to NMAC

CFR 91.113: “...each person operating an aircraft [shall] see and avoid other aircraft ... the pilot shall give way to that aircraft and may not pass over, under or ahead of it unless well clear.”

* It is possible for the CAT to be greater than the WCT.
SIERRA-B UAS with Low C-SWaP A/A Sensor

Flight Test CONOPS

- NASA SIERRA-B Group 3 UAS equipped with low C-SWaP A/A sensor performing DAA encounters with manned intruder(s)
  - A/A sensor tracks downlinked to the GCS and LVC GW for processing by DAA algorithm
  - DWC alerts and maneuver guidance provided to VSCS
  - UAS pilot employs VSCS display to meet encounter test objectives
**Medium-Sized UAS with Low C-SWaP A/A Sensors**

**Flight Test CONOPS**
- NASA SIERRA Group 3 UAS and partner Group 2/3 UAS equipped with low C-SWaP A/A sensor(s) performing DAA encounters with manned intruder(s)
  - A/A sensor tracks downlinked to the GCS for processing by DAA algorithm
    - SIERRA-B equipped with non-coop and coop (ADS-B In) sensors and a tracker to correlate multiple sensor tracks
  - DWC alerts and maneuver guidance provided to DAA display
  - UAS pilot employs an integrated DAA display to meet encounter test objectives
  - Pilot response data collected using subject pilots

**Ownship**
- Group 2/3 partner UAS
- Group 3 NASA SIERRA-B UAS
- Low C-SWaP A/A non-coop and coop sensors
## Sensor Integrated Environmental Remote Research Aircraft (SIERRA)

### Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Span</td>
<td>20 feet</td>
</tr>
<tr>
<td>Length</td>
<td>11.8 feet</td>
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<tr>
<td>Height</td>
<td>4.6 feet</td>
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<tr>
<td>Wing Area</td>
<td>42.4 feet²</td>
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<tr>
<td>Empty Weight</td>
<td>320 pounds</td>
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<tr>
<td>Max Gross Weight</td>
<td>480 pounds</td>
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<tr>
<td>Max Operating Speed ($V_{mo}$)</td>
<td>80 knots</td>
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<tr>
<td>Cruise Speed</td>
<td>55-63 knots</td>
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<tr>
<td>Stall Speed (No flaps $V_{so}$)</td>
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<tr>
<td>Aspect ratio</td>
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<tr>
<td>Rate of Climb (S/L Std Day, Max Gross Wt)</td>
<td>500 fpm</td>
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<tr>
<td>CG Range</td>
<td>27-33% MAC</td>
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<tr>
<td>Payload weight</td>
<td>100 pounds</td>
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<tr>
<td>Payload power</td>
<td>24V DC</td>
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<tr>
<td>Load Rating (Utility)</td>
<td>+4.4 g, -1.7 g</td>
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<tr>
<td>Duration</td>
<td>8-10 hours</td>
</tr>
</tbody>
</table>

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*Armstrong Flight Research Center*