697DCK-22-C-00381

Final Report for Piloting Multiple, Simultaneous UAS BVLOS

(Public)

Submitted: 25 September 2023

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Revision	Description of Change	Page(s)	Date	Approved by
-	Initial release	All	9/25/2023	Wendy Ljungren

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1. Executive Summary

As part of the 697DCK-22-C-00381 *Standards for Piloting Multiple, Simultaneous UAS BVLOS* project, the team led by Anzen Unmanned (Au) developed the minimum criteria and open-source flight control software for a Remote Operator (RO) to operate multiple small unmanned systems (UAS) simultaneously (also known as m:N where "m" is the number of flight crew and "N" is the number of UAs in operation) operating Beyond Visual Line of Sight (BVLOS).

This project successfully included defining, developing, and testing the:

- Safety case to obtain 107.31 (BVLOS) and 107.35 (m:N) waivers needed for flight test
- Minimum UA performance and behaviors for normal and off-nominal conditions, including the flight control modes and level of automation necessary to support Remote Operator (RO) responses
    - Included submitting the resulting ArduPilot and MAVLink software updates to the open-source repositories
- RO interfaces (e.g., display, alerts, controls) needed to maintain m:N situational awareness and enable timely, correct RO responses
- Minimum sUAS equipage needed to support the m:N safety case
- Operational pre-flight and flight procedures
- Location checklist that can be scaled nationwide
- Minimum RO qualifications and training
- Organizational practices, including safety management, quality management, configuration management, and training programs

The safety risk controls established using the Safety Management System (SMS) safety risk management process effectively identified the human factors (HF) hazards associated with the m:N BVLOS UAS operation and mitigated the risks to acceptable levels.

Safety risk controls and associated procedures and open-source flight control software were validated using Asylon's DroneCore system. The validation was accomplished initially via simulation using Asylon's DroneCore system and human factors assessment with both Asylon and NUAIR pilots. Once the maximum safe m:N ratio was established using both analytical and observational human factors assessment in concert with the safety risk controls, the safety controls were validated via flight operations conducted at the New York UAS Test Site (NYUASTS).

The resulting minimum criteria and requirements will be provided to standards development organizations as the starting point for establishing m:N industry standards.

Asylon's DroneCore displays, controls, and automation provided the crew members with critical and timely information needed to support nominal and off-nominal operations. Alerts provided the crew members the information needed for safe operation by providing aural and visual alerts for the crew members to recognize, comprehend, and take appropriate and timely actions to mitigate risks associated with off nominal and emergency situations.

Asylon's Remote Operations Center (ROC) provided the tools needed for the RO to successfully fly multiple UAs in a sterile, comfortable, and secure environment. The support equipment provided the crew members with the information needed to perform their duties and achieve mission goals.

Like crewed aviation, UA operations are evolving. The simulation captured two aspects of that evolution in terms of the definition and integration of automation and the application of crew resource management associated with a complex operation.

Using SAE J3016's definition for levels of automation, level 3 human-in-the-loop automation permits crew members to take control at any time. Based on Asylon's level 3 automation while performing the Asylon security mission, the Au-developed task analysis indicated the operation is theoretically limited to 1:6 UAs. All the crew members were able to achieve the 1:6 mission goals safely and efficiently with the provided level of automation during the simulation and then flight test at Griffis (RME) airport in conjunction with the NYUASTS operator NUAIR.

Four types of Human Factors evaluations were performed during simulator and flight testing: NASA's Task Load Index (TLX) survey, HF Observers, post operation interviews, and audio/video analysis. Unplanned air traffic combined with planned events impacted the RO workload but the implementation was found to be manageable and safe.

This Final Report:

- Describes the project approach
- Shares the m:N BVLOS lessons learned
- Provides the content to be shared with a Standards Development Organization for the development of m:N BVLOS standards
- Meets the Statement of Work (SOW) deliverable for Tasks 8.8 (Lessons Learned) and 8.9 (Final Report) in support of FAA project: *697DCK-22-C-00381 Standards for Piloting Multiple, Simultaneous UAS BVLOS.*

1.1. Scope

The m:N project focused on the end-state with an RO (and support crew) piloting multiple UA, where the RO will not have the UA in sight (may not even be at the physical site). The analysis is intended to be used by operators who already have a track record of successful, compliant multicopter Beyond Visual Line of Sight (BVLOS) operations and want to advance to m:N operations.

It is expected that an operator planning to use this project's artifacts will have a BVLOS capable UAS, Concept of Operations (ConOps) consistent with section 0, incorporate the requirements found in: *PUBLIC_697DCK-22-C-00381_Operational Hazard and Safety Assessment for m RO operating N UA simultaneously* (OHSA) and this document.

The OHSA and this document will be provided to a Standards Development Organization (SDO) to form the basis for industry standards for multicopters to operate m:N BVLOS (reference Figure 1).

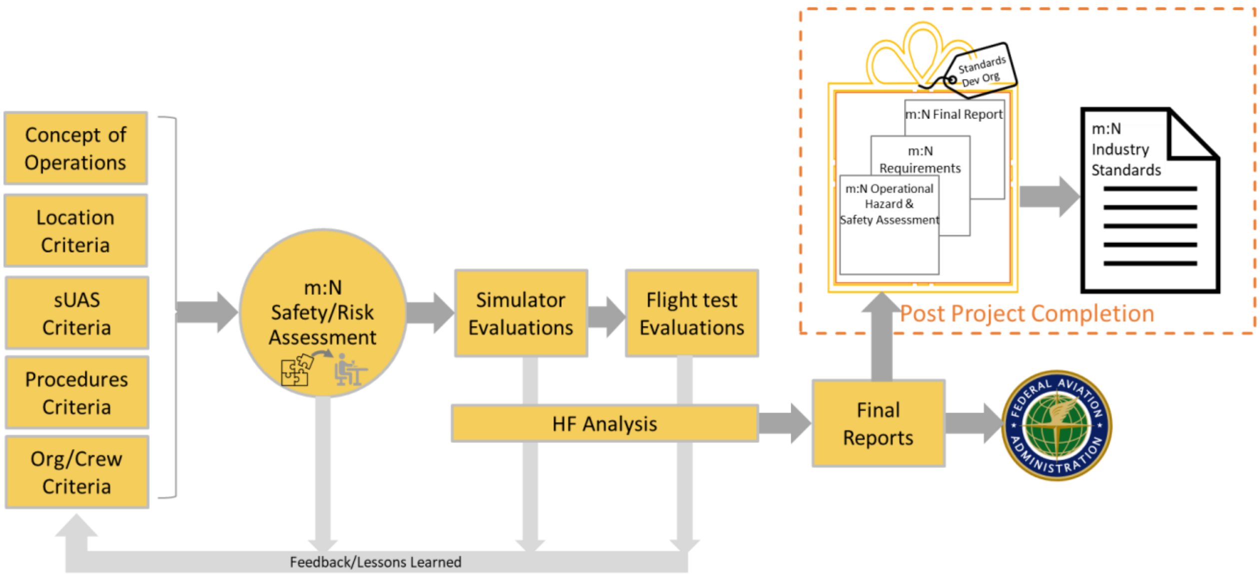

Figure 1 – m:N Project Flow

1.2. Partnership

This project would not have been successful without the support of strong relationships between Au and its partners.

- Asylon Robotics, Inc for developing the reliable BVLOS m:N DroneCore system, building an impressive ROC simulator, providing most of the ROs, and willingly sharing their lessons learned with the industry.
- New York UAS Test Site operator NUAIR for sharing their expertise, providing ROs with varying levels of experience giving honest RO feedback during the simulator testing, and hosting the flight test program.
- Purdue University for providing academic rigor during the simulator and flight testing, and much of the analysis for the Human Factors report.

- Anzen Unmanned team who continues to assist the industry with system and safety engineering solutions resulting in precedent setting regulatory approvals for advanced operations.

1.3. Reference Documents

Below are the Anzen Unmanned documents referenced in this document:

Doc #	Full Name
Au-REP-0019	697DCK-22-C-00381 – Operational Hazard and Safety Assessment for m RO operating N UA simultaneously (OHSA) (Public)
Au-REP-0031	697DCK-22-C-00381 – Human Factors Simulator Report for Piloting Multiple, Simultaneous UAS BVLOS (Public)
Au-REP-0035	697DCK-22-C-00381 – Flight Test Report for Piloting Multiple, Simultaneous UAS BVLOS (Public)
Au-REP-0036	697DCK-22-C-00381 – Human Factors Analysis for Piloting Multiple, Simultaneous UAS BVLOS (Proprietary)

The following documents are referenced in this analysis:

Doc #	Full Name
FAA-HF-STD-001	Human Factors Design Standard
FAA-HF-STD-002	Baseline Requirements for Color Use in Air Traffic Control Displays
FAA-HF-STD-003	Alarms and Alerts in the Technical Operations Environment
FAA Order 7110.65	Air Traffic Control
NASA Task Load Index	NASA Task Load Index 'Paper and Pencil Package' Document, Version 1.0, Report by Human Performance Research Group NASA Ames Research Center Moffett Field. California.

The following academic articles are referenced in this report:

Doc #	Full Name
Devlin (2020)	Transitions between low and high levels of mental workload can improve multitasking performance. IISE Transactions on Occupational Ergonomics and Human Factors (Vol 8, Issue 2, pp 72-87).
De Waard (1996)	De Waard, D., & Brookhuis, K. A. (1996). The measurement of drivers' mental workload. The university of Groningen, Traffic Research Centre

Grier, R. A. (2015, September).	How high is high? A meta-analysis of NASA-TLX global workload scores. In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 59, No. 1, pp. 1727-1731). Sage CA: Los Angeles, CA: SAGE Publications.
Hart, S. G. (2006)	NASA-task load index (NASA-TLX): 20 years later. Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 50, pp 904-8.

1.4. Acronyms and Abbreviations

Table 1 lists the acronyms and abbreviations used in this document.

Table 1 – Acronyms/Abbreviations

Term	Full Name
1:1	One RPIC/RO controlling one UA
1:6	One RPIC/RO controlling up to six UA
AE	Associated Elements
AGL	Above Ground Level
ASY	Asylon Incorporated
Au	Anzen Unmanned, LLC
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CI	Critical Infrastructure
ConOps	Concept of Operations
CRM	Crew Resource Management
DAA	Detect and Avoid
FAA	United States Federal Aviation Administration
GCS	Ground Control Station
HF	Human Factors
HITL	Human-in-the-loop
m:N	“m” RPIC/ROs operating multiple “N” UAs
MM	Maintenance Manual
NUAIR	Northeast UAS Airspace Integration Research Alliance, Inc.
RO	Remote Operator who performs the functions of a RPIC
ROC	Remote Operations Center
RPIC	Remote Pilot in Command
RTL	Return to Launch
SDO	Standards Development Organization
SMS	Safety Management System

Term	Full Name
SOP	Standard Operating Procedures
SOW	Statement of Work
SP	Safety Pilot
SRM	Safety Risk Management
SUP	Supervisor
TLX	Task Load Index
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UFM	Unmanned Aircraft Flight Manual
UTM	UAS Traffic Management
VLOS	Visual Line of Sight
VO	Visual Observer

1.5. Glossary

The following terms that have specific meaning in the safety analysis and requirements.

Term	Definition
Associated Elements (AE)	UAS AE are defined as the system components, other than the UA, which are necessary to perform the intended function, such as ground controls, displays, communications, etc.
Automation	The execution of predefined processes or events that do not require direct UAS crew initiation and/or intervention.
Caution alert	Yellow/amber visual indication to increase the RO awareness of potential safety conditions.
Critical Infrastructure	Facilities referenced in FESSA 2016 section 2209, such as power substations, high-power transmission lines, water treatment plants, etc.
Human error	Human action with unintended consequences.
Human Factors	Principles applied to aeronautical design, certification, training, operations, and maintenance and which seeks safe interface between the human and other system components by proper consideration to human performance.
Human-in-the-loop (HITL)	SAE automation level 3 with nominal and most of the off-nominal operations fully automated. The HITL always holds the authority to take over the operation.
Human machine interface (HMI)	Involves issues with UAS control station displays, controls, functionality, automation, operator workload and system maintainability.

Term	Definition
Human performance	Includes human capabilities and limitations which have an impact on the safety and efficiency of aeronautical operations.
Intruding Aircraft	Manned aircraft within 2 miles of a SP/VO and 1000' AGL or within the DAA system's Detection Volume (reference ASTM F3442-20)
Procedure	A preplanned series of actions (steps) to accomplish a specific end task. Generally, amplified checklist procedures contained in the UAS Flight manual identify procedures for a type of aircraft.
Remote Pilot in Command (RPIC)	A person who holds a Remote Pilot Certificate with a small UAS rating and has the final authority and responsibility for the operation and safety of a small unmanned aircraft operation.
Remote Operator (RO)	An organizational role that oversees the m:N UA flight operations. The RO has a Remote Pilot Certificate and operates the UAs from a remote location. The RO becomes the RPIC when they are in command.
Remote Operations Center (ROC)	Location where the RO controls and monitors the UA.
Safe Altitude	Minimum altitude where manned/Intruding Aircraft can be expected to <u>not</u> fly and >50' above the location's obstacles.
Safety Analysis	Systematic evaluation of the potential hazards associated with the m:N BVLOS operations that includes the mitigations to reduce the likelihood and severity of the hazards. The results are contained in the project's Operational Hazard and Safety Assessment (OHSA)
Safety Pilot (SP)	An on-site qualified Part 107 pilot who performs UA inspection and visual observer duties in support of the BVLOS operation. In support of contingency operations, the SP may assume RPIC responsibilities from the RO.
Small Unmanned Aircraft (sUAS)	Small unmanned aircraft that weighs less than 55 pounds on takeoff, including everything that is on-board or otherwise attached to the aircraft, and the systems needed to control it.
Standards	The minimum degree of proficiency to which the task must be performed.
Supplemental Data Service Providers (SDSP)	Services that disseminate essential or enhanced information to ensure safe operations within low-altitude airspace. These services include terrain and obstacle data, specialized weather data, and surveillance data.
Supervisor (SUP)	The SUP is a current and qualified Part 107 RPIC located in the ROC to maintain general situational awareness for all remotely

Term	Definition
	operated flights and, when needed, to support a contingency operation. The SUP can assume RO duties for multiple UAs.
Task	A specific operation that a crewmember is responsible to be able to successfully perform, as exemplified by the FAA's task list in its Practical Test Standards (PTS). Tasks may be divided into two subtypes: ♦ Technical tasks – measure the crewmember's ability to plan, preflight, brief, run up and operate onboard systems and sensors. ♦ Performance tasks – measure the crewmember's ability to perform in flight tasks under specific conditions by control manipulation or control station input. For the Task analysis, a Task is an indivisible set of activities to be performed by a crewmember
Unmanned aircraft (UA)	An aircraft operated without the possibility of direct human intervention from within or on the aircraft.
Unmanned Aircraft System (UAS)	An unmanned aircraft system (UAS) comprises of an unmanned aircraft, control equipment including the control station and data terminal, and support equipment including launcher (if required), spares and consumables.
Warning Alert	Red visual indications and aural annunciation indicating a potential safety issue needs immediate attention.

2. Approach

Section 2.1 provides an overview of the approach used for this project followed by the details in subsequent subsections.

2.1. Approach Overview

In previous work at AiRXOS, the Au team members developed and gained FAA approval of several 107.35 waivers. What differentiated the waivers was the FAA approval of the use of checklists for both acceptance of the sUAS to be flown and compliance of locations in the continental US with criteria established in the safety case. Certificate of Waiver 107W-2019-00526 allowed the AiRXOS RPIC to perform demonstrations with different models of sUAS and at locations nationwide that met the minimum checklist criteria.

After AiRXOS disbanded, the Anzen Unmanned team was formed and has assisted customers in obtaining BVLOS and other advanced aviation approvals. Au has worked with Asylon to get BVLOS (107.31) operations approved at multiple locations. This project built upon our joint expertise to develop BVLOS m:N standards for operators that have been previously approved for BVLOS operations.

This project extended previous waiver and exemption experience and created a m:N BVLOS framework suitable for incorporation into industry standards. To control the scope of the one-year program, the assumptions were described in the Concept of Operations (ConOps – section 2.2). Key assumptions were:

- Same model of a <55 lb. multicopter for each UAS in an operation,
- Geographically separated operating areas, and
- Prior BVLOS approval with a Remote Operator (RO) acting as the Remote Pilot in Command (RPIC).

Au used a safety risk assessment process consistent with FAA Order 8040.6 and the FAA ATO Safety Management System Manual's DIAAT process (Figure 2) to identify the hazards and safety mitigations for BVLOS m:N operations.

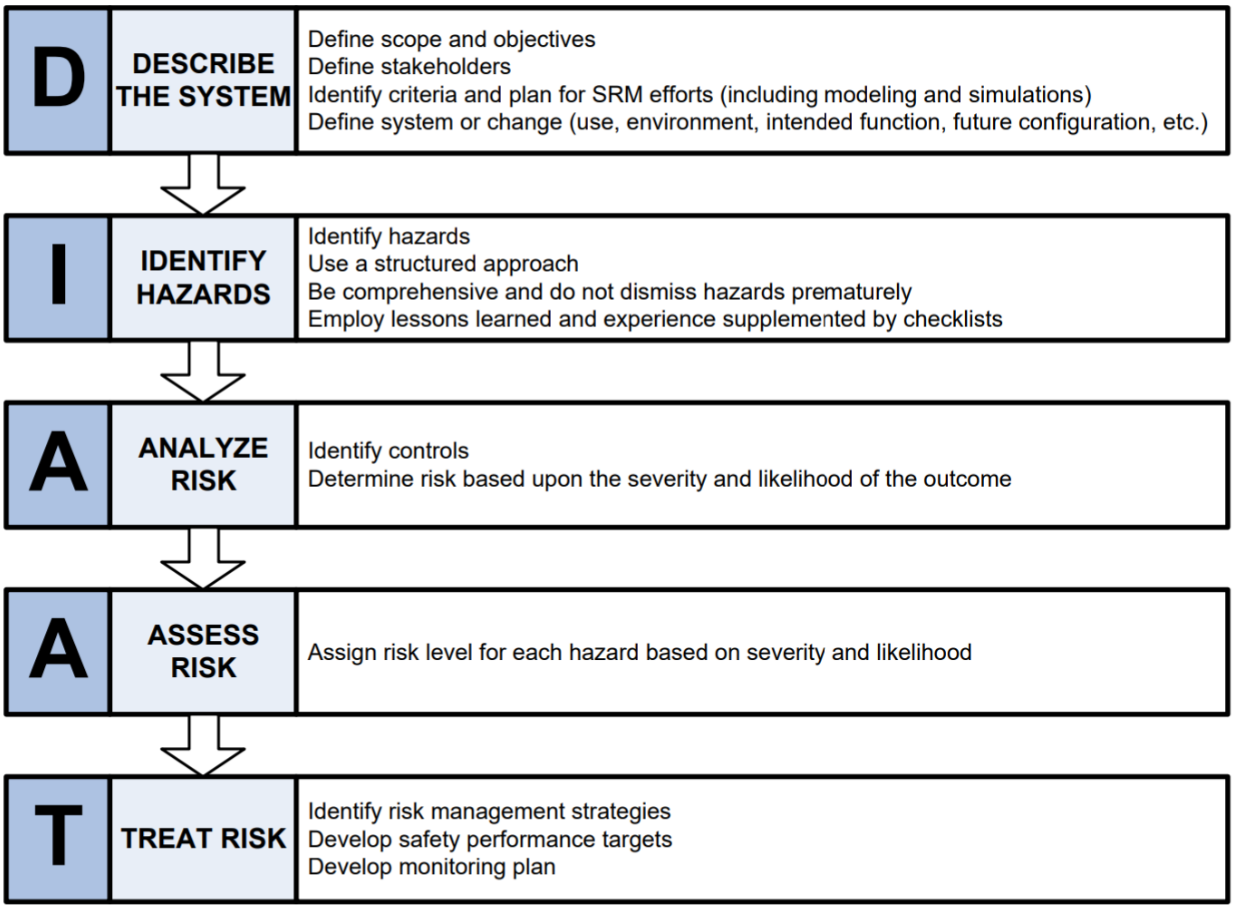

Figure 2 – FAA ATO SMS Manual DIAAT process

The initial Operational Hazard and Safety Assessment (OHSA) addressed both BVLOS and m:N in order to provide the safety case needed to obtain the operational waivers to FAA Part 107.31 (BVLOS) and 107.35 (m:N). As the projects assumes the operators already have BVLOS approval, the m:N safety case and specific requirements were captured in the document Au-REP-019 697DCK-22-C-00381–Operational Hazard and Safety Assessment for m RO operating N UA simultaneously (OHSA).

In addition to the m:N safety requirements, the FAA guidance on Human Factors (FAA-HF-STD-001/002/003) was reviewed. The review of the FAA's manned/ATC HF guidance led to additional m:N requirements to minimize the likelihood of human error (Section 2.3.2), which Asylon also incorporated into the software.

The m:N safety and HF requirements were incorporated into the:

- Organizational Assessment Criteria (OHSA Appendix B)
- Location Assessment checklist (OHSA Appendix C)
- ArduPilot UA software (section 2.3.1)

- Asylon DroneIQ software
- Asylon Remote Operations Center
- Asylon Standard Operating Procedures, which includes Crew Resource Management
- Asylon UAS Flight Manual
- Asylon Training Manual

Once the BVLOS m:N procedures were implemented, a task analysis was performed to establish a set of tasks for crewmembers and system components required for operation of an individual UAS for the specific UAS and ConOps. The task analysis included both nominal tasks as well as the tasks required for contingency operations when needed. The model was then used to analyze the operator workload over the duration of an operation as the ratio of UAS to operator increases. From timeline analysis of both the Cruise and critical phase scans for the specific UAS and ConOps, a m:N ratio of 1:6 was found to be the maximum ratio that supports the Required Period and Deadline for periodic tasks supporting system, airspace, and environment situational awareness (see section 2.5). Note that this maximum ratio will differ for UAS implementing different levels of automation and for different ConOps and its associated tasks.

Initially, the m:N software changes were evaluated via simulation to ensure the changes did not affect single UAS useability. Once single UAS operations were validated in both the simulator and actual flying, the simulator was updated to support multiple UAs by adding additional displays to the workstation.

The pilots were trained on the additional m:N features and procedures in the classroom and on the simulator. Each of the classroom modules included a knowledge test, and the simulator modules included proficiency checks. The proficiency checks included RO response to normal mission events and contingency/emergency events.

After simulation confirmed the minimum requirements and an acceptable ratio of sUAS per RO (m:N), flight tests were performed to validate ROs can safely and effectively operate multiple UAs simultaneously.

The validated requirements are intended to form the basis of future industry standards. By way of a Standards Development Organization (Figure 1), this project makes available to industry:

- Proven M:N safety and human factors requirements that should be implemented in the UAS and operational procedures
- Checklist for key attributes of a safety management system an organization implementing m:N operations should have in place
- Training requirements
- Checklist to assess location viability for safe, effective m:N BVLOS operations

- m:N safety assessment that can be used to justify the expansion of an organization's BVLOS approval to m:N

The following subsections provide additional details on the m:N BVLOS approach.

2.2. Concept of Operations (ConOps)

Below is a high-level summary of the BVLOS m:N project ConOps to provide perspective for the BVLOS m:N requirements identified, implemented, and tested. Implementation of this ConOps is expected to enable scalable Part 107 operations with waiver/authorizations for 107.35 (m:N) in conjunction with the operator's previous waiver/authorizations for 107.31 BVLOS operations.

2.2.1. Location

Each of the UAs is located at a different site with each of the sites separated by at least a buffer distance (Figure 3).

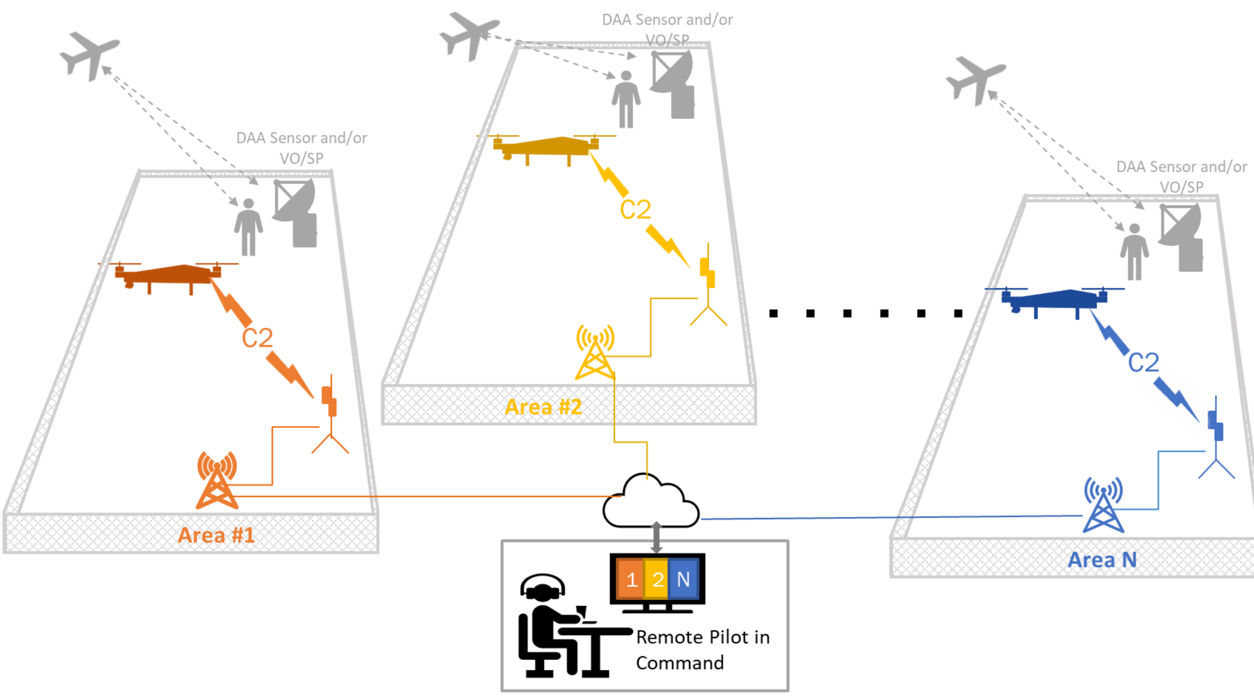

Figure 3 – Multiple System architecture

Each site using this analysis meets Au's location assessment checklist contained in the OHSA appendix C. Key location characteristic include:

- Compatible with BVLOS operations
- Distance between each UA's operating area is at least the buffer distance. The size of the air risk buffer is determined as a function of the UA speed and the longest time between

UA loss of control and mitigation(s) successfully completed. Manned aviation traditionally uses the criteria of 1 second for recognition and 3 seconds for response during normal cruise operations.

- Operating area is within the maximum geofence
- Nearest airport is at least 5 miles away; nearest heliport at least 2 miles away
- Operating altitudes per Part 107 (i.e., below 400 ft AGL or around buildings/structures)

2.2.2. Flight Crew

The minimum BVLOS m:N flight crew is:

- Remote Operator (RO) located in the Remote Operations Center (ROC) with overall flight responsibility. The RO is responsible for meeting the regulations as an RPIC.
- ROC Supervisor (SUP) monitoring one or more RO's performance and providing back-up for events
- If required, a Safety Pilot at each of the physical sites to complete on-site daily/preflight inspections and/or act as a visual observer for BVLOS operations

Prior to m:N training, the flight crew should have BVLOS experience with the UAS. Using the prior BVLOS experience as a foundation, the ROs and ROC supervisors should be trained on the unique aspects of m:N, including knowledge and performance tests, before being allowed to operate multiple UAs on the simulator. Simulator training is required prior to operations with the physical UAs.

The company's crew management practices should be documented in the company's Flight Operations Standard Operating Procedures (SOP). The m:N operational requirements are in summarized in the Crew Management section 2.4.

2.2.3. System Description

The BVLOS m:N automated system is comprised of three main sub-systems:

- A Part 107 compliant multicopter using a flight controller and communications system implementing the m:N requirements (section 2.3.1.1). For the Asylon system, this is ArduPilot and MAVLink, respectively. A key aspect of this project is ensuring the functionality needed for m:N operation is available to other UA manufacturers/operators. By updating and using the ArduPilot software, the UA safety features can be used directly on ArduPilot equipped UAs or the software can be analyzed, and the equivalent implemented in other UA code bases.
- Onsite portion of the Ground Control Station (GCS) enclosed in a secure area. The GCS at a given location is largely driven by the functionality needed for BVLOS (e.g., C2,

surveillance sensors, micro-weather sensors). The safety analysis assumes each UA has its own GCS.

- Cloud-based (or similar) command and control software suite that provides the remote GCS functions (section 2.3.2). This software provides the primary interface with the RO.

2.3. UAS m:N Enhancement Development

This section describes the process used to develop the UAS enhancements that underwent simulator and flight test evaluations, including:

- Automation to minimize the RO workload for both normal and off-nominal conditions (section 2.3.1)
- Human/Machine interfaces needed to provide the RO with the needed situational awareness, controls, and reliability (section 2.3.2).

2.3.1. Automation

Multiple simultaneous UAS operating BVLOS requires a level of automation that aligns with the scope, scale, and complexity of an operation. As the level of automation increases, the RO role shifts from an active hands-on pilot to a hands-off safety monitor.

Defining the level of automation is foundational to understanding the role of the human as a causal factor contributing to an occurrence. Based on the SAE International driving automation standard (as defined in SAE J3016), a UA automation standard was created as part of this study to ensure human factors are captured within a defined automation context (Table 2). It is also important that any changes with the automation level will require an updated OHSA and HF analysis.

Table 2 – Automation Levels

Automation Level and Name	Description
Level 0 (No automation)	Human pilots do all the flight operations.
Level 1 (Crew Assistance)	UAS is controlled by the crew, but some flight assist features may be included that can assist the RO with telemetry, speed, and altitude.
Level 2 (Crew Partial Automation)	UAS has combined automated functions, but the crew must remain engaged with the flight tasks and always monitor the environment.
Level 3 (Conditional Flight Automation)	An automated flight system on the UAS can perform all aspects of the flight tasks under some circumstances. Crew is still required to monitor the status of the UAS in operation. The RO

	is expected to be takeover-ready to always take control of the UAS with notice.
Level 4 (High Flight Automation)	The UAS can perform all flight functions under certain conditions. The crew may have the option to control the vehicle.
Level 5 (Full Automation)	The UAS can perform all flight functions under all conditions. The crew, as a safety monitor, never needs to be actively involved in flight tasks.

This project's automation level was designed to be level 3 throughout the human-in-the-loop (HITL) operations. For level 3 with the HITL, the crew is still required to monitor the status of the UAS in operation. The RO is expected to be ready at all times to take control of the UAS with notice. The RO, as HITL, always holds the authority to take over the operation. Also, for this project the Asylon security mission and certain off-nominal operations required the RO or SUP to assume manual control over the operation.

2.3.1.1 Aircraft Automation

A task analysis was performed to determine the theoretical maximum number of UAs that an RO could effectively operate given the level of automation (see section 2.5). During normal and contingency operations, the RO workload was designed to be low since the UA had the following features:

- Pre-planned automated flight routes including take-off and landing
- Lateral and vertical Geofence at Operating Area perimeter
- Lateral Exclusion Zones around obstacles and other areas
- Deterministic activation of automated contingency actions, including
    - On-UA lateral and vertical geofence preventing UA excursion from the defined operating area
    - On-UA Exclusion Zones preventing incursion into high-risk areas (e.g. unavailable C2, assemblies of people, etc.)
    - On-UA Exclusion Zones placed around obstacles higher than Safe Altitude (or lower near landing site), and Critical Infrastructure that is not part of the operation
    - C2 anomalies trigger Return To Launch (RTL)
    - On-UA ADS-B-in aircraft detection and descent to Safe Altitude
    - GNSS/GPS anomalies result in landing using secondary/barometric altitude
    - Low battery caution triggers RTL
    - Low battery warning triggers Landing

2.3.1.2 Automated Controlled Descent and Landings

Since abnormal/emergency landings may be needed away from the initial take-off point, it is important to limit the kinetic energy at low altitudes to less than the Association for the Advancement of Automotive Medicine AIS 3 injury criteria. It is also important to ensure the UA can descend fast enough to avoid collisions with Intruding Aircraft. Figure 3 shows the vertical speed requirements during descent and landing.

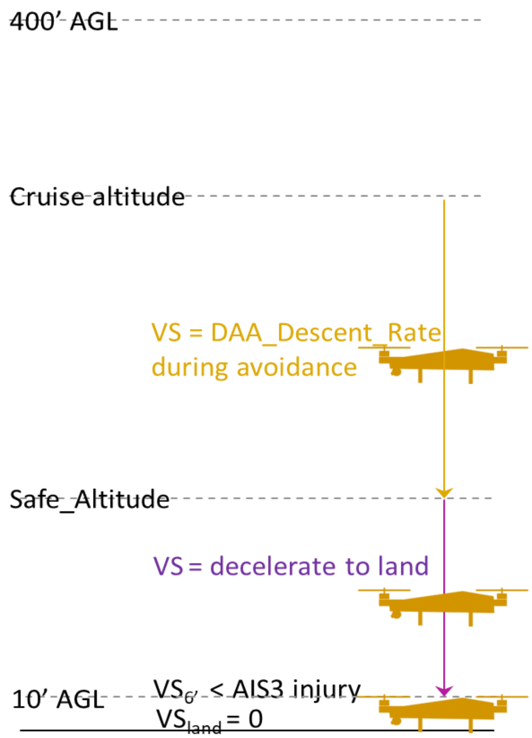

Figure 4 – Controlled Landings

2.3.1.3 On-site Ground Control Station Automation

The base station provides the on-site GCS infrastructure needed for remote operations. Key safety features include:

- Means for automated safe and accurate takeoff and landing
- Secure, reliable communications infrastructure to ROC and UA
- DAA Surveillance Sensor, where approved for BVLOS operations

2.3.2. Human/Machine Interface

Since Part 107 UAS typically lacks the integrity and availability assurance needed for more complex operations, the RO is frequently needed to maintain situational awareness for the UAs and provide some mitigations. A detailed safety analysis was performed of the m:N BVLOS operations; most hazards and safety mitigation measures are driven by BVLOS operations. The OHSA details the potential origins of hazards specific to m:N, and the requirements needed to mitigate the hazard. As the RO is involved with multiple UA, the m:N OHSA analyzed and identified mitigations for potential hazards due to an erroneous or lack of an RO action.

In addition to the m:N safety requirements, the FAA guidance on Human Factors (FAA-HF-STD-001/002/003) was reviewed. For manned aircraft and air traffic operations, the FAA has performed significant research into how to minimize human error for manned aircraft operations. The review of the FAA's manned/ATC HF guidance led to additional m:N requirements to minimize the likelihood of human error (appendix B). The resulting safety and human factors m:N requirements were implemented in the UAS (section 2.3) and the supporting organizational procedures (section 2.4).

The following subsections describe the m:N human factors requirements needed in the:

- ROC Environment
- RO Display
- Supervisor Display
- Aural Alerts
- RO Primary Controls
- RO Backup Controls

The entire UAS design had a general requirement from FAA AC 25.1302-1 for "error prevention and management to the extent practicable so that the:

- Design enables the flight crew to detect and/or recover from errors resulting from their interaction with the equipment; or
- Design makes the effects of such flight crew errors on the airplane functions or capabilities evident to them and enables them to continue a safe flight and landing; or
- Design discourages flight crew errors by switch guards, interlocks, confirmation actions, or other effective means; or
- Effects of errors with potential safety consequences should be precluded by system logic or other aspects of system design that will detect and correct such errors."

2.3.2.1 Remote Operations Center (ROC)

The ROC houses the equipment needed for the RO and the ROC supervisor to monitor and control the UAs. Safety Analysis requirements for the Remote Operating Center (ROC) include:

- Physical separation from non-flight functions to support a sterile cockpit approach

- Secure, reliable infrastructure to eliminate common failure modes for multiple flight operations (e.g., internet, servers, computers, displays, speakers, controls, etc.)
- Display of safety related parameters to ensure situational awareness
- Visual and aural alerts for safety issues to increase pilot awareness
- Activation of individual aircraft modes, as well as All-hold, All-land, All-RTL to minimize the RO workload during events
- Ability to easily coordinate transfer of UA control to/from the supervisor for personal reasons and handling of events

Figure 5 – Remote Operations Center

2.3.2.2 RO Display

The displays are the primary means of ensuring the RO has the situational awareness needed. Most of the display content is determined by what is needed for BVLOS operations (e.g., C2/battery/UA health, position, DAA, weather, etc.).

In addition to the requirements from the safety analysis, additional human factors requirements were placed on the display design based on lessons learned from the FAA's guidance material (see Appendix B).

Since few organization's ROs are expected to be exclusively focused on flying the UA, the RO was also expected to perform the Asylon security monitoring mission, as well as monitor for incoming weather and the DAA sensor feeds. The project's overall BVLOS m:N resulted in a 6-display format to operate 6 UAs (Figure 6)

Figure 6 – Six Monitor Configuration for One of the Workstations with Displays in the RO Configuration

Asylon's design utilizes a stacked monitor format whereby the bottom monitor contains the UA's video and telemetry, command and control buttons, mini-map for situational awareness, and text logs (including alerts), while the upper monitor contains a weather interface for the site and the Detect and Avoid (DAA) interface. Each monitor is split vertically, with the information for one UA on the left and a second UA on the right. Figure 7 below shows a representative example of four UAs displayed across four monitors.

Figure 7 – Representative Live Ops Display Showing Four UAs

As shown in Figure 7, each vertical slice has a specific-colored border so as to distinguish one UA from the others. Within each vertical slice, from top to bottom, the displays are:

- Weather
- DAA
- Payload video
- UA controls
- Mini-map and text logs

The bottom right display in Figure 8 shows how a visual alert will be displayed in both the text log section and overlaid on the UA's video window.

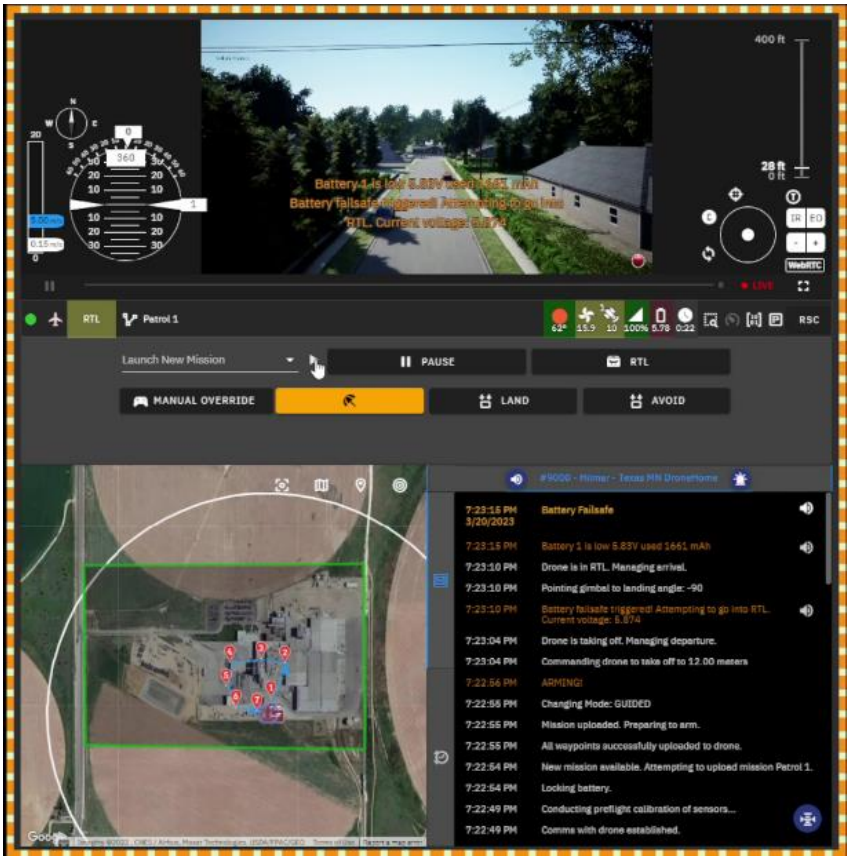

Figure 8 – Visual Alert for Single UA on Live Ops Page

For critical alerts that necessitate an immediate response from the RO, the border around the UA transforms into a flashing red border to draw the RO's attention to the appropriate UA and an aural alert is played. Given the multitude of displays with m:N operations, the flashing border allows the RO to quickly focus on the UAS of concern. Figure 9 below shows this transformation in the event of an intruding aircraft entering the alert volume of the DAA system: the entire border for that UA flashes red, the DAA rings turn red, and a "WARNING" label appears.

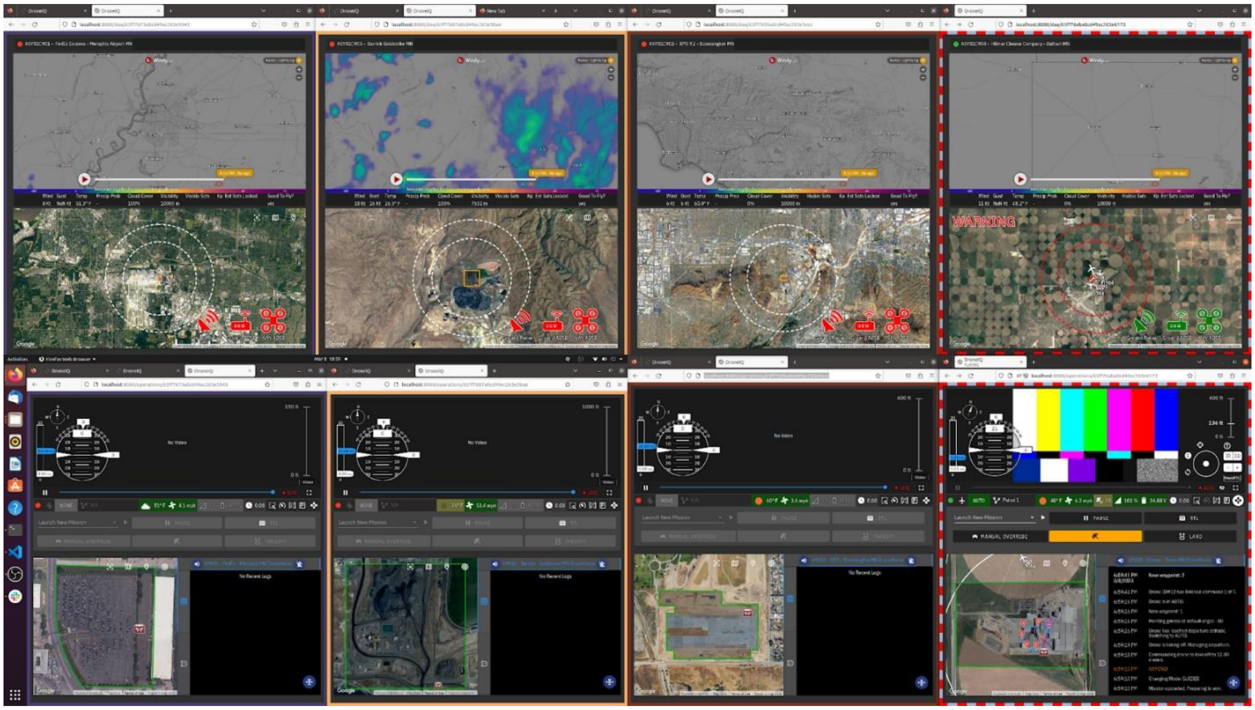

Figure 9 – DAA Alert on Live Ops Page

2.3.2.3 Supervisor Display

To satisfy the requirements associated with the ROC Supervisor having prompt access and awareness to ROs' UAs, Asylon developed a new interface to facilitate those requirements. The interface is comprised of lists of UAs, separated by RO, and mirrors much of the design used for the RO's tablet display (section 2.3.2.6). From this interface, the ROC Supervisor may request control of UAs as well as assign UAs to other ROs. Additionally, the ROC Supervisor can select a UA from the Supervisor display to access a preview of that UA's Live Ops page (weather, DAA, payload video, mini-map, etc.) for additional situational awareness. Figure 10 below shows a representative example of how this display could be used across four horizontal monitors. The left side shows the status summary and minimum controls for the active flights for each of 6 ROs. The display format (Figure 10) for each operation is the same as the RO's tablet interface (Figure 11). The SUP may bring up specific operations on the right side.

Figure 10 – Supervisor Screen (over-seeing 6 RO)

The Supervisor Screen is also capable of highlighting Cautions and Warnings for individual UAs. As these events occur, the Supervisor Screen will highlight that UA's row and, if that UA is selected, also highlight the Live Ops Preview window.

2.3.2.4 Alerting

Audio and visual alerts were put in place to ensure the RO was aware of conditions that could potentially lead to safety events. The conditions for the alerts were determined by the OHSA with cautions requiring additional awareness and warnings needing immediate attention. The best practices from FAA Human Factors (FAA-HF-STD-001/002/003) were reviewed with a subset identified as being critical to m:N operations. Additional human factors requirements were placed on the design to minimize the likelihood of human error (Appendix B).

2.3.2.5 RO Primary Controls

While most contingency responses are driven by BVLOS operations and have been automated, the RO is needed for some responses (i.e., human-in-the-loop). In order to ensure the UA response is performed before an adverse condition, the command and controls must be easy to quickly and accurately use. Additional m:N safety and HF requirements were placed to ensure timely RO responses to m:N events (Appendix B).

2.3.2.6 RO Backup Controls

To satisfy the requirements for the RO to easily send commands to multiple UA while also providing a redundant interface in the event of a failure of the operation center's internet or the RO's workstation, Asylon implemented a software interface for a tablet connected to the GCS via cellular data. The device allows for the cloud-based monitoring and command functions to operate independent of the ROC's internet connection and the primary computer/display. This new interface does not provide any maps or video from the UA but includes the most relevant telemetry information and command and control buttons for quickly commanding the UA when needed. Figure 11 below shows the current implementation of the RO tablet interface.

Figure 11 – RO Tablet Interface

2.4. Crew Resource Management (CRM) Maturation

Like operating a complex crewed aircraft, Crew Resource Management is applicable to complex multi-crewed m:N BVLOS UAS operations. Complex UAS operations require communication, situational awareness, leadership, and followership skills to optimize decision-making based on the effective use of all available resources.

CRM skills are required to enhance crew coordination and teamwork to successfully and safely operate in the complex UAS m:N BVLOS flight test environment. The organizational requirements are captured in the OHSA Organizational Assessment Checklist (OHSA Appendix

B) and this document's Appendix B. The following subsection summarizes the CRM aspects designed into the project.

2.4.1. Safety Management System

Within the context of the larger safety culture, effective CRM is an attribute of an organization's commitment to safety. During the m:N BVLOS tests, all required crew members were qualified under the organization's voluntary SMS. In addition to the FAA SMS guidance, the human factors requirements included:

- Safety culture with open and honest communication
- Active engagement in identifying emerging hazards
- Management commitment to addressing safety risks
- Role based training

2.4.2. Standard Operational Procedures (SOP)

Most of the SOP content is driven by BVLOS operations. The unique HF aspects with m:N include:

- Clearly defined roles, responsibilities, and authorities between the RO, Supervisor and Safety Pilot (if applicable)
- Minimum qualifications for each role, which included prior BVLOS experience and training (section 2.4.4)
- Flight Operations standards including transfer of displays/controls to/from RO, Supervisor and Safety Pilot (if applicable)
- Frequency of briefings and use of checklists. For this project, all the ROs met with the Supervisor at the beginning of the shift. A full pre-flight was done on each UA by the on-site safety pilot. An abbreviated pre-flight was performed before successive flights.
- Communications standards (section 2.4.3)

Note, the required content included in the SOP was defined by the OHSA.

2.4.3. m:N Communications

In a remote operating center, a supervisor may be overseeing multiple ROs flying multiple UAs. In order to minimize miscommunications, the following were implemented:

- "Call and response" communication style, similar to traditional ATC towers and ARTCCs
    - Example: RO: "SUP, your controls" SUP: "RO, my controls"
- Call signs to distinguish the different ROs that are unique, consistent, easy to pronounce, and easy to distinguish via voice communications

- Location or UAS identifiers that are unique, consistent, easy to pronounce, and easy to distinguish via voice communications
- Terminology standards that cover:
    - All modes of operations, including contingencies
    - Current UAS status conditions
    - Transition of control
- Phraseology consistent with FAA Order 7110.65 is recommended to minimize misunderstanding between the RO, SUP, and SP (when applicable).

2.4.4. Training

CRM training is essential for m:N BVLOS operations to enhance system safety, efficiency, and overall human performance. The operator's training program must have BVLOS training in place prior to adding m:N operations. The training should be designed to provide a comprehensive understanding and hands-on experience with every aspect of the flight operations.

This project's m:N training program utilized a combination of:

- Ground school "classroom" sessions covering the relevant rules and regulations, as well as the m:N specific policies, operations, and waiver conditions.
- m:N simulator training for familiarity and more challenging m:N scenarios without the flight risk (see section 2.6.1 for the scenarios tested)
- Flight training designed to expand pilot competency to comfortably maintain situational awareness and control of the multiple UAs during simulated normal, abnormal, and emergency operations (see section 2.6.4 for the scenarios tested)

Additional m:N training requirements included simulator and then flight proficiency checks for:

- Positive transfer of aircraft control between SP, RO, and SUP
- Supervisor recognition and response for RO issues (e.g., health, excessive workload, errors)
- Acceptable response times for warnings needing immediate response
- m:N communications standards
- Simulated normal, abnormal, and emergency operations to ensure pilots are able to safely recover and/or land up to the maximum number of allowed UAs.

2.5. Task Analysis

Key goals of this project are to establish thresholds for safe operation of multiple UAS by a single operator and the procedures operators can use to ensure safe operation is preserved. In support of these goals, the team conducted a task analysis to form an initial expectation of the acceptable number of UAS under control of a single operator. The task analysis was based on establishing a set of tasks for crewmembers and system components required for operation of an individual UAS, including the tasks required for contingency operations when needed, and then analyzing the operator workload over the duration of an operation as the ratio of UAS to operator increases. This analysis explored different ConOps for sequencing flight phases (e.g., preflight, launch, climb, mission execution, descent, landing, postflight) as well as variations based on contingency response to events during different phases of flight.

2.5.1. Task Analysis Methodology

For the analysis, operation of each UAS was modeled as a series of modes composed of one or more tasks, each of which is performed by a crewmember or system component. During an operation, the UAS progresses through a series of system modes. Timelines were created for both nominal and off-nominal (i.e., contingency) operations for an individual UAS. Subsequently, composite timelines for N UAS were generated by combining the individual UAS timelines, resolving conflicts between the timelines, and then evaluating the composite timelines against criteria such as:

- Safety deadline requirement satisfaction
- Crew and system component workloads and utilization
- Robustness to variations in timing, spontaneous events, etc.

The foundational assumptions for task definitions are:

- A UAS operation is composed of a sequence of tasks
- Task = an indivisible set of activities to be performed by a crewmember
    - If a task is interrupted, it must be restarted and performed to completion to be considered complete
        - It may be necessary to consider some tasks to be uninterruptible if they cannot be restarted effectively prior to completion (e.g., communications protocol test)
    - The amount of time taken to complete a task includes the overhead to switch from the previous task to the current task
- A crewmember can only perform one task at any given time

Tasks fall into two categories – periodic tasks and aperiodic tasks. All tasks may be planned tasks for an operation, or unplanned tasks performed in response to an event.

- Periodic
    - Have a maximum repetition period to ensure safe operation
        - Completing these tasks at smaller periods (i.e., more frequent completion) does not impact safety

- Examples
    - Planned (e.g., instrument scan, surveillance scan)
    - Unplanned (e.g., intruder tracking)

♦ Aperiodic (a.k.a., event driven)
- Initiated by an event
    - May have a completion deadline from the event that must be met to ensure safe operation
        - Assumption: Completing the task prior to the deadline does not impact safety
- Examples
    - Planned (e.g., launch, landing)
    - Unplanned (e.g., intruder alert response, UAS failure response)

Some tasks must be synchronized with tasks from other roles (e.g., crew communications) or system components (e.g., test result), so these tasks are identified as having a synchronization constraint with one or more other tasks.

Using the method of mode, task, and timeline definition described above, the team first constructed a single UAS timeline using modes and tasks defined in the UAS Flight Manual and operator training, with task durations estimated by experienced crew when the durations were not specified (and then later confirmed via testing). Composite timelines were then constructed for increasing m:N ratios (m = number of operators, N = number of UAs). As the composite timelines were constructed, different scheduling methods were used to explore tradeoffs between allocation of crew resources between multiple UAS. The factors that emerged as the primary influencing factors for different scheduling methods were:

♦ Optimization of human and system time to maximize m:N ratio vs reasonable operator workflow

♦ Optimizing flexibility of beginning/ending operations for any individual UA vs robustness to issues during preflight and launch

When considering the tradeoffs between different scheduling methods, the team used a prioritized framework consisting of:

1. Satisfaction of safety requirements identified in the hazard and safety analysis

2. Situational awareness of system performance to identify and respond to issues prior to requiring alerts and contingency response actions

3. Situational awareness of airspace and environmental factors to identify and respond to issues prior to requiring alerts and contingency response actions

    a. For example, potential intruding aircraft or developing weather conditions

4. Simplicity of crew procedures to minimize risk of incorrect or delayed response

5. Time to perform visual monitoring in support of the Asylon security surveillance mission

6. Resilience to variability in flight timelines between different UA under control of the same operator

7. Optimized use of crew and system resources

Only scheduling methods that supported the satisfaction of safety requirements were considered, so in effect, all scheduling methods satisfied criteria #1. Ultimately, the team chose the following method:

1. Preflight all UAs prior to launching the first UA

2. Get first UA flying in cruise, then when bringing on another UA or landing an UA (i.e., critical phases of nominal operations), or performing a critical phase of a contingency response, interleave the controls and display scan of the UA implementing the critical phase with the nominal scan pattern for all other UAs in cruise

3. At transitions between modes, perform a full scan pattern for all UA in cruise

    a. Ensures cruise scan deadlines are not missed

4. Otherwise perform continuous scans for all UAs in cruise

This method satisfies safety requirements in that any task can be interrupted by a warning and restarted after responding to the warning within the latency required by the safety analysis. Since priorities #2 and #3 involve maintaining situational awareness per the goals of the Required Period and Deadline for their periodic tasks, these requirements drive the m:N ratio. It should be noted that this method of scheduling tasks is not the only method that will satisfy criteria #1.

2.5.2. m:N Ratio Determination

From timeline analysis of both the Cruise and critical phase scans, a m:N ratio of 1:6 (one RO simultaneously operating six UAs) was found to be the maximum ratio that supports the Required Period and Deadline for periodic tasks supporting system, airspace, and environment situational awareness for the Asylon surveillance mission. This analysis included both nominal and contingency operations.

2.6. Verification and Validation Testing Approach

After the m:N requirements in the previous sub-sections were implemented (including functional testing and crew training), the system was evaluated for its safety and human factors viability. The human/machine interface (section 2.3) used by the ROs and Supervisors to control the UAs was the same during the simulator and flight test (including simulated UAs and the physical UAs). Figure 5 shows the Remote Operations Center (ROC) and Figure 6 shows one of the RO's display layout. Figure 12 shows the layout of the simulation environment, including the test equipment and test personnel (i.e., human factors observers, flight director, and equipment technicians).

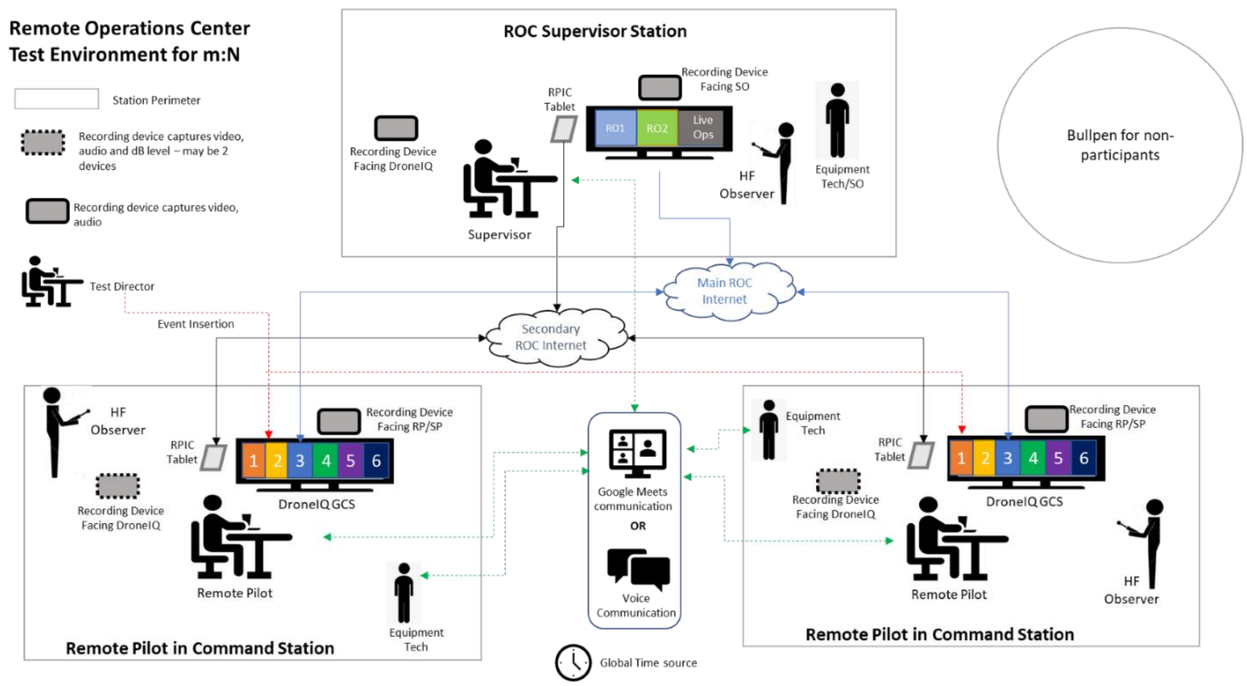

Figure 12 – Simulation Environment

To maximize the similarities between the testing with the simulations and the physical UA flight test, all testing utilized the same communication and checklist procedures (section 2.4). Additionally, the simulators used the same flight controller software, ArduPilot, as that used on the physical UAs so that the flight characteristics and vehicle behavior closely matched the physical UAs. This provided a seamless experience between the simulators and physical UAs for the operators.

2.6.1. Simulation Test Cases

Simulation testing of 26 scenarios (52 test cases) was performed with 7 ROs using up to 6 simulated UAs at different simulated locations as an initial means of testing and evaluating the system and crew member performance.

The ability to simulate nominal and off-nominal/abnormal events was integrated into the simulation software. The simulation presented the crewmembers with a realistic interface based on the pre-designed test case scenarios. Injected events included:

- Nominal operations
- Fly away associated with lost C2 (command and control link)
- Loss of radar feed
- Detect and Avoid Caution
- Detect and Avoid Warning (single and multiple aircraft)
- Lost display monitor
- Lost system internet
- Weather – high winds and lightning
- Low battery
- RO unable to perform duties during an operation
- Interruption in the flight plan due to security events in support of Asylon's security mission

Feedback from the simulation testing was used to establish the complexity level of each test case. A complexity level scale of 1 meaning low complexity to 10 meaning extremely challenging was used to rate each test case. The following criteria was used to assign the complexity levels assuming a baseline of zero for a 1:1 operation without any hazard events:

- Number of UAs: Complexity increases with each additional UA
- Transfer of Controls: Complexity increases when a Transfer of Controls is unexpected as with contingencies
- Number of Hazards: Complexity increases when the number of hazard events increases
- Phase of Flight: Complexity increases if the hazard occurs during take-off or landing
- Mitigation Type: Complexity increases if the mitigation requires a manual response

2.6.2. Flight Test Objectives

To ensure a meaningful flight test, the following objectives were established:

- Simulation timing and responses effectively matched the real-world
- UAS m:N automation provided the mitigations needed for contingency/abnormal operations

- User interfaces were easy to use and provided the situational awareness needed for timely, correct RO responses
- Procedures and training were adequate for real operations
- Pilot workload was within acceptable levels
- Recommended ratio of RO to UAs from the task analysis are supported by flight test (1 RO can safely operate 6 UA while also performing security surveillance mission).

2.6.3. Variations needed for Flight Test

The following accommodations were needed to account for the flight test operations:

- Two UAs operated at the NYUASTS Griffiss Class D airport, which also required the approval of an FAA waiver to 107.51 airspace. Significant manned air traffic was observed resulting in either delayed UA launches or automated descents to safe altitudes.
    - The BVLOS m:N safety analysis and resulting requirements were intended for lower risk airspace although they successfully mitigated safety risks and ensured safe operations in the higher risk airspace.
- SP co-located with each UA during flight test to perform pre-flight inspections and provide additional situational awareness.
- All flights were performed in daylight even though the m:N requirements can be applied to BVLOS night operations.

2.6.4. Flight Test Cases

The test cases used in this flight test were based on the complexity assessment and specifically engineered to test the various mitigations identified as m:N requirements by the operational hazard and safety analysis.

Table 3 – Overview of Test Cases and Complexity Level

ID	TC Name	m:N Simulation Test Case Description	Comp-lexity	Rationale / Expected Result
MN_TC6	1:6	1:6 (1 RO, 6 UA) BVLOS operation with no unexpected events.	3	Establish a 1:6 flight test baseline
MN_TC8	1:6 SE	1:6 (1 RO, 6 UA) BVLOS operation with security event observed on UA3 at approximately 5 minutes after UA3 takeoff.	6	CRM challenge/ Gimbal management.
MN_TC11	1:3 C2	1:3 (1 RO, 3 UA) BVLOS operation with lost C2 signal for UA3 at approximately 5 minutes after UA3 takeoff.	4	Transfer of control
MN_TC13	1:4 BB	1:4 (1 RO, 4 UA) BVLOS operation with bathroom break 5 minutes after UA4 takes off.	3	Routine temporary transfer in ROC

MN_TC14	1:4 MF	1:4 (1 RO, 4 UA) BVLOS operation with monitor failure for UA3 at approximately 6 minutes after UA3 takeoff.	4	CRM with transfer due to system malfunction
MN_TC15	1:5 LB-DAA	1:5 (1 RO, 5 UA) BVLOS operation with low battery alert for UA1 at approximately 15 minutes after UA1 takeoff and DAA caution alert that turns to a warning alert for UA5 at approximately 8 minutes after UA5 takeoff. Low Battery alert should occur shortly before DAA caution alert and while RO is monitoring UA1's RTL.	5	Multiple simultaneous events – Low battery RTH followed by a DAA
MN_TC16	1:5 LS	1:5 (1 RO, 5 UA) BVLOS operation with loss of Radar surveillance feed for UA1 at approximately 3 minutes after UA1 takeoff.	3	With SP/VO, may elect to continue or abort the sortie profile
MN_TC18	1:6 LI	1:6 (1 RO, 6 UA) BVLOS operation with loss of primary internet at RSOC for all UAs at approximately 2 minutes after UA6 takeoff.	7	CRM with management of multiple UAs in various phases of flight
MN_TC19	1:6 DAA-DAA	1:6 (1 RO, 6 UA) BVLOS operation with DAA warning alert for UA1 and UA2 at approximately 9 minutes after UA1 takeoff.	6	Multiple alerts will stress RO situational awareness
MN_TC20	1:6 DAA-DAA-DAA	1:6 (1 RO, 6 UA) BVLOS operation with DAA warning alert for UA1 and UA2 at approximately 10 minutes after UA1 takeoff and DAA caution alert that turns to a warning alert for UA6 at approximately 3 minutes after UA6 takeoff.	7	Multiple DAA alerts during complex mix of different phases of flight

The specific mitigations tested during flight test included:

- Automatic return-to-launch upon lost C2 signal
- Automatic return-to-launch upon low battery condition
- Automatic avoidance maneuver (descend to safe altitude) upon an ADS-B track entering a defined radius
- RO interpretation and alerts in response to display indications and alerts
- Effectiveness of back-up devices (displays, controls, internet, transfer of control)

2.6.5. Flight Test Locations

The RO and supervisor were based in the ROC at Asylon's headquarters in Norristown, PA. The safety analysis required geographically separated flights in order to not require time coordination such as that provided by an Unmanned Traffic Management System (UTM). Flight test operations were performed at 6 locations (2-3 real/physical UA and 0-4 simulated). As part of the FAA BAA, flight test was required at a UAS test site. Au chose the NYUASTS which is operated by NUAIR out of the Griffiss airport (RME) in Rome, NY. Two RME zones (Figure 13) were chosen for operations to emulate potential Asylon surveillance operations:

- UA "Alpha" operated out of Zone A and performed taxiway and perimeter monitoring
- UA "Delta" operated out of Zone D and performed hangar and a nearby warehouse monitoring

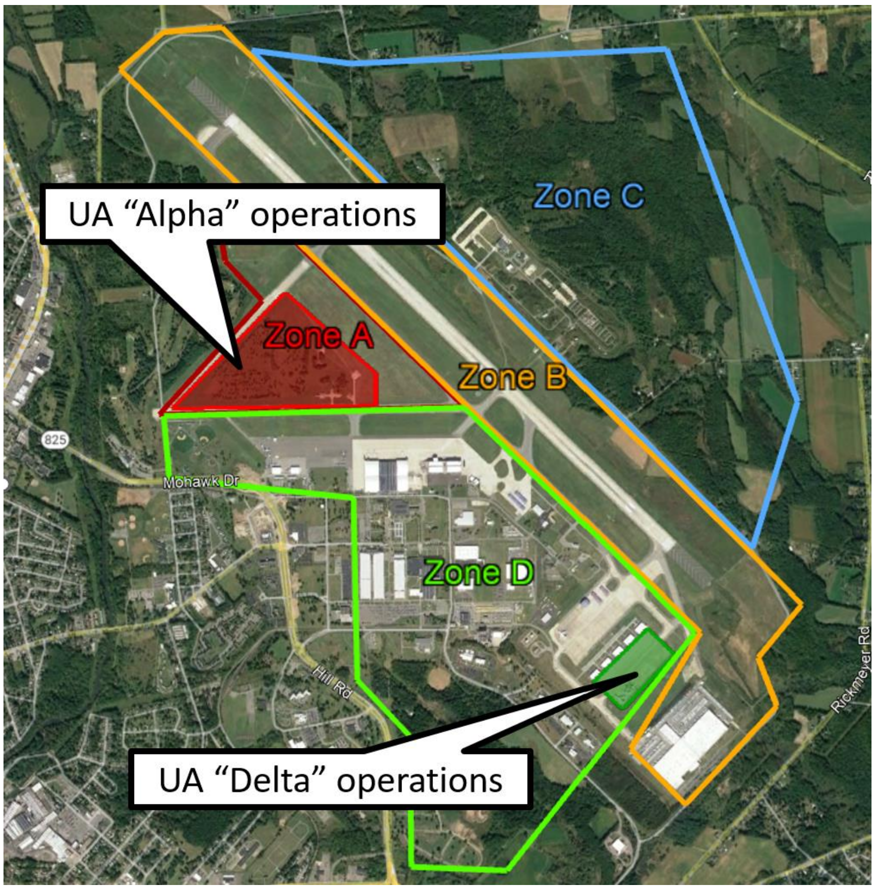

Figure 13 – Test locations at NYUASTS Griffis (RME) airport)

A third UA operated at the test center located adjacent to the Asylon headquarters in Pennsylvania with the mission to perform perimeter security (Figure 14).

Figure 14 – Asylon Headquarters Operating Area

Leveraging the work previously done for the Human Factors Assessment, Asylon prepared four simulators to be utilized as part of the flight test. All four simulators utilized the Industrial Park AirSim environment as it most closely represented the types of sites with which Asylon's operators are most familiar – that is, a logistics warehouse requiring perimeter security and surveillance. The four simulators represented four different geographic locations. Table 4 below summarizes the site configurations for the simulators. Additional simulator information is in the HF Simulator Report.

Table 4 – Simulator Site Configurations

VM #	Site Name	AirSim Environment	UA Launch Coordinates
9000	Clayton MN	Industrial Park	39.60466063, -86.48158273
9001	Whiteland MN	Industrial Park	39.55615717, -86.04790127
9002	Greenwood MN	Industrial Park	39.59984487, -86.05744512

9003	Horn Lake MN	Industrial Park	34.94926232, -90.01839406

As demonstrated previously in the Human Factors Assessment, the simulated UAs behaved nearly identically to the real UAs used in this flight test. This included the ability to stream video from a simulated onboard payload camera, control the orientation of the simulated onboard payload camera, and send ad hoc waypoints to control the location and orientation of the simulated UAs.

2.7. Human Factors Evaluation Approach

To put the HF hazards and RO's response to those simulated hazards in proper context within the given m:N and BVLOS system, quantitative and qualitative data was collected. The following evaluations were designed to provide relevant and meaningful data needed to assess the complex interplay of human, material, and environmental factors during nominal, off-nominal, and emergency operations during both simulator and flight tests:

- Crew Characterization
- NASA Task Load Index (TLX)
- Human Factors Observer Observations
- Interviews
- Post simulation/flight test analysis of videos and recordings

The following sections go through each of the evaluation methods. The resulting HF lessons learned are covered in section 4.

2.7.1. Crew Characterization

There is a lack of established standards for crew and staffing requirements for m:N BVLOS operations. A recent study by the FAA that included a survey of UAS Air Carrier Operations (Williams, 2023) to understand the crew/staffing requirements emphasizes the fact that the crew/staffing requirements are going to be different for different operations and are driven by large differences in the level of automation present in the system, number and type of aircraft involved, and the length and tempo of the operations. The study concludes by pointing out the need to explore the right mix of crew members for a particular operation. Given the lack of prior data for the efficacy and safety requirements for crew members operating m:N BVLOS UAs, it was essential to conduct tests to extend our understanding of the right fit for the type and number of crew members to conduct such an operation.

In this project, we recruited the crew members in accordance with the crew descriptions provided under 14 CFR Part 107. Another important aspect of recruiting a diverse group of individuals was the difference in the age, certification, and experience of the crew members. While having a diverse crew may introduce additional variables in the study, it is desirable to incorporate the diversity since there is no specific datum established as to what would work the best for m:N BVLOS UAS surveillance operations.

A pre-operations survey was deployed to the participants prior to the HITL simulations and was completed prior to functioning as a required crewmember. The information contained in the survey provided an objective quantitative baseline for all ROs and SUPs who performed in a required crew position during the HITL simulation. Table 5 shows information about each RO and SUP, including their age and flight hours with different classes of aircraft. None of the pilots had civil m:N experience before starting simulator training.

Table 5 – Pre-Operations Survey Results

Characteristics			Approximate Total Flight Hours						Approx. hours	Total Years
Sim ID	FT ID	Gender	Age	Crewed A/C	Part 107 UAS	Drone Sentry	BVLOS	Night	Video Gaming	Military UAS
SUP1	SUP1	Female	25	0	949	949	949	321	26,000	0
SUP2	SUP2	Male	45	0	600	31	544	350	500	0
SUP2	RO1	Male	45	0	600	31	598	350	500	0
RO4	RO2	Male	29	0	35	35	35	0	10,000	2
R01	N/A	Female	25	75	200	180	0	36	N/A	0
RO3	SP1	Male	28	0	0	552	552	420	5,000	2
RO5	SP2	Male	28	400	1,100	601	600	750	5,000	7
RO2	SP3	Male	24	27	241	87	0	7	29,120	0
RO6	SP Liaison	Male	23	0	32	2	0	4	400	0
RO7	SP Liaison	Male	62	23	70	0	0	0	0	0

2.7.2. Crew Workload Assessment via NASA TLX

In 1988, Sandra Hart at NASA released the Task Load Index Survey (TLX) as a measure of perceived workload. Workload, like usability, is a complex construct but essentially means the amount of effort people have to exert both mentally and physically to use the interface. Hart operationalized workload using six dimensions: Mental, Physical, and Temporal Demands, Frustration, Effort, and Performance. The ROs were asked to rate each of the aspects on a 20-point scale for the first part of the survey (Appendix A).

The second part of the TLX survey in Appendix A intends to create an individual weighting of these subscales by letting the subjects compare them pairwise based on their perceived importance. This required the RO to choose which measurement was more relevant to the workload. The number of times each is chosen is called the weighted score.

The TLX survey was deployed to and completed by crew members after each simulator and flight test sortie. The survey was used to collect and assess the crew members' qualitative perceptions of workload when operating in an m:N BVLOS environment while being exposed to various complex off-nominal scenarios.

A quantitative comparison of the TLX workload values between the simulator and flight test is difficult due to the additional unplanned events that occurred during flight test for each test case. These unplanned off-nominal events added to the level of complexity over what was planned as a part of the flight test. Due to lack of similarity with respect to the level of complexity involved between the simulator runs and flight test runs and owing to the uncertainty of real-world operations, we have included the quantitative results only from the flight testing. The participant flight test HF responses were compiled and analyzed in the next section.

NASA TLX assessment includes six factors contributing to the overall mental workload experienced by the crew members while performing a test case. These six factors include mental demand, physical demand, temporal demand, performance, effort, and frustration level. Based on the NASA TLX survey data analysis mental demand and temporal demand were the most significant factors while physical demand was the least significant factor contributing to the overall mental workload.

The NASA TLX survey asked the crew members to rate each of the six factors on a scale of 0 to 20. Except for 'performance', for the remaining five factors contributing to the mental workload, a rating of zero signifies the least amount while 20 signified the highest amount of that respective factor. For 'performance' 0 signifies good performance whereas 20 signifies poor performance. The ratings reported by the crew members on a scale of 0 to 20 for all six workload contributing factors answer the question of how much each factor contributes to their mental workload. Each point on the 0 to 20 scale represents a score of 5. So, for example, a rating (also regarded as 'raw rating') of 0 would account for a score of 0 while 20 would account for a score of 100.

Next, the crew members were asked to answer fifteen pair-wise comparison questions to understand which factor(s) is most influential in contributing to crew member's workload from the crew member's perspective. The number of times each factor is marked by the crew member as a factor contributing to the workload is counted and is regarded as the 'weight' of that factor. In a nutshell, the ratings help us understand the magnitude by which each factor affects the overall crew workload while the pair-wise comparison helps us understand the source of the overall workload. The ratings on a scale of 0 to 20 and the pair-wise comparison data was compiled using a two-step computation to calculate the overall workload score.

$$Adjusted\ Rating\ =\ (Raw\ Rating)\cdot(Weight)$$

Adjusted rating is calculated for each of the six factors and added together. Thus, the overall workload score is computed as follows,

$$Overall\ Workload\ Score\ =\ \frac{Sum\ of\ Adjusted\ Rating}{15}$$

Note that in the above formula 15 in the denominator represents the 15 pairwise comparison questions asked in the NASA TLX survey.

The results of the NASA TLX analysis are in section 3.2.1.

2.7.3. Human Factors Observations

This section explores the feedback and observations related to the integration of system design, information displays, and the human-machine interface as related to situational awareness for operations within a defined area, with UAs taking off and landing at the same location. The criterion in the section is based on FAA Advisory Circular 00-74, Avionics Human Factors Considerations for Design and Evaluation.

During both the simulation and flight test evaluations, HF observers were assigned to monitor the RO and Supervisor located at the ROC. The HF observers were silent observers who observed how the RO and supervisor performed and handled each of the simulation test runs. It was HF observers' responsibility to ensure all the required data for HF analysis of the system is collected during the simulator test runs. During the simulator test runs, the data was collected by the HF observers in multiple formats including structured hand-written notes, videos that captured front and rear view of the ROs, the supervisor, screen recording of the control interface, ambient noise capture using a decibel meter, etc. Figure 15 shows the template used by the HF observers for recording observations during the simulator test runs.

Day		Test Case Number	
Shift		Flight start time [actual time]	
RO		Time required to take response action [s]	
Supervisor			

Pre-flight		
Take off and climb		
Cruise		
Descend		
Land		

Human Factors Guide for HF observer	
Perception	PCP
Comprehension	COMP
Projection	PRO
Human Error	HE
Attention	ATTN
Distraction	DSTRN

Figure 15 – HF Observer Observations Template

2.7.4. Post Test Interviews

The HF Observers held semi-structured interviews with the ROs, SUPs, and SPs after the operation. The post-op interviews consisted of 21 questions based on FAA Advisory Circular 00-74, Avionics Human Factors Considerations for Design and Evaluation (Table 6). The questions provided a prompt for further, shift-specific conversations with the required crew operating in a shift.

Table 6 – Post-Ops Interview Questions

	STANDARDS
1	Did the operational procedures provided to you give a clear distribution and assignment of tasks?
2	Did the checklist support CRM and ensure crew were aware of the situation and adequately performed assigned tasks?
3	Do you think the Operational procedures took human error into consideration?
4	How adequately do you think the communications requirements were defined, clear, and concise enough to smoothly carry out the mission?

5	How adequately do you think the checklists provided to you gave clear instructions for normal and off-nominal operations?
	SUPPORT
6	How adequate were the facilities and/or services provided to you to perform the mission smoothly?
7	Were all the equipment/materials provided to you enough for you to complete the mission smoothly? Do you feel the need for any additional equipment/materials or design improvements in the current equipment/materials?
8	What are your thoughts on the number of people involved in the mission in the Ground control station? Was the number of people just right, do you think the Ground control station was understaffed or over staffed?
9	What are your thoughts on the type (i.e., with respect to the role of the people involved) of personnel involved in the mission in the Ground control station? Do you feel the need for any additional person assigned with a different role to be involved in the mission?
10	Did the communication devices support critical timely communication requirements?
	INDIVIDUAL
11	During or after operation did you feel any of the following: Fear/Excitement, Overconfidence, Lack of Confidence, Lack of motivation, Fatigue, Illness, Lack of discipline?
12	During or before the operation were there any instances where you lacked trust in the automation/equipment/tools/personnel or any other entity that was a part of the mission success?
13	What % of your total flight time do you think was dedicated to flying and flying related tasks and what % was dedicated to performing surveillance?
	TRAINING
14	Was the training adequate to operate the interface, equipment, etc. required to complete the mission?
15	Was the practice/exposure with regard to operating the controls, screens, other equipment adequate?
	ENVIRONMENT
16	Did you encounter any noise distractions, discomfort due to the temperature of the room, way the workspace was set up, displays were set up, ambient lighting, etc.
	HUMAN MACHINE INTERFACE
17	Did the interface or information presented on the screens cause any confusion during the mission?
18	Did any part of the ground control station/mission cause an unreasonable fatigue to you?
19	Do you think the level of automation was enough to support your mission?
20	How do you feel about the colors, font size, icon size
21	Did you experience any latencies while operating the controls and giving commands to the UA?

The post-operations interview questions were structured in a way to probe the crew members and enable them to freely express their issues, concerns, and recommendations.

The insights gained from the ROs, SUPs, and SPs from the semi-structured interview and follow-up conversations were recorded and transcribed into a written format. The interview transcriptions were then analyzed in NVivo using qualitative coding to identify broad themes characterizing the crew experience of m:N BVLOS UAS operations. Through qualitative analysis of the interview data, a detailed understanding of what went wrong and what went right is gained and presented in the form of a hierarchical tree map. The hierarchical tree map consists of nested rectangles. with the size of each rectangle representing the significance of that theme relative to other themes. Figure 27 shows a hierarchical tree chart for the challenges and issues that were faced by the crew members during flight testing. A variety of perspectives were expressed during the post operations interviews which pointed toward some common themes of issues that the crew members faced during the flight testing.

2.7.5. HF Data categories

Objective data associated with each operation was captured to put the human factors data into a meaningful and relevant context. These HF data elements were put into the following Root Cause Analysis (RCA) categories with examples of each:

Category	Subcategories	Definition
Information Processing	Attention	Selective = Greater attention being given to one or more sources (cocktail party effect – m:N) Divided = Multitasking (timesharing effect) Focused = Focusing upon one single source not paying attention to other important information Sustained = Ability to maintain attention and remain alert (e.g., not distracted or fail to maintain situational awareness)
	Perception	Failure to process information due to lack of interpretation of the stimuli from the surrounding to perceive an emerging hazard (e.g., gusting winds)
	Short Term Memory	Failure to keep track of large information and collect all the momentary sensory inputs (e.g., Missing out on one of the multiple DAA warnings on multiple UAS at the same time.)
Human Error	Slips	An action not carried out as intended—finger trouble (e.g., not putting in correct inputs to the intended UA)
	Lapses	Forgetting (e.g., forgot to switch over to the correct UA) Monitoring (e.g., did not pay attention and did not recognize a flight plan deviation or intruding aircraft)
	Mistakes	Faulty plan (e.g., flight plan/decision for course took UA though controlled airspace without an authorization)

Category	Subcategories	Definition
	Knowledge Base	Errors at the knowledge-based performance level are related to incomplete or incorrect knowledge or interpreting the situation incorrectly (makes an incorrect diagnosis of a situation without having a full understanding of how the aircraft systems work)
Workload	Ability to Cope	Readiness to cope with events in which the RO is overwhelmed by events through the increased workload demands; thus, loses the ability to cope or manage the event (e.g., contingency operations result in an inability to manage other systems and or cannot complete the input in a timely manner leading to the event)
	Fatigue	Tired and became overworked (e.g., not at best for flight and became overworked and distracted, not responding to a caution alert.)
	Stress	♦ Physical—Any physically challenging factor such as heat, cold, noise, vibration, presence of something damaging to health. ♦ Psychological—such as emotional upset (e.g., due to bereavements, domestic problems) ♦ Reactive—such as events occurring in everyday life (e.g., working under time pressure, encountering unexpected situations)
Situational Awareness	Distractions	External stimuli that diverts flight crew attention from the task (e.g. people talking, addition noise/lights)
	Orientation	Lost (disorientated as to position during return to home) Confused (disorganized and loss of situational awareness)

The results of the HF Observations are integrated into the Lessons Learned (section 4).

3. Verification and Validation Results & Analysis

Table 5 above shows the results of the crew characterization. From the simulator evaluations involving seven ROs, two representative ROs were selected to be the ROs for flight test. The other ROs transitioned to support roles for flight test.

The following were done during both simulator and flight testing:

- NASA Task Load Index (TLX)
- Human Factors Observer Observations

- Interviews
- Task Load Analysis

3.1. Simulation Test Results

The m:N procedures and UAS were evaluated in a simulated environment from May 15, 2023, to May 19, 2023. The HF Simulator report provides the results of the human factors assessment of the performance of Remote Operators (ROs) of varied genders, ages, and aviation experience operating up to six UAs while also performing security surveillance monitoring in an HITL simulation setting. Fourteen different types of contingency events were injected into more than fifty simulated operations to determine if crew responses aligned with requirements and human factors mitigation plans.

The 7 ROs and 2 SUPs were able to constructively deal with the multiple contingency test cases with no potential safety issues observed.

The simulator testing:

- Confirmed the m:N automation and user interfaces were easy to use and provided the situational awareness needed for timely, correct RPIC responses
- Validated the task analysis output for the number of UAs that an RO is expected to successfully operate (1:6 in this project).
- Evaluated the UAS changes and m:N operational procedures prior to flight test
- Shown and enabled flight crew trust in the automation
- Provided baseline data for the test cases

Minor updates were implemented prior to flight test (see lessons learned).

3.2. Flight Test Results

Flight test was successfully held June 26-30, 2023 at the locations listed in section 2.6.5. The flight test cases in section 2.6.4 were flown and summarized in Table 7.

Table 7 – Flight Test Metrics

	Real UA	Sim. UA	Total UA
Scenarios	17	17	17
Flights	47	40	87
Flight hours	11	14	25

Flight test satisfied the objectives in section 2.6.2. In particular, the flight test confirmed safety of flight can be maintained for Remote Operators (ROs) operating up to six UAs (while also performing security surveillance monitoring) during BVLOS m:N operations when provided with a Level 3 UAS automation and a good human/machine interface.

The Flight test was especially challenging given the significant air traffic at NYUASTS's RME airport. Operating at an active airport resulted in multiple unplanned events, which increased the flight crew workload.

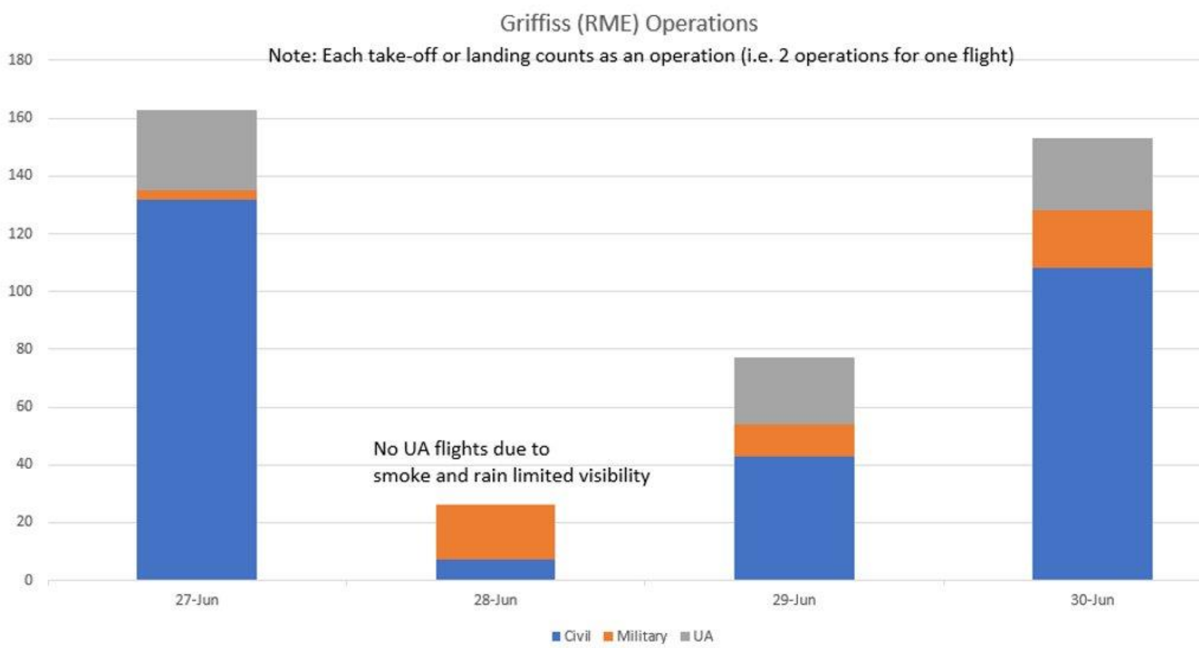

Figure 16 – RME Airport Operations During Flight Test

If the air traffic was detected before take-off, the flight was delayed which affected the planned sequencing of flight test aircraft. In-flight, the automation provided by on-UA ADS-B-in detection and on-UA avoidance provided the timely responses needed to mitigate the air risk associated with multiple manned aircraft approaching the operating areas (section 2.3.1.1).

Operational procedures mitigated the risk for the two uncooperative aircraft (1 military and 1 general aviation) that were in-bound to the airport. The on-site SP were effective at identifying the aircraft and communicating the approaching aircraft to the RO. The following sections outline the human factors test results.

3.2.1. NASA TLX Workload Survey Results

During the flight test, there were multiple unplanned events (e.g. airport traffic) that makes it difficult to compare the RO's perception of workload between the simulator and flight test.

Following the process outlined in section 2.7.2, this section gives the key results from the flight crew's completion of the NASA TLX Survey (Appendix A).

Box plots were used to represent workload scores and provide a holistic visual summary of how the workload scores are distributed and highlight the outliers to investigate further. Figure 17 shows the distribution of overall workload scores for all the crew members who participated in the flight test and reported their experience through the NASA TLX survey.

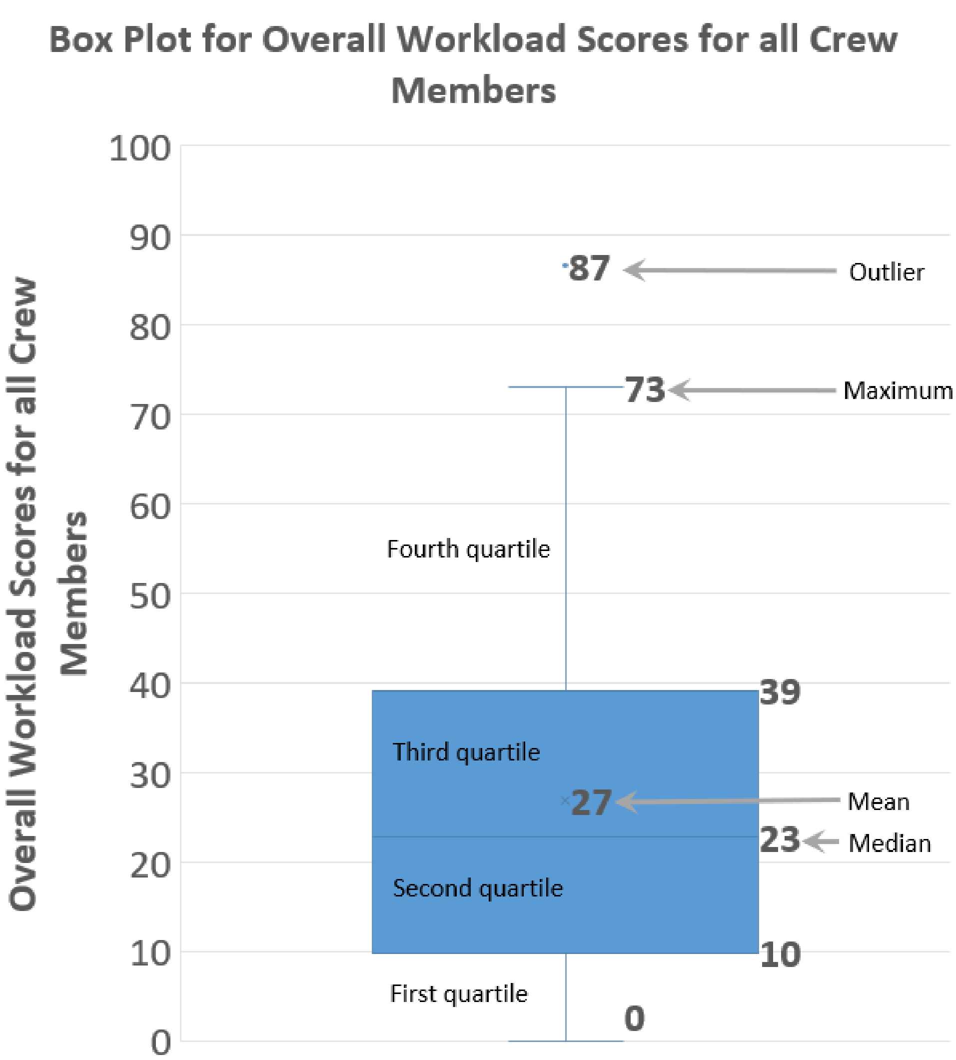

Figure 17 – TLX Workload Box Plot – all Crew Members

Figure 17 indicates that the overall workload scores for m:N operations conducted during the flight tests were relatively low. Upon investigation, the outlier involved operating 6 UAs along with multiple simultaneous, unplanned DAA alerts at 3 locations. The next highest scores were planned test cases for security/battery failure events and unplanned airport traffic.

Exercising CRM principles and transfer of control while managing multiple UAs are the key areas that suggest further standardization, training, and practice to minimize workload and ensure continued safe operation.

3.2.1.1 Remote Operators (RO) TLX Responses

Figure 18 shows the TLX data for the flight test ROs.

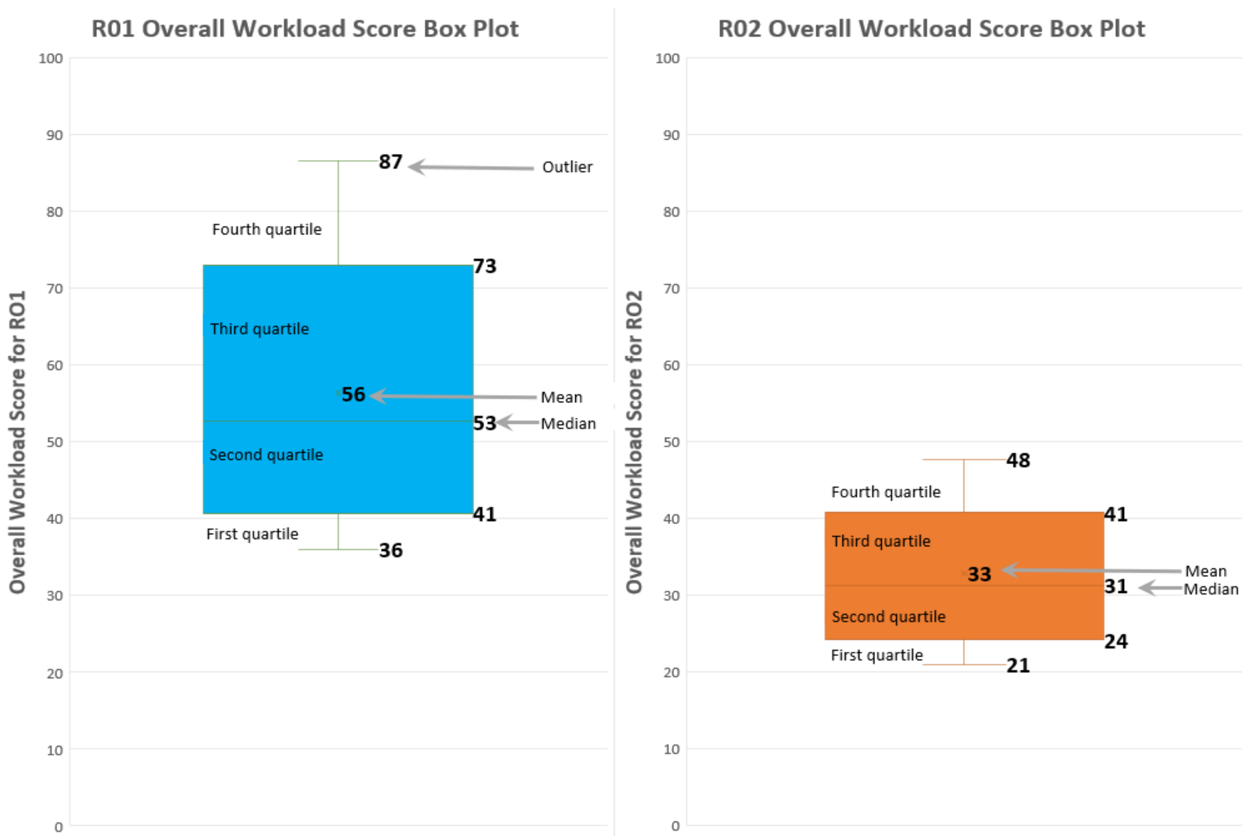

Figure 18 – TLX Workload Box Plot – RO 1 & 2

Average overall workload experienced by RO1 is observed to be more than RO2. RO1 has a comparatively lower competency and experience in video gaming with no military experience with UAS. RO2 on the other hand, has two years of military experience as a UAS operator and high level of video gaming competency and experience.

Figure 19 shows that RO1 experienced the highest overall workload for TC20 followed by TC18, and TC15 and TC6 (see 3.2.1 for the multiple unplanned events). RO2 experienced the highest overall workload in TC14, followed by TC20, and TC6; all three test cases had multiple unplanned events. Figure 20 - Figure 21 shows the influence of each NASA TLX factor on RO's overall workload score for different test cases.

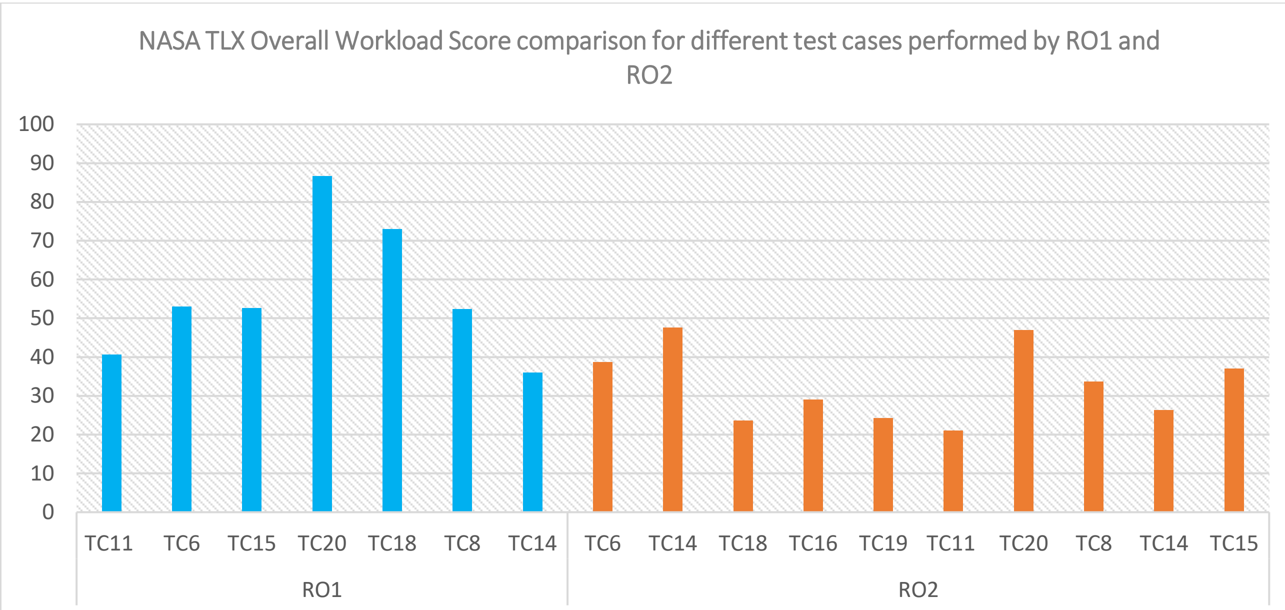

Figure 19 – RO 1 & 2 Workload by Test Case

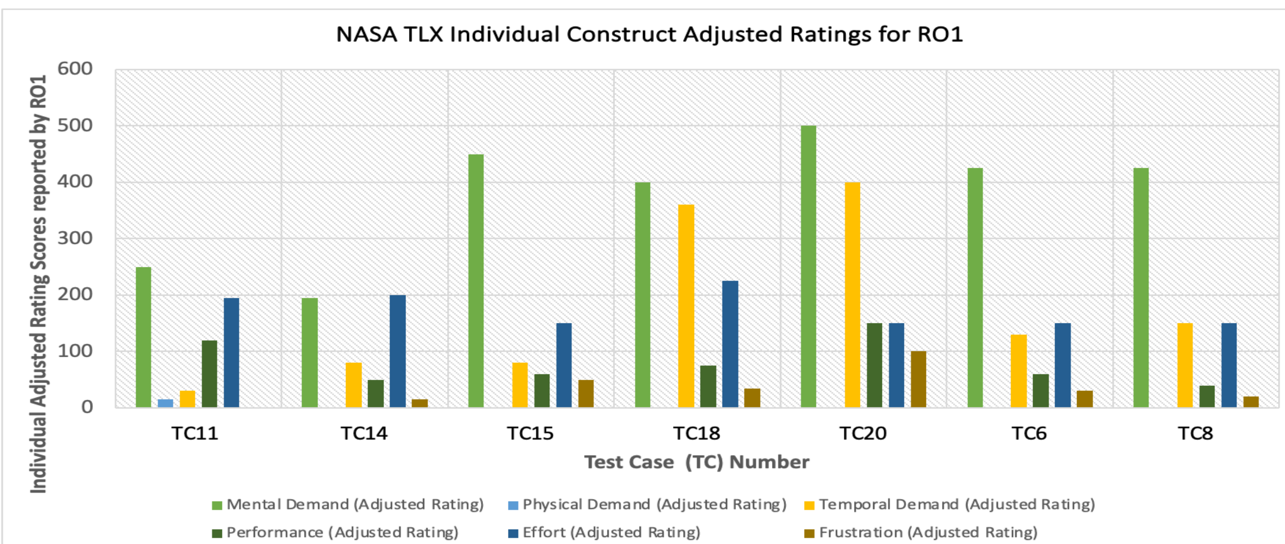

Figure 20 – R01 Workload per Test Case

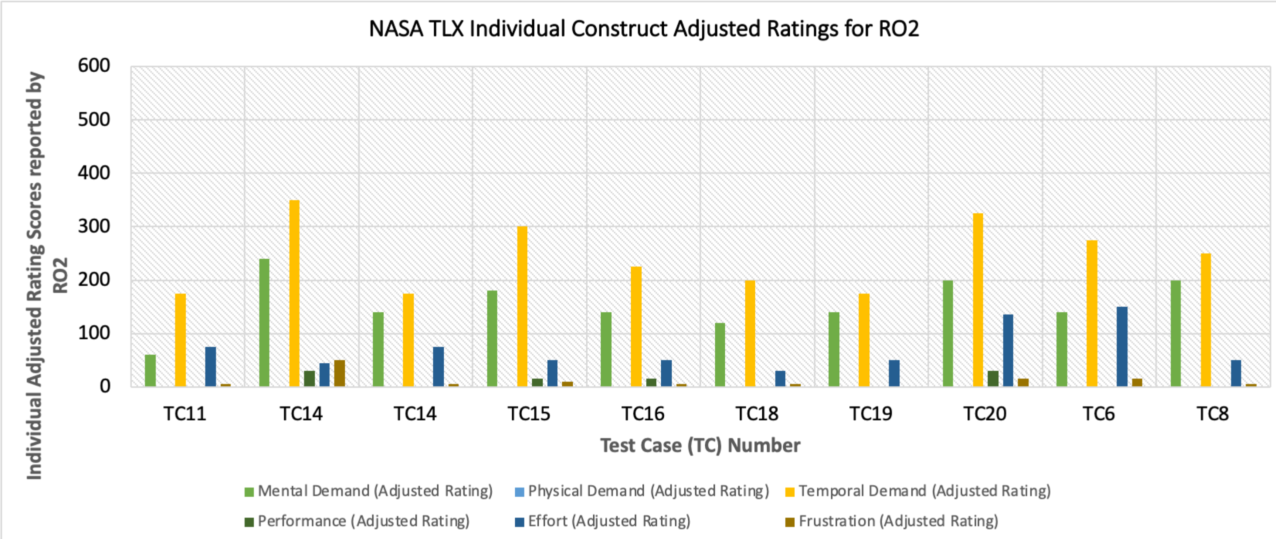

Figure 21 – R02 Workload per Test Case

The main contributors to the high overall workload for RO1 in all three test cases was the mental demand posed by the task with unplanned intruders. The main contributors to the overall workload for RO1 were Mental Demand, Temporal Demand, and Effort requirement for each task.

RO2 has relatively high video gaming experience of 10,000 hours. RO2 has reported his level of competence in video gaming as moderate. In flight certifications, RO2 has Part 107 with 2 years of military experience. During both the simulator runs and flight runs, RO2 played the role of a Remote Operator. RO2's age is below the average age of the flight test crew. RO2 reported temporal demand as the most contributing factor to the overall workload. The second highest factor that caused mental workload to RO2 (as reported by RO2) was the mental demand posed by each of the tasks.

To summarize, based on the plots, the main contributors to the overall workload for RO1 were Temporal Demand, Mental Demand and Effort requirement. RO2 has better self-assessed TLX performance scores and lower overall workload scores as compared with RO1 for all the test cases performed during the flight testing. This may be attributed to RO2's video gaming skills and experience, and their previous exposure to UAS as an operator in the military. RO1 may have faced a higher workload during flight test than RO2 due to 1) RO1 being a supervisor (and not an RO) during the simulator testing so less experience in the RO role 2) significantly less video game experience, and 3) no military experience. Both RO1 and RO2 experienced a higher overall mental workload for the test case involving handling of multiple UAs and CRM. Another observation that supports this relationship is the number of flight hours that RO1 and RO2 have with UA and BVLOS UA operations. Even though RO1 had a substantially higher number of flight hours recorded for experience with UAS operations (including DroneSentry and other operations) and BVLOS UAS operations, RO1 experienced a higher average overall workload and a higher mental demand than RO2.

3.2.1.2 Supervisor TLX Results

The following summarizes the supervisor specific TLX results.

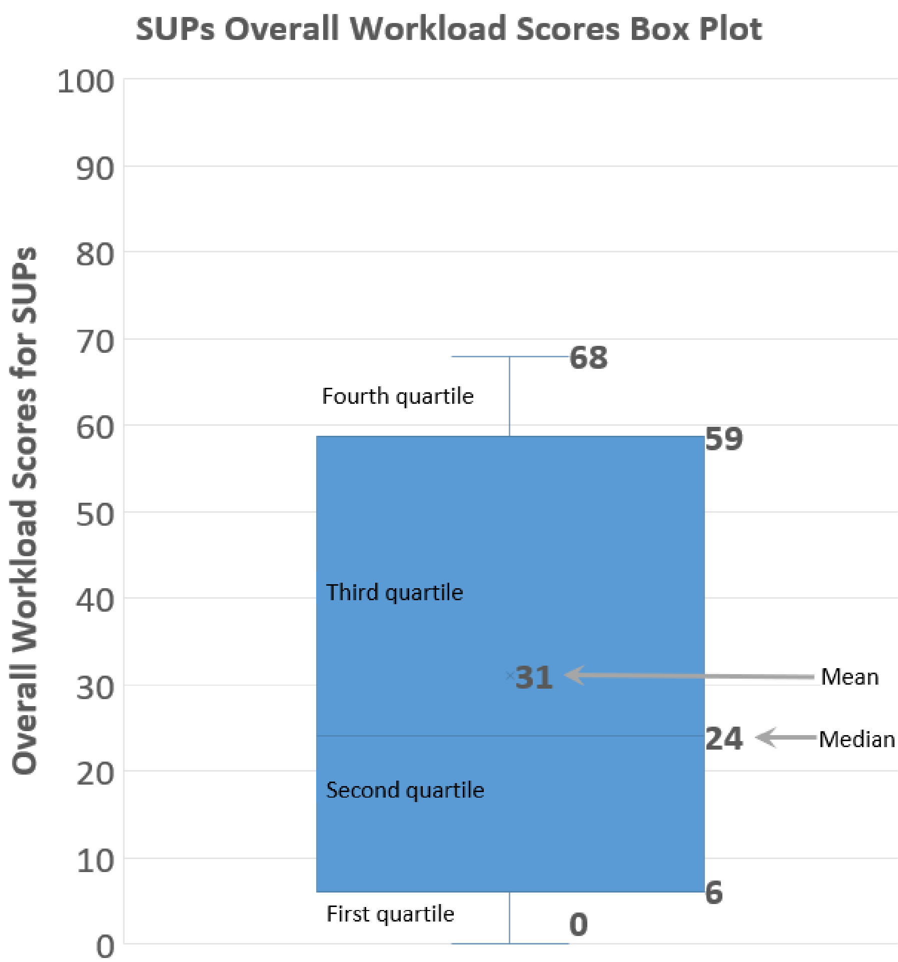

Figure 22 – TLX Workload Box Plot – Supervisor

SUP1 supported flights with both RO1 and RO2, while SUP2 only worked with RO2. Thus, the number of test cases performed by SUP1 and SUP2 differ drastically as seen in Figure 23. The higher workloads were experienced when unplanned air traffic approached the operating areas during the planned events.

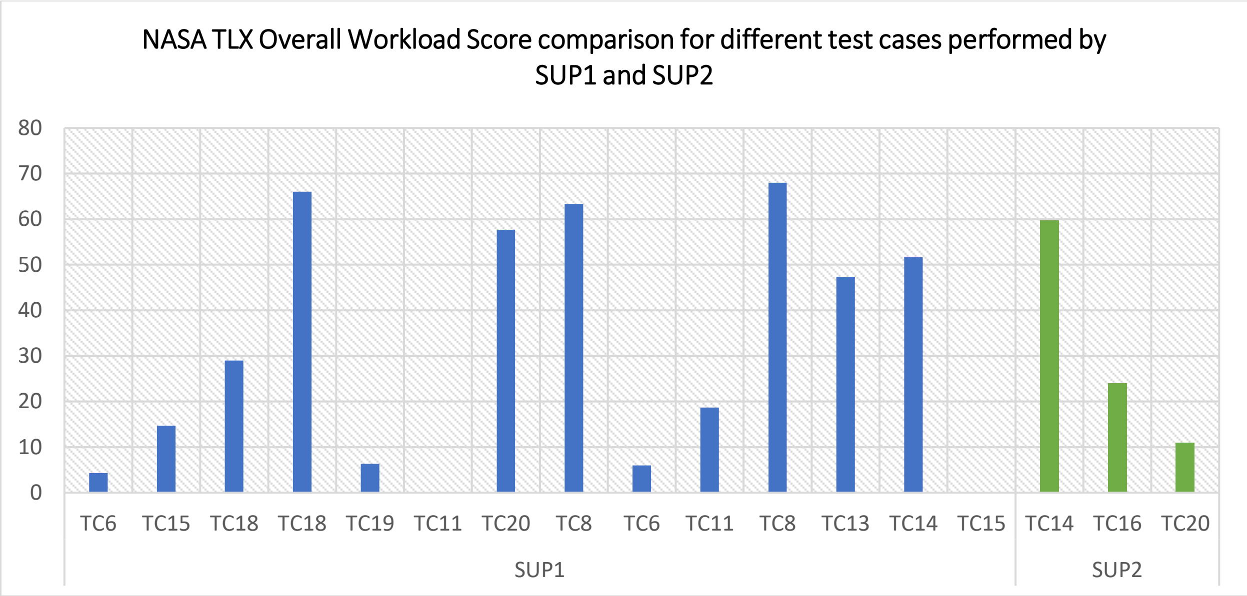

Figure 23 – Supervisor Workload Ratings

Figure 24 and Figure 25 show the different workload ratings for each of the supervisors. As noted earlier, SUP1 supported flights with both RO1 and RO2, while SUP2 only worked with RO2.

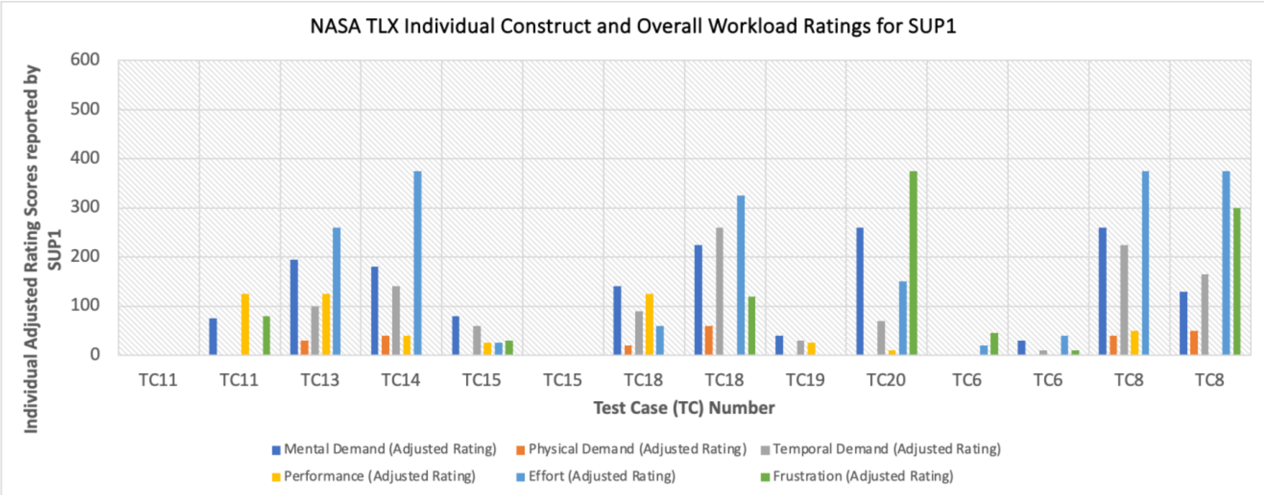

Figure 24 – SUP1 TLX workload rating

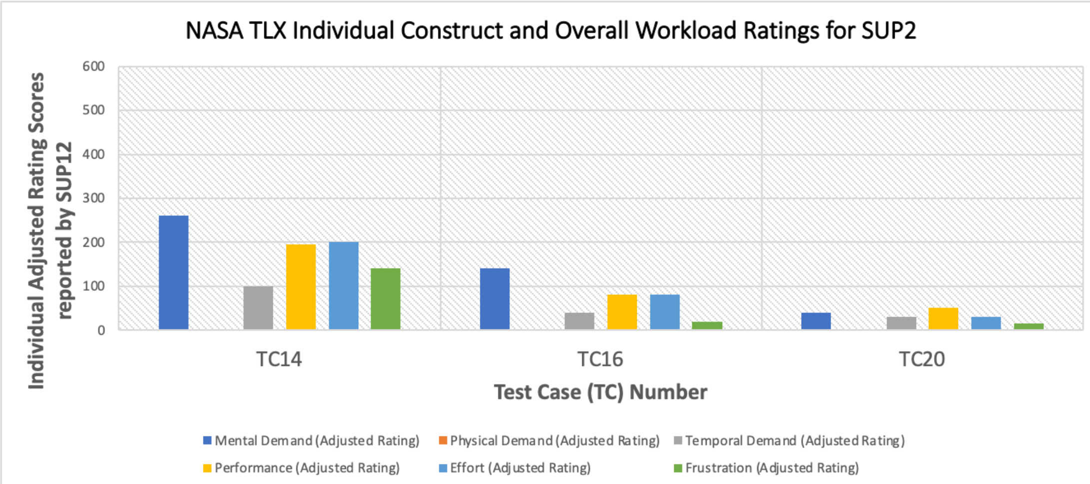

Figure 25 – SUP2 TLX workload rating

3.2.1.3 Safety Pilot TLX Ratings

Figure 26 below shows a comparison of overall mental workload experienced by the three on-site SPs. It should be noted that the Safety Pilots were required as part of the waiver for pre-flight checks and to act as visual observers at the Griffiss (RME) airport. They may not be needed for drone-in-a-box solutions with a technical DAA solution.

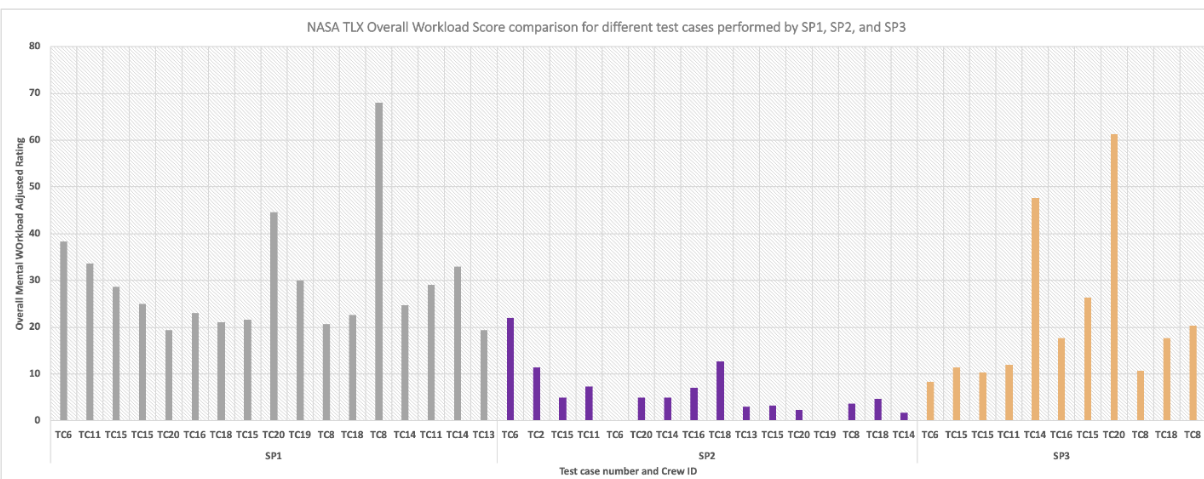

Figure 26 – On-site SP Workload Ratings

SP1 was observed to experience the highest average overall workload followed by SP3 and SP2. SP1 performed as an RO during the simulator runs and did not have any SP specific test case training before performing as an SP for the flight test runs, as well as dealing with multiple simultaneous unplanned activities occurring at the Griffiss airport. This may have been the reason for SP1's higher overall mental workload than SP3 and SP2. SP2 on the other hand, had performed as an RO during the simulator runs and has significantly contributed to training the entire flight crew for simulator and flight operations. SP1 experienced the highest overall mental workload during test cases TC8 followed by TC20, and TC6. SP3 experienced the highest overall mental workload for test cases TC20, which experienced unplanned intruding aircraft.

3.2.1.4 TLX Workload Ratings Conclusion

Overall workload scores obtained for the flight test crew members suggest that the scores are relatively low when compared to other human factors tests. One TLX researcher has noted that a limitation of NASA TLX is that there is no demonstrated way of interpreting the overall workload scores (Hart, 2006). In a 2015 study presented by Grier, the author conducted a meta-analysis of over 1000 global NASA TLX scores from over 200 publications (Grier, 2015). In their study, the workload scores from different publications were categorized into different task types such as Air Traffic Control, Command & Control, Mechanical Tasks, Navigation Tasks, etc. For each task category, descriptive statistics of the overall workload score data were computed and presented in the study. For this paper, we found that the values for the descriptive statistics of overall workload score for m:N UAS flight operations are lower than the values of the descriptive statistics presented in Grier, 2015 for the Air Traffic Control, Pilot Aircraft, Robot Operations, and Video Game tasks. The table below is based on the tabular data presented in Grier, 2015. The last row in the following table represents the values for descriptive statistics of overall workload score as computed from the scores that m:N BVLOS UAS flight test crew reported in the NASA TLX survey post every flight test case.

Table 8 – Comparison Across Studies of Workload Descriptive Statistics

Task	Task Description	Minimum value	25%	50%	75%	Maximum value
Grier, 2015 Workload assessment						
Air Traffic Control	Real or simulated monitoring and maintenance of safe air space	6.21	42.81	52.44	68.32	85.00
Pilot Aircraft	Real or simulated control and operation of airplanes/helicopters	16.00	37.70	47.78	54.80	74.00
Robot Operation	Real or simulated control of unmanned system	9.59	41.00	56.00	63.00	80.00
Video Game	Tetris™, M-SWAP, etc...	14.08	48.23	56.50	63.72	78.00
Anzen Unmanned for FAA m:N BVLOS operations (this report)						
m:N BVLOS	Piloting multiple UAS beyond visual line of sight	0.00	10.00	23.00	39.00	73.00 (see Note)

Note: section 3.3 describes 3 simultaneous intruding aircraft a different locations which caused outlier score of 87.

3.2.2. Interviews and Observations Results

As mentioned in 2.7.5, the flight crew feedback from the post scenario interviews and HF Observations was categorized. The insights gained from the flight crew were recorded and transcribed into a written format. The interview transcriptions were then analyzed in NVivo using qualitative coding to identify broad themes characterizing the crew experience of m:N BVLOS UAS operations. Through qualitative analysis of the interview data, a detailed understanding of what went wrong and what went right is gained and presented in the form of a hierarchical tree map. The hierarchical tree map consists of nested rectangles. with the size of each rectangle representing the significance of that theme relative to other themes.

Figure 27 shows a hierarchical tree chart for the challenges and issues that were faced by the crew members during flight testing. A variety of perspectives were expressed during the post operations interviews which pointed toward some common themes of issues that the crew members faced during the flight testing.

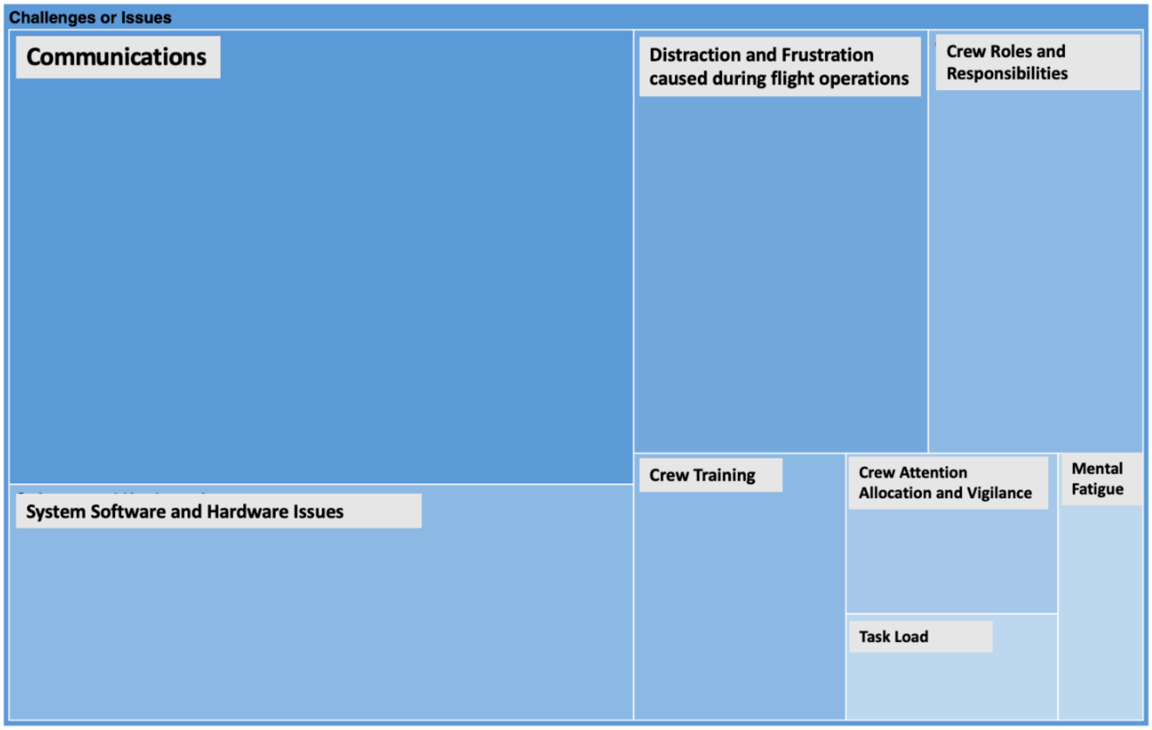

Figure 27 – Challenges & Issues Hierarchical Tree Map

Table 9 summarizes the issue categories that were experienced by the crew members during the flight tests. These categories are listed in the order of significance to the crew members. For example, communication related challenges and issues were the most common challenges that the crew members faced during the flight test. The qualitative summary of each category is covered in the lessons learned sections below.

Table 9 – Human Factors Themes

Rank	Area	Lessons Learned
1	Communications	4.2.1
2	Distraction & Frustration	4.2.2
3	Crew Attention Allocation & Vigilance	4.2.4
4	Crew Roles & Responsibilities	4.2.5
5	Software & Hardware	4.1
6	Crew Training	4.2.6
7	Mental Fatigue	4.2.2
8	Qualitative Task Load	3.2.3

During the post operations interview, the crew members discussed positive aspects of the flight test in addition to areas that need further research and improvement. Using qualitative coding for analyzing the interview transcription data, a set of positive takeaways from the flight test were identified. These positive aspects span over three main categories or themes – Crew Behavior, System Software and Hardware, and Communications and Procedures. Figure 28 shows the hierarchy tree map generated using NVivo as a result of the qualitative data analysis.

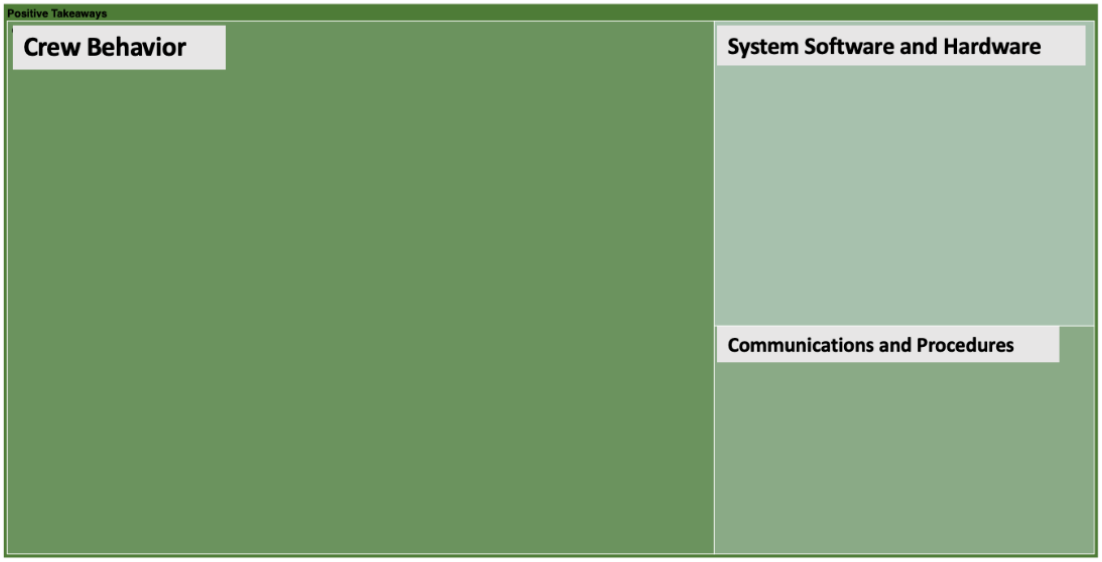

Figure 28 – Positive Aspects of m:N BVLOS Flight Test

Below is additional information on the flight crew's positive feedback:

Crew behavior

- The crew felt they could show even better performance with increased simulator training.
- Crew had full trust in automation that developed over time with increasing exposure to system operation in different nominal and off-nominal scenarios.
- SUP felt that they can allocate more attention to surveillance function performance than the RO could. This is because given the responsibilities that the SUP was assigned to, the SUP had more cognitive resources available to conduct surveillance.

Software and Hardware

- Crew felt that the automation level 3 was adequate to perform m:N BVLOS operations
- Controls and displays were easy to understand and use
- Alerts helped SUP to gain situational awareness while doing their supervisory tasks
- Simulator runs were able to replicate flight test runs to a significant extent, providing confidence in the crew members to exhibit desired performance during flight testing.

Overlapping communication is not a problem if handshake between the crew members is performed uniformly and timely (or where an on-site SP is not needed)

Shared situational awareness helped crew members in decision-making. Visual sensory cues were available to the SP helped them gain situational awareness. Further, in the absence of any other airspace surveillance sensor, the SPs helped the ROs in gaining and maintaining the required situational awareness about present and upcoming air traffic because the SPs were in direct contact with the SP Liaison who were in contact with the airport ATC.

3.2.3. Qualitative Task Load

The tasks for flight test runs were planned in a way to understand crew mental workload levels when performing those tasks. The task demands posed by the tasks on the crew members affect their mental workload levels and consequently their performance levels. De Waard (De Waard, 1996) presented the relationship between workload and performance using six theoretical regions of task demands:

- D for deactivation - the operator's state is affected
- A2 performance is optimal, the operator can easily cope with the task requirements and reach a (self-set) adequate level of performance
- A1 and A3 performance remains unaffected but the operator has to exert effort to preserve an undisturbed performance level
- B this is no longer possible and performance declines
- C performance is at a minimum level: the operator is overloaded

Figure 29 shows that performance tends to degrade in case of too little or too much task demands. The performance levels are optimal when the task demands are optimal.

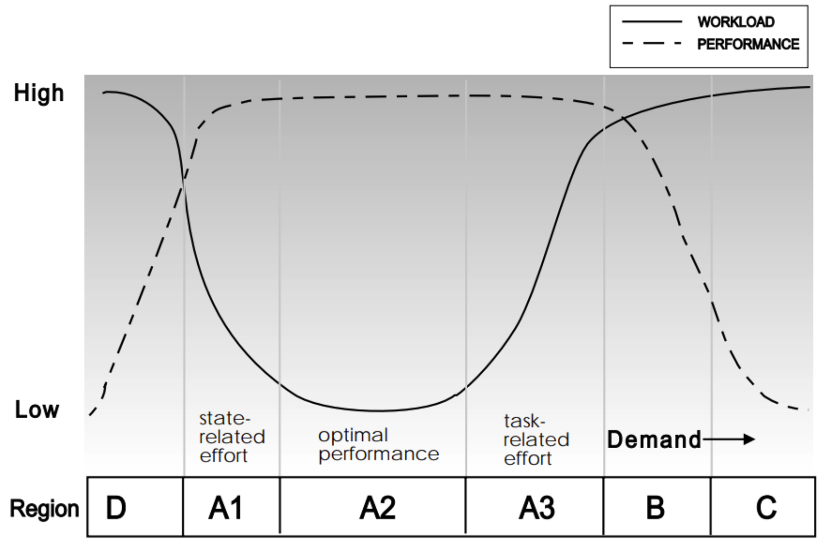

Figure 29 – Workload and performance in 6 regions (De Waard, 1996)

For different instances, the SUP and SP both mentioned that there were occasions when they experienced boredom. Due to the low task demands for most of the time during the flight test, the SUP was observed to become complacent in their role resulting in higher reaction time when there was an occurrence of an off-nominal situation. Note, no such performance degradation was observed for the SP. In a work presented by (Devlin et al., 2020), it was observed that transitions in workload result in a better reaction time and accuracy in comparison when the workload is constant. Considering the effect of task demands on the crew performance and attitude, it is essential to develop and assign tasks in a way that keeps the crew engaged throughout the operation to avoid being in the region D, B, and C as shown in Figure 29.

3.3. Flight Test Task Analysis Results

The safety assessment and subsequent task analysis outlined in section 2.5 and in Au-REP-0031 (“Human Factors Simulator Report for Piloting Multiple, Simultaneous UAS BVLOS”) identified a set of flight modes, tasks, and their associated characteristics necessary for safe m:N operations. The m:N safety requirements related to RO task execution time (vs. user interface or system capabilities) that mitigate safety risks for m:N operations are related to contingency operations, and most specifically avoidance of other aircraft (Intruder Avoidance and Lost Link). The set of these tasks is shown in Table 10.

Table 10 – Contingency Tasks

Mode	Task ID	Task	Type	Responsible	Duration (D) seconds	Required Period (P) seconds	Scheduling Period (S) seconds	Deadline (L) seconds	Expected Duration (s)	Sync Constraint
Intruder Avoidance	IA1	Process intruder alert	Aperiodic	RPIC	5					
Intruder Avoidance	IA2	Initiate transition to Descent mode	Aperiodic	RPIC	2					
Intruder Avoidance	IA3	Transition to Descent Mode	Aperiodic	RPIC	2					
Intruder Avoidance	IA4	Monitor descent to safe altitude	Periodic	RPIC	2	10	10	15	22	
Intruder Avoidance	IA5	Initiate hold at safe altitude	Aperiodic	RPIC	2					
Intruder Avoidance	IA6	Monitor safe altitude hold until intruder clear	Periodic	RPIC	2	10	10	15	104	
Intruder Avoidance	IA7	Initiate transition to resume mode	Aperiodic	RPIC	2					
Intruder Avoidance	IA8	Monitor climb to operational altitude	Periodic	RPIC	2	10	10	15	30	
Automatic Parachute Landing	AP1	RPIC observes deployment	Aperiodic	RPIC	3					
Automatic Parachute Landing	AP2	RPIC monitors descent to landing	Periodic	RPIC	2	10	10	15	22	
Automatic Parachute Landing	AP3	SP monitors descent to landing	Aperiodic	SP	22					
Automatic Parachute Landing	AP4	RPIC reports parachute landing location	Aperiodic	RPIC	4					
Manual Parachute Landing	MP1	RPIC states intentions and triggers deployment	Aperiodic	RPIC	2					
Manual Parachute Landing	MP2	SP confirms parachute deployment	Aperiodic	SP	2					MP3
Manual Parachute Landing	MP3	RPIC receives parachute deployment confirmation	Aperiodic	RPIC	2					MP2
Manual Parachute Landing	MP4	RPIC monitors descent to landing	Periodic	RPIC	2	10	10	15	22	
Manual Parachute Landing	MP5	SP monitors descent to landing	Aperiodic	SP	22					
Manual Parachute Landing	MP6	RPIC reports parachute landing location	Aperiodic	RPIC	4					
Lost Link	LL1	Command UA to "brake"	Aperiodic	RPIC	2					
Lost Link	LL2	Triage issue	Aperiodic	RPIC	5					

Non-contingency (i.e., normal operations) timelines were constructed as described in the Human Factors Simulator Report and verified by team members. Contingency operations task timelines were then inserted into the non-contingency timelines to define expected behavior of both the crew and the system during contingency operations. The flight test cases defined in section 2.6.2 define the contingency operations tested as part of the flight test cases. For these contingency operations, task timelines were developed to identify the expected task loading on operators and then those timelines were compared against flight test observations.

Flight test results for this test case were analyzed and compared with the modeled task timeline. Of interest for MN_TC_20, the flight test results for the DAA contingency responses show that while the task durations, periods, and deadlines were developed to account for both automated ADS-B based DAA and human monitored/initiated DAA, the flight test data showed that both the initial ADS-B based DAA and the human monitored/initiated DAA performed much better than the task timeline model. Better performance in the first DAA response is attributed to the automated response, while better performance in the second (human monitored/initiated) response is attributed to having the RO prepared for the warning by first having a caution to raise attention to the potential need for action.

A summary of the flight test contingency events, their expected maximum duration per the timeline model, and the observed values during flight test are shown in Table 11.

Table 11 – Safety Contingency Events – Flight Test Summarized Data –

Event	Model (seconds)	Flight Test			
		Number of Events	Average (sec.)	Min (sec.)	Max (sec.)
DAA alert - DAA avoid mode	9	10	3.9	0.3	24.7 Note 1
DAA avoid mode - DAA maneuver complete	24	8	19.6	16.8	22.6
Loss of C2 - RTL	7	2	28.2	6.9	49.4 Note 2
Low Battery Alert - RTL	2	2	1.1	0.4	1.7
Loss of radar surveillance - RTL	9	1	6.5	6.5	6.5

Note 1: Max outlier due to 3 simultaneous aircraft detections (project assumed non-airport locations with only 2 simultaneous intruders)
Note 2: Max outlier due to lack of clarity in recording

There were two cases where modeled safety thresholds were not met:

- MN_TC_11: The quantification of loss of C2 to RTL was challenging given the method used to establish the timeline and the nature of loss of C2 (i.e., RTL could not be directly observed by the GCS due to loss of C2). The timeline was measured by verbal exchange between the RO and on-site SP. In one instance of MN_TC_11, the verbal exchanges confirmed the RTL was within the analysis threshold; however for another instance, the RO was engaged in a message exchange with another SP so verbal confirmation of when the UA actually transitioned to RTL was uncertain.

- MN_TC_20: The instance of MN_TC_20 where the time from annunciation of a DAA warning until the RO activated DAA avoidance mode exceeded the analysis threshold occurred in a context where two other DAA actions were already in progress – one which was expected as part of the test case, and another due to an overly conservative alerting threshold configured for a UA. The combination of the added cognitive load of two simultaneous DAA contingencies already in progress, with the nature of one of the two being an unexpected alerting threshold that resulted in an unexpected situational display causing additional cognitive burden, manifested in a response timeline that exceeded the defined threshold. Observations:
    - The previous analysis that determined the 1:6 m:N ratio assumed that the likelihood of more than two locations having simultaneous DAA events is extremely remote, and therefore test cases were constructed to only address two simultaneous DAA events at different sites. In effect, this exceedance of the threshold confirmed that the addition of a third simultaneous DAA event exceeded the operator workload capacity. Unlike the airport flight tests locations, the original assumption is expected to hold true (i.e., that 3 or more simultaneous DAA events is extremely remote given geographically separated operating areas). The location checklist includes confirmation that operations are at least 5 miles from airports.
    - The hazard analysis addresses hazards associated with configuration parameters and operators are expected to have tested those parameters in an operationally representative environment. The testing of the newly modified m:N automated interfaces, in this case, did not identify the potential of creating a higher load of DAA events than expected.
    - The testing environment for two of the six sites was at an active airport with a likelihood of intruding aircraft much higher than would be expected in a representative operational environment.

It should be noted that, while there were two test cases that exceeded the modeled m:N thresholds, no actual safety events resulted. Well Clear was maintained with a significant margin.

The RO response timing validates the design of the ROC automation and human/machine interface.

4. Lessons Learned

This section summarizes the key lessons learned during the project. The full list is contained in Appendix C.

Section 5 has the recommended approach for developing, integrating, verifying, and validating application of these lessons learned that should be embedded in industry standards and used by other operators.

4.1. Human/Machine Interface

4.1.1. Display

The display design philosophy and implementation were based on successful cockpit designs used for crewed aircraft. The location of the safety critical dynamic data displays (altitude, location, flight mode, attitude, and video feed) used eye reference points based on the location of the attitude directional and heading indicators in a crewed aircraft. The more static data displays associated with weather data and DAA, located above the dynamic displays, were accessible in a location that provided the RO and SUP critical and timely safety data when applicable. The display configurations, based on accepted aircraft display design standards and adopted by Asylon for all UAS operations, provided an ergonomic visual, aural, and tactile platform that supported safe operations in a m:N BVLOS operation. It was noted that the ROs and SUPs had no negative comments associated with their level of comfort or ergonomic display designs during the simulator and flight test scenarios.

As the SUP may be supervising multiple RO and may need to respond quickly to events, it is important that the SUP can see the necessary display and alerts promptly. Additional automation is recommended to speed up the start-up and transition of multiple screens. This resulted in additional requirements:

A-3997	The ROC_Supervisor shall be able to see the safety related displays of a RPIC within 5 seconds.
A-3922	Regardless of control status, the ROC_Supervisor shall be able to hear the aural warnings for an RO within 5 seconds.
A-3924	Regardless of control status, the ROC_Supervisor shall be able to verbally communicate with an RO and the SPs (if used) within 5 seconds.

4.1.2. Electronic Display Information Elements and Features

One crew member stated the weather information used to identify weather hazards could be improved. The weather display took up a quarter of the display space per UA (weather data is critical when there is approaching convective weather). However, the weather display did not include ceiling and visibility data, both of which were factors during the flight testing. During flight test, the on-site SPs reported weather, which effectively mitigated risks associated with weather hazards. To better capture macro and micro weather during off-airport BVLOS operations without input from an on-site crew member, the following should be considered to improve weather situational awareness:

- Enhance the training on adjusting the range of the weather radar display to maintain the weather specific situational awareness needed to evaluate and mitigate risks associated with macro-weather hazards.
- Provide distance and intensity scales on the weather radar display to determine the distance and rain intensity of approaching weather from the UAS operations area (UOA)
- Clearly identify the UOA, intended flight path, and crew base on the weather map (and not just the operational area map)
- Provide links to access current
    - Meteorological Aerodrome Reports (METARs)
    - Terminal Aerodrome Forecasts (TAFs)
- Based on the UAS performance specifications and operational requirements, provide the RO with hourly forecast weather that displays low, medium, and high-risk forecast weather hazards (and not just current):
    - Chance of Precipitation
    - Ceiling Height
    - Surface Visibility
    - Winds Aloft (at or near operating altitudes)
    - Surface Temperatures
    - Density Altitude
    - Geomagnetic Activity (KP-index)
- If operating in areas susceptible to localized micro weather hazards or when accurate real-time weather data is required to maximize operational efficiency, ROs may require weather data inputs from a local ground weather station and/or sensors attached to the UA to detect and mitigate the risks associated with localized turbulence, extreme temperature variations, and localized surface and winds aloft.
- Residual standard deviations may be integrated into weather models to enhance weather related safety risk controls associated with micro weather environments.

4.1.3. Alerting

This section addresses both the aural and visual altering designs adopted as safety risk controls to mitigate risks associated with non-normal conditions and operational events requiring crew awareness. The use of color in display design is an essential safety risk control for coding visual information. The project implemented requirements derived from the FAA Human Factors guidelines for the color, priority, and prominence for the warnings and alerts (section 2.3.2.4).

An opportunity for improvement, based on numerous comments, was related to the frequency of aural alerts during m:N operations. The aural alerts were activated during the pre-launch and post-launch checks, which were not related to an actual triggering event. In the m:N operations, the alerts frequently occurred during nominal operations for the other UAs operating in various phases of flight. In addition, the RO and SUP were unable, by design, to silence alerts associated with a DAA event. This design was intended to ensure the RO continues to track the target aircraft until it is safe to continue the flight. The constant activation of aural alerts was a distraction with an unintended consequence of desensitizing ROs when there is an alert related to an actual triggering event.

As a result, after the flight test, several additional requirements were added.

A-7023	The RPIC shall be able to acknowledge aural cautions and warnings, which results in the current aural alerts being muted.
A-7024	New caution or warning alerts shall result in unmuted aural alerts.
A-7025	Warning_Alerts shall have priority over cautions.
A-7026	Aural alerts shall be easily deactivated (but not easily deactivated inadvertently).

Other aural alert recommendations include:

- Determine if additional automation is viable to eliminate some of the nominal pre/post-flight aural alerts. Note, the confirmation of appropriate alert volume during pre-flight should not be eliminated.
- During training, improve the RO understanding of the different aural alerts.
- Ensure aural alerts are obvious but not overpowering.

4.1.4. Organizing Electronic Display Information Elements

Acquiring and maintaining situational awareness requires timely analysis and understanding of both dynamic and static information. In an m:N BVLOS environment, as number of aircraft increase the quality and location of the data are critical to:

- Maintain situational awareness, i.e., safety of flight of each UA.
- Maintain situational awareness – the location and environment.
- Maintain situational awareness related to mission requirements.
- Manage nominal and off-nominal checklists.
- Think ahead based on projected states or environments.
- Make accurate risk assessments.

The location of critical data elements depends on the UAS, crew composition, level of automation, and mission requirements. However, it is essential to arrange the dynamic and static data displays to minimize complexity, workload, and stress for the crew to maintain situational awareness during nominal and non-nominal operations.

During the simulation tests, the ROs found it challenging to keep track of the identity/name of the UA, SP, and area of operations due to the data being displayed on the top display screen. As a result of the feedback, this information was moved to make the information more accessible for flight tests. The feedback from the crews was that locating this information to a more central location improved the ability to identify and use the information in support of the operation.

The flight status indicator provides the RO and SUP with the phase of flight information. On a few occasions the RO missed the "RTL" transition and failed to resume the operation when the UA was in "Guided" mode. A more prominent display of the phase of flight may be an opportunity to improve situational awareness.

The phase of flight indicator continued to provide an "RTL" indication with a flashing background after the UA landed and was secure. For non-operating UAs, non-operational distractions should be eliminated to decrease the burden placed on the flight crew.

The location of critical data elements will depend on the on the UAS, the crew composition, the level of automation, and the mission requirements; however, it is essential to arrange dynamic and static data displays to minimize complexity, workload, and stress for the crew to maintain situational awareness during nominal and off-nominal operations.

4.1.5. Error Management, Prevention, Detection, and Recovery

The automated DAA function was effective at mitigating air risk; however, the following changes should be considered to improve situational awareness:

- Ensure the automated DAA descent function is aligned with the visual caution and aural warning alert function on the displays. Note, observed misalignments were due to an ArduPilot parameter setting that was inconsistent with the needed DAA caution thresholds.
- Enhance the visual alert functions when there is an automated change in a phase of flight associated with a DAA or a required manual input to resume the flight plan once the DAA is no longer a threat.
- Standardize communication procedures between the RO and SP when going into "avoid" mode to identify the threat and best determine when it is safe to continue the mission.

4.2. Crew Resource Management (CRM)

The concept of CRM, designed to enhance crew coordination and teamwork, grew primarily from two aircraft accidents, the 1977 Tenerife airport accident, in which two Boeing 747 aircraft collided on the runway, killing 583 people. The birth of CRM is also associated with a United DC-8 fatal accident that occurred in 1978. The DC-8 accident was the result of the captain, distracted by an issue with the landing gear, failing to properly monitor the aircraft fuel status and to respond to the crewmember advisories regarding the fuel status. The aircraft ran out of fuel and forced to land in a suburban neighborhood, resulting in 10 fatalities.

After the United accident, NASA sponsored a workshop to mitigate risks associated with communication failures and interpersonal relationships. In 1981, United was the first U.S. airline to launch a CRM program. CRM is now a global standard for commercial crewed aviation.

Like operating a complex crewed aircraft, CRM is applicable to complex multi-crewed m:N BVLOS UAS operations. Complex UAS operations require communication, situational awareness, leadership, and followership skills to optimize decision-making based on the effective use of all available resources.

CRM skills were required to enhance crew coordination and teamwork to successfully and safely operate in the complex UAS m:N BVLOS flight test environment.

The following subsection describes how each of the CRM aspects were evaluated. Subsequent subsections go over the results and recommendations for the following CRM elements:

- Safety Management System (SMS)
- Operational Procedures
- Roles and Responsibilities
- Training
- Fatigue Management
- Communications

In a multi-crewed operation, CRM is a function of accurate and correct communications associated with crew tasks and responsibilities, all within the context of changing nominal and off-nominal operations. Maintaining an effective CRM training program is essential for crewmembers to effectively monitor and be aware of the safety priorities within a complex multicrew operational environment.

4.2.1. Communications

Human factors refer to the study of how humans interact with systems, products, and environments. It encompasses various aspects of human cognition, behavior, physical capabilities, and limitations. Communications, within the context of human factors, involves the exchange of information, ideas, and emotions between individuals or groups. In the HF study, we assessed the communications system design, interfaces, and technologies involving verbal communications between the various crew members in terms of clarity, accuracy, timeliness, and accuracy; all essential components needed to convey understanding.

Like the relationship between a pilot and air traffic control in the crewed environment, communications in a m:N BVLOS operation is critical to the safety of the overall operation. Without the benefit of visual cues, in the context of the m:N BVLOS flight test scenarios, the RO was required to communicate with up to six SPs to run checklists, clear for traffic, and maintain situational awareness during an intense 45-minute window.

4.2.1.1 Communications Technology

The crew communications system operated using Google Meet via an internet connection with a backup Google Meet room preset on mobile telephone via LTE in the event of internet failure. The successful transfer to the telephone breakout room was observed during the test case for ROC internet failure. All the ROs, SUP, and SPs were able to continue seamless communications. The system also allowed for breakout rooms to support one-on-one communications between the ROC and an individual SP when needed to support unplanned contingency operations, which was observed during a security event test case. In one test case involving a security operation, the RO elected to transfer the UA to the SUP. With a positive transfer, the SUP was able to assume responsibility for the UA, establish communications with the individual SP in a separate Google Meet room, and support the safe operation while performing security operations. The RO was able to focus attention on operating the remaining 5 UAs.

In terms of opportunities for improvement, when the SUP went into a separate Google Meet room with the SP at one site, the system did not allow the SUP to reenter the backup Google Meet breakout room when combined with a planned ROC internet failure. The RO was observed establishing communications with all the SPs. With the SUP just a few feet away from the RO, the continuity in communications with all crewmembers was maintained. However, to enhance continuity, it would be ideal if the SUP and the on-site SP were able to reenter the common chat room. The following requirement was added:

A-3924	Regardless of control status, the ROC_Supervisor shall be able to verbally communicate with an RO and the SPs (if used) within 5 seconds.

The system supported seamless communications with the RO, SUP and SPs all communicating via an open line using Google Meet. The mute function is needed to eliminate interference associated with background noise from having SPs at multiple locations. The SPs would mute their line when not in use with the SUP and RO remaining on a hot mic. Though waivers may require hands-free duplex communications, in m:N situations with multiple crewmembers, the RO should always be able to communicate with all crewmembers, but the SPs should have push to talk communications that are muted when not active.

Google Meet was used as the communications medium for the simulation and flight test. It worked and was effective throughout the various test cases; however, there may be alternative communication systems that would improve communication procedures associated with breakrooms and contingency operations. This is an area that would require additional evaluation.

Also, communications requirements are dependent on crew complexity and mission requirements. During complex UAS operations, the verbal communications systems should be assessed/designed to minimize the workload and stress during nominal and non-nominal operations.

4.2.1.2 Flight Crew Communications:

The aviation industry operates in a fast-paced environment. To enhance safety during commercial crewed aircraft operation, the FAA established safety risk controls (Federal Aviation Regulation 14 CFR part 121.542 and 135.100) to limit the crew to only those duties required for the safe operation of the aircraft during critical phases of flight below 10,000 feet. One-to-many (m:N) BVLOS operations are intense, requiring the entire crew to maintain communications situational awareness. Though the sterile cockpit rule does not apply to Part 107 operations, the rule was adopted and enforced. Sterile cockpit is a safety requirement for the m:N BVLOS operation between the time that the system is activated with the purpose of flight and the time that the system is deactivated at the conclusion of the mission.

Communications between the RO and each SP were disciplined and professional, which was essential for the m:N flight test operations. As a result of the simulations, checklists were streamlined with the removal of nonessential items, such as the RO stating repeated battery voltage readings on each UA.

The use of aviation terminology was an essential aspect of the operation to ensure effective communications (FAA Order 7110.65). With 8 crew members involved in an m:N BVLOS operation (RO, SUP, and up to 6 SPs) with 2 of the UAs operating at an active airport, clear and precise communications were conveyed and understood by direct and active SPs crew members listening to the flow of communications. By adhering to standards, information was accurately conveyed, which minimized errors and misunderstandings that may contribute to a safety event.

The flight crew mostly used standard terminology with some added phrases, which were understood by all parties. Non-standard terminology usually occurred during periods of increased stress. Terse and correct communications are ideal; however, non-standard communication caused some momentary confusion and/or blocked communications. The breakdowns, associated with more complex scenarios, were the exception, with all parties regaining communication situational awareness within seconds.

When communicating without visual cues in a multi-crew operation, communication situational awareness applies to all crew members. Communications discipline and protocols are essential in an m:N BVLOS environment. If understanding is the key to communications, following procedures, establishing connections on initial contact, and using proper terminology are the tools needed to convey understanding that is both terse and correct. The bottom line - good phraseology enhances safety. Asylon (and all operators) should determine if some of the vocabulary noted in flight test should be standardized and added to the SOP and training.

4.2.2. Fatigue

Human factors are closely associated with fatigue. Fatigue is a state of mental or physical exhaustion resulting from prolonged periods of physical or mental activity, inadequate rest periods, irregular shift work, or sleep deprivation. It can have a significant impact on human performance, decision-making, and overall safety.

The ICAO Fatigue Management Guide for Air Traffic Service Providers defines fatigue-related safety performance indicators (SPI). These fatigue SPIs allow individuals and organizations to classify fatigue related data that may contribute to an incident or accident; thus, improving the ability to assess the impact of fatigue as related to the effectiveness of safety risk control.

Attention

- Overlooked sequential task element.
- Incorrectly ordered sequential task element.
- Preoccupied with single tasks or elements.
- Exhibited lack of awareness of poor performance.
- Reverted to old habits.
- Focused on a minor problem despite the risk of major one.
- Did not appreciate gravity of situation.
- Did not anticipate danger.
- Displayed decreased vigilance.
- Did not observe warning signs.

Memory

- Forgot a task or elements of a task.

- Forgot the sequence of task or task elements.
- Inaccurately recalled operational events.

Alertness
- Succumbed to uncontrollable sleep – in form of microsleep, nap, or long sleep episode.
- Displayed automatic behavior syndrome.

Reaction Time
- Responded slowly to normal, abnormal, or emergency stimuli.
- Failed to respond altogether to normal, abnormal, or emergency stimuli.

Problem-Solving Ability
- Displayed flawed logic.
- Displayed problems with arithmetic, geometric or other cognitive processing tasks.
- Applied inappropriate corrective action.
- Did not accurately interpret the situation.
- Displayed poor judgment of distance, speed, and/or time.

Though the fatigue SPIs are in an ICAO document related to air traffic controllers, this classification of fatigue events has a universal application. In addition, the reason for referencing a document referring to human factors experienced by an air traffic controller is that in an m:N BVLOS environment, the RO and SUP work environment is like that experienced by air traffic controllers. Similarities include:

- Overseeing and communicating multiple aircraft
- From a remote location
- Dependent on multiple data displays
- Requiring constant monitoring
- Maintaining situational awareness for nominal and abnormal operations
- Without the benefit of direct sensory inputs

4.2.2.1 Fatigue Lessons Learned

With the RO and the SUP work environment aligning with that of an air traffic controller, human factor fatigue work scheduling requirements for m:N BVLOS operations should integrate fatigue-related safety risk controls for complex UAS operations based on fatigue guidance developed by the FAA for controllers. The list represents possible operations limitations, which could be changed based on a safety assessment of the operational complexity:

- Scheduled shifts will not exceed 10 hours.
- Must have a minimum of 15-minute break every two hours.
- Must have at least 9 consecutive hours off duty before a shift starts.

- A regular day off is required after working 6 consecutive days.
- Operational work beyond 10 hours must be approved by the Safety Leader on a case-by-case basis.

To mitigate risk of fatigue for UAS operations, the operator adopted the "I'M SAFE" program for all required crew members during the initial preflight and when mission requirements extended operations beyond 2 hours. Though voluntary for UAS operations, embedding this checklist into standard procedures should be a required safety risk control to mitigate risk of for complex UAS operations.

- Illness: Do I have any symptoms?
- Medication: Did I take prescription or over-the-counter drugs that could affect my performance?
- Stress: Am I worried about financial matters, health issues, or family discord?
- Alcohol: Have I consumed alcohol within the last 8 hours?
- Fatigue: Am I tired and not adequately rested?
- Emotion: Am I emotionally upset?

For the SPs and support crew working outdoors, the Center for Disease Control and Prevention (CDC) created a work/rest schedule based on temperature, humidity, and sunlight. The impact on fatigue of these environmental factors may vary based on the specific worksite, access to shelter, and the workers' conditioning. When an operation requires crew members to work outdoors for extended periods of time, UAS operators should establish safety criteria to ensure the crew members are able to perform their safety duties. The Operational Safety and Health Administration and the CDC have developed this safety criteria for exposure to heat and humidity, an example of which can be found at the following website: https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/2017-127.pdf

Two types of fatigue may have existed during flight testing: one crew member may have been impacted by fatigue due to failure to get adequate amounts of sleep the night before the operation, and there were numerous operations in sequence for an extended time without providing a break period for the crew.

During a few challenging scenarios, one RO used non-standard terminology, calling out to crew members without using a standard protocol, which interfered with communications between the crew members causing momentary confusion. Also, during a 1:6 launch sequence it appeared the RO was preoccupied with running checklists and monitoring each departing UA in sequence without communicating with the SP for the operating UAs. During that time, the RO did not appear to check on the status of the operating UAs. Decreased vigilance, preoccupation, and sequential task management, all of which were observed, can be associated with fatigue.

Due to weather delays the mission schedule was compressed, with one extended sequence of flight sorties running over a four-hour period. Though the health and wellbeing of the crew members was assessed during the later flights using the "I'M SAFE" protocol, all the personnel involved in the flight test were motivated to press on. There was no reason to believe any of the crew members were fatigued; however, without a written fatigue policy, mission requirements, peer pressure, and groupthink may allow a mission to continue when there is a silent human factors fatigue issue among the required crew members.

We recommend an operator be required to establish minimum requirements to mitigate risks related to fatigue and related conditions as a prerequisite for approval to conduct m:N BVLOS operations. The policy should apply to all required crew members involved in safety critical positions, including subcontractors who are on-site or working remotely. The fatigue policy should be developed based on the scale, scope, and complexity of the operations based on fatigue-related safety standards used to mitigate fatigue risk for pilots, air traffic controllers, and, for individuals working outdoors, based on unique aspects of mission complexity and environmental characteristics.

4.2.3. Safety Management System

Within the context of the larger safety culture, effective CRM is an attribute of an organization's commitment to safety. During the m:N BVLOS flight tests, all required crew members were qualified under the organization's voluntary SMS. The management team's commitment to safety was observed during the flight test scenarios with all crew members displaying a positive attitude about safety during the operation. Crew members were professional and disciplined, applying communications and safety procedures in accordance with their training. Beyond procedures, crew members were actively engaged in the identification of an emerging hazard, e.g., crewed aircraft movements and nonparticipant activities.

Evidence of the organization's safety culture was also evident in post-operation interviews. The crew members were open and honest about what worked and what did not. Without hesitation or fear of retribution, crew members were open and honest about their experiences during the flight tests.

The established safety culture promoted open communications and reporting, focusing on their commitment to continuous improvement by analyzing errors, identifying opportunities, and learning from mistakes.

The justification for recommending a voluntary SMS for operators involved in m:N BVLOS UAS operations is simple and straightforward, as part of the safety risk management, safety risk controls would be designed to achieve intended safety risk objectives. In terms of performance, the collection, analysis, and assessment of data would be used to ensure the designed safety risk controls are meeting or exceeding the safety objectives. In an ideal world, standardizing and sharing UAS safety assurance database within a government-industry partnership could serve to expedite the safety and efficient integration of advanced UAS operation into the national airspace system.

4.2.4. Organizational Procedures/Standards

This category includes the operator's written procedures for operation under normal, abnormal, or emergency conditions. The simulation results are contained in the HF Simulation Report and not duplicated here.

Team building supported by CRM training, along with the development of mature safety procedures, as an extension of the voluntary SMS program, were essential for the establishment and application of the safety risk controls needed to support the complex UAS m:N BVLOS flight test operations.

CRM encourages crew members to appreciate and understand their roles both as leaders and followers. The definition of these terms seems intuitive – leadership equates to the pilot in command, who, according to § 107.19 (b), is, "directly responsible for and is the final authority as to the operation of the small unmanned aircraft system." While followers take direction, get in line, and deliver on what is expected. In crewed aircraft history, strict application of these definitions, with the pilot-in-command being the sole authority and the copilot getting in line, was identified as a key contributing factor in the Tenerife and United 173 accidents.

During the m:N BVLOS flight test scenarios there was an increase in complexity in the leadership and followership roles of each of the required crew members. The ROs were required to establish and maintain open communications with up to 6 SPs. The SPs, in their followership roles, were required to monitor and participate in all required communications, and actively contribute to the decision-making process with the RO during off-nominal operations.

4.2.5. Roles and Responsibilities

The relationship between the RO and the SUP added an additional level of complexity. Unlike a copilot in a crewed aircraft who is engaged in safety duties during critical phases of flight, the SUPs were instructed to perform non-safety supervisory duties during the flight test scenarios. When defining the operational procedures, care needs to be taken to ensure the SUP is promptly available to assist the RO while also performing meaningful tasks to minimize boredom.

- There were scenarios where the RO transferred command of one or more UAs to the SUP. In one test case involving an RO needing to leave their post without warning, it took the SUP approximately 30 seconds to establish situational awareness and communications with multiple SPs. Safety was maintained, though the transition could have been faster. Additional display requirements were added to minimize the SUP start-up and transition time.

- During the flight tests, the SUP initiated transfers associated with the Asylon security mission events, which required focused surveillance. The transfer of controls was positive and seamless.

The positive transfer of aircraft control is essential for safe UAS operations. During flight testing the RO and SUP successfully exercised positive transfer of controls and effectively maintained communication with the associated SPs. Procedures for the positive transfer of UA control and training on procedure for the forced transfer of control for security and safety issues should be included in classroom and simulated training.

During the flight test there were times the SP was aware of pending aircraft movements at RME that could create a hazard. In their followership role, the SPs actively communicate the potential hazard to the RO. It was noted that some of the potential aircraft movements were not a factor. The added communications did increase the RO's situational awareness; however, an unintended consequence was increased radio traffic was a distraction, which could have created a new hazard. Operating in an active airport environment is challenging. The sharing of aircraft movement information was appropriate; however, SPs should have training on effective communications with an RO in an m:N BVLOS operation to better contribute to the decision-making process.

During actual operations away from an airport, it is expected that far fewer off-nominal events will be encountered. Additional study is needed to determine if the RO and SUP become bored given the Level 3 automation and therefore inattentive, which has been a problem with highly automated manned aviation cockpits.

4.2.6. Training

Both CRM and human factors share a common goal of understanding and optimizing human performance within complex systems. CRM training is essential from m:N BVLOS operations to enhance system safety, efficiency, and overall human performance.

In terms of future opportunities, it was observed during the flight test that additional skills beyond having Part 61 and/or Part 107 were helpful to the ROs in terms of cognition and communications. For a multi-crewed operation, the crew members with prior military experience had acquired the skills needed to work within a team, displaying an understanding of CRM leadership-followership dynamic. In addition, the crew members with video gaming experience displayed improved cognition, which was more evident during off-nominal operations. Though correlation between video gaming/military experience and improved performance during complex UAS operations may not be indicative of causality, the relationship was supported by the NASA TLX data submitted by the crew members. Further studies are suggested to determine the safety value of these experiences when involved in complex UAS operations.

Simulator training provided valuable experience. Including complex scenarios in an accepted training devise will have a significant impact on improving CRM, communications, and safety associated with off-nominal operations.

5. Recommendations for BVLOS m:N HF Analysis Standards

This section is intended to provide guidance to operators that wish to successfully implement this BVLOS m:N ConOps (section 0) and apply the supporting Safety Analysis. It assumes the operator already has a proven solution for BVLOS operations. The following are the recommended requirements to be put in an m:N HF testing standard:

- The m:N Safety analysis and HF requirements (Appendix B) shall be implemented in their entirety.
- The simulator (or a comparable experiential training environment) shall use the same UAS software and user interface that will be used in actual operations.
    - ArduPilot supports a robust simulation capability that can be relatively easily augmented by commercial-of-the-shelf simulation engines (see the HF Simulator report for more information).
    - If simulation testing is not viable, then a representative environment may be possible at a UAS test range that has an m:N authorization or other alternate environment with a m:N flight authorization.
- All the m:N and supporting BVLOS requirements (including CRM/operational) shall be verified and validated on the simulator with a subset tested on a physical UAS in a 1:1 operation.
- A task analysis shall be performed to determine the maximum feasible number of UAs than can be safely operated, “N” (section 2.5).
- The operational procedures and training shall be updated to reflect operations with “N” UAs.
- The operator’s flight crew shall be characterized to identify a representative set of capable ROs (see Safety Analysis requirements for minimum criteria for capable ROs).
    - The representative ROs should reflect the range of typical ROs and not the ones much more capable than most ROs. Factors associated with lower performance were minimal RO experience, low involvement in fast action

video games, and no military experience. Higher performance was tied to higher RO experience, many hours of fast action video games, and military UAS experience.

- At least 5 representative ROs shall be identified for the simulator validation testing.
    - Organizations with fewer than 5 ROs should test with as many ROs as they have.
- The representative ROs shall receive m:N specific training in the classroom and on the simulator (or representative environment). The training shall include knowledge testing and performance demonstrations.
- Test data shall be gathered to confirm the task analysis timing, occurrence of errors, and ROs perception of workload (e.g., NASA TLX survey).
- Each of the representative ROs shall successfully complete the following validation test cases on the simulator or in the representative environment:
    - Normal 1:1 to gather timing data to confirm the task analysis and to establish baseline performance
    - 1:1 testing of all manual contingencies (note that this can be done in conjunction with testing the requirements, but the operator needs to make sure data is gathered for baseline timing)
    - Normal operations with mid-point number of UAs (i.e., N/2) – optional test case to confirm the infrastructure, performance, and procedures can scale
    - Normal N UA to check timing, performance, and procedures
    - N UA all manual contingencies
    - N UA representative/critical automatic contingencies
    - N UA realistic common mode failures (e.g., internet connection, area outages, computer failure, etc.)
    - N UA with transfer of control to supervisor (e.g., sudden health issue)
    - N UA with multiple realistic events – combination auto and manual contingencies
- The operator shall select at least two representative ROs to perform flights with actual UAs.
- Flight test shall not proceed until:
    - The timing and sequences in the m:N task analysis are confirmed. This ensures the number of UAs flown in a physical environment is supported by the theoretical maximum number of UAs "N".
    - Data from the RO's perception of workload is determined to be acceptable (e.g., lower than Air Traffic Control values as highlighted in section 3.2.1.4).
    - The cause of any potentially hazardous conditions detected during simulation or previous flight testing is identified (e.g., software anomalies, confusion, inadequate response times, etc.).

  - Regression testing is done on any updates from simulation testing.
  - Regulatory authority operating approvals are obtained using the simulator data prior to flight test (unless testing is performed at a UAS test site with an m:N approval or other alternate environment with a m:N flight authorization).
- Each of the representative ROs shall complete the following validation flight test cases:
  - Normal N UA to check timing, performance, and procedures (may be done during prior normal operations)
  - N UA representative, realistic manual and common mode contingencies
  - N UA with multiple events combination auto and manual contingencies

In addition to establishing the initial BVLOS m:N operations, the organization should also:

- Implement annual training that includes proficiency checks from the most challenging simulation and flight test cases (e.g., low battery during intruding aircraft on one UA with C2 loss and intruder on another) and lessons learned.
- Establish a monitoring program focused on continuous improvement that proactively evaluates the effectiveness of the safety mitigations and implements correct actions to prevent future incidents. An example of such a program is a Safety Management System that conforms to 14 CFR §5 and FAA AC 120-92B.

Appendix A – NASA TLX Form

The following is an extract of the TLX forms completed by the flight crew immediately following completion of a test case. During the simulator testing, the survey responses were gathered using Adobe's form tools. During the flight test, the flight crew entered their workload in an electronic survey (Qualtrics) on their local computer.

Start of Block: Consent

NASA TLX Form for Flight Test

In the most general sense we are examining the workload you experienced, Workload is a difficult concept to define precisely, but a simple one to understand generally. The factors that influence your experience of workload may come from the task itself, your feelings about your own performance, how much effort you put in. or the stress and frustration you felt. The workload contributed by different task elements may change as you get more familiar with a task. perform easier or harder versions of it. or move from one task to another. Physical components of workload are relatively easy to conceptualize and evaluate. However, the mental components of workload may be more difficult to measure.

Because workload may be caused by many different factors, we would like you to evaluate several of them individually rather than lumping them into a single global evaluation of overall workload, The set of six rating scales, presented in this form, was developed for you to use in evaluating your experiences during different tasks. Please read the descriptions of the scales carefully. If you have a question about any of the scales in the table, please ask the Human Factors Observers about it. It is extremely important that they be clear to you. You may keep the descriptions with you for reference during the experiment.

This form has two sections:

1. Demographic questions
2. NASA TLX Questionnaire

After performing each of the tasks, you will be marking your responses for each of the six scales presented below. **You will evaluate the task you performed by selecting one point between 0 to 20 on each of the six scales at the point which matches your experience. Each line has two endpoint descriptors that describe the scale. Note that "own performance" goes from "good" on the left to "bad" on the right. This order has been confusing for some people, so be careful when you mark your response.**

Next, we would be assessing the relative importance of six factors in determining how much workload you experienced. The procedure is simple: You will be presented with a series of pairs of rating scale titles (for example. Effort vs. Mental Demands) and asked to choose which of the items was more important to your experience of workload in the task(s) that you just performed.

Each pair of scale titles will appear as a separate question in the form.

Please consider your responses carefully in distinguishing among the different task conditions. Consider each scale individually. Your ratings will play an important role in the evaluation being conducted, thus, your active participation is essential to the success of this experiment and is greatly appreciated by all of us.

- ○ I acknowledge that I have read and understood clearly why I am filling out the NASA TLX form and the procedure to complete the NASA TLX form.

End of Block: Consent

Start of Block: Demographic Questions

Please enter your first name

____

Please enter your last name

____

Please indicate your position in the flight test by selecting one of the options below

- ○ Remote Operator (RO)
- ○ Supervisor (SUP)
- ○ Safety Pilot (SP) / Visual Observer (VO)
- ○ Safety Pilot Liaison
- ○ Human Factors (HF) Observer

Please enter the test case for which you are submitting this NASA TLX form.
Please enter your response using the following format ONLY: TC# where # is the number

associated with the scenario performed. So for example, if you performed test case number 1 then you would enter TC1 as your response.

____

Please enter the scenario for which you are submitting this NASA TLX form.
Please enter your response using the following format ONLY: SC# where # is the number associated with the scenario performed. So for example, if you performed Scenario number 1 then you would enter SC1 as your response.

____

Please enter the date you performed the above-mentioned test case and scenario for the flight test.
Please follow MM/DD/YYYY format ONLY to enter your response.

____

End of Block: Demographic Questions

Start of Block: NASA TLX Questionnaire

Please give a rating for the 'Mental Demand' experienced during the task. Specifically, give your rating based on:
How much mental and perceptual activity, was required (e.g., thinking. deciding, calculating, remembering. looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting, or forgiving?

	0 (Low)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 (High)
Mental Demand	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Please give a rating for the 'Physical Demand' experienced during the task. Specifically, give your rating based on:
How much physical activity was required (e.g. pushing, pulling, turning. controlling, activating,

etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous restful or laborious?

	0 (Low)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 (High)
Physical Demand	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Please give a rating for the 'Temporal Demand' experienced during the task. Specifically, give your rating based on:

How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

	0 (Low)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 (High)
Temporal Demand	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Please give a rating for how you perceive your 'Performance' for the task. Specifically, give your rating based on:

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Please note that here, 0 indicates "good performance" and 20 indicates "poor performance".

	0 (Good)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 (Poor)
Performance	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Please give a rating for the 'Effort' you required for the task. Specifically, give your rating based on:

How hard did you have to work (mentally and physically) to accomplish your level of *performance?*

	0 (Low)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 (High)
Effort	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

Please give a rating for the 'Frustration' you experienced during the task. Specifically, give your rating based on:
How insecure, discouraged, irritated. stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

	0 (Low)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20 (High)
Frustration	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

End of Block: NASA TLX Questionnaire

Start of Block: Pairwise Comparison

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ○ Effort
- ○ Performance

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ○ Temporal Demand
- ○ Frustration

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Temporal Demand
- ◯ Effort

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Physical Demand
- ◯ Frustration

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Performance
- ◯ Frustration

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Physical Demand
- ◯ Temporal demand

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Physical Demand
- ◯ Performance

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

○ Temporal Demand

○ Mental Demand

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

○ Frustration

○ Effort

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

○ Performance

○ Mental Demand

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

○ Performance

○ Temporal Demand

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Mental Demand
- ◯ Effort

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Mental Demand
- ◯ Physical Demand

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Effort
- ◯ Physical Demand

Select the factor below that represents the more important contributor to workload for specific test case that you recently performed.

- ◯ Frustration
- ◯ Mental Demand

End of Block: Block 2

Appendix B – m:N Safety and HF Requirements

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
D-0001	Drone-General	All changes to the UA and AE baseline configuration shall go through the change management process.	SME should review of all planned changes and confirm scope of needed regression testing
D-0050	Drone-ADS-B	The UA shall have an ADS-B-in receiver installed with the capability to detect cooperative aircraft.	Higher severity aircraft are more likely to be ADS-B equipped and automatic response provides additional safety buffer.
D-0056	Drone-FC	The UA shall have automatic on-aircraft contingency responses for common hazards including loss of C2, loss of GPS, low battery, etc.	
D-0042	Drone-FC-Control	The UA shall transition to a controlled descent of at least the DAA_Descent_Rate when the on-board ADS-B-in detects an aircraft at or within the ADS-B-in warning thresholds (lateral or vertical).	
D-0505	Drone-FC-Mode	If the UA does not receive a valid freshness/heartbeat signal from the ROC at least every 30 seconds when in flight, the UA shall Return_To_Launch.	This covers the case of a frozen computer or intermediate stage causing a loss of control that may not be immediately detected by the RPIC.
D-0070	Drone-Safety-visibility	The UA shall be equipped with a >3 mile high visibility anti-collision light.	Frequently a provision of approved BVLOS waivers and exemptions.
U-0240	UFM-Daily	Daily checklist shall confirm the Cellular_Control device is able to operate as a back-up for internet and computer issues in the Operations Center.	
U-0361	UFM-Daily	Daily checklist shall include confirmation that the geomagnetic activity has a Kp-index of 6 or lower.	
A-0504	UFM-Preflight	Preflight values shall be cross-checked between GCS/plan and UA (e.g. battery voltage, flight plan wrap-around, geofence/Exclusion_Zones feedback, UA identifier number, GNSS/GPS, altitude, mode, etc.).to ensure consistent data, calculations, and communications.	This can be automatically or manually.
U-0505	UFM-Preflight	The Preflight checklist shall confirm that the UA's reported GNSS/GPS take-off location is within 5 meters of the actual launch location.	This is desirable for BVLOS but becomes a requirement for m:N as safe operation relies on automated flight with accurate position and less RPIC oversight. This confirmation may be performed by monitoring software that confirms for fixed launched locations or via RPIC checking maps.
A-4027	AE-Alerts	Alarms and alerts shall occupy the same general location within a system and across related systems	Guidance from FAA-HF-STD-003 STANDARD PRACTICE ALARMS AND ALERTS IN THE TECHNICAL

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
			OPERATIONS ENVIRONMENT section 5.4.9.2
A-4032	AE-Alerts	A system or application shall provide users with a means of acknowledging alarms and alerts as well as a means of turning off alarm and alert signals once they have been acknowledged or the condition generating the signal has been corrected	Guidance from FAA-HF-STD-003 STANDARD PRACTICE ALARMS AND ALERTS IN THE TECHNICAL OPERATIONS ENVIRONMENT section 6.2.8.1
A-4028	AE-Alerts-Aural	When absolute identification is required, the number of audio alarm signals to be identified should not exceed four	Guidance from FAA-HF-STD-003 STANDARD PRACTICE ALARMS AND ALERTS IN THE TECHNICAL OPERATIONS ENVIRONMENT section 6.2.1.1
A-4029	AE-Alerts-Aural	When several different audio signals will be used to alert a user to different conditions, the signals shall be distinctive in intensity, pitch, or use of beats and harmonics	Guidance from FAA-HF-STD-003 STANDARD PRACTICE ALARMS AND ALERTS IN THE TECHNICAL OPERATIONS ENVIRONMENT section 6.2.2.4
A-4030	AE-Alerts-Aural	The frequency range of an alarm or alert signal shall be between 200 and 5,000 Hz, preferably between 500 and 3,000 Hz	Guidance from FAA-HF-STD-003 STANDARD PRACTICE ALARMS AND ALERTS IN THE TECHNICAL OPERATIONS ENVIRONMENT section 6.2.6.1
A-4031	AE-Alerts-Aural	An alarm or alert signal shall provide an audio level (at least one octave band between 200 and 5,000 Hz) so that the sound pressure level (SPL) of the signal is at least 10 dB(A) above the ambient noise level, or 20 dB(A) above the amplitude of the masked threshold (or at such a level that assures personnel are adequately alerted to the danger or status) when measured within a foot (1 foot) of the responder's ear or at more than 2 feet from the signal	Guidance from FAA-HF-STD-003 STANDARD PRACTICE ALARMS AND ALERTS IN THE TECHNICAL OPERATIONS ENVIRONMENT section 6.2.7.1 section
A-0048	AE-Alerts-Aural-Caution	The RPIC shall receive an aural caution tone for automatic abnormal mode transitions (e.g. low C2/battery resulting in RTH, descents due to Intruding_Aircraft or loss of GNSS/GPS, etc.).	The RPIC shall receive aural tone and visual alerts for automatic abnormal mode transitions (e.g. low C2/battery resulting in RTH, descents due to Intruding_Aircraft or loss of GNSS/GPS, etc.)
A-0042	AE-Alerts-Aural-Warning	Distinctive aural Warning_Alerts shall be provided to the RPIC for actions needing immediate attention.	Safety aural alerts: - DAA intruders - Geofence exceedance - Automatic activation of the Flight_Termination_Systems (i.e. Parachute deployment)
A-7024	AE-Alerts-Aural-Warning	New caution or warning alerts shall result in unmuted aural alerts.	

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
A-7025	AE-Alerts-Aural-Warning	Warning_Alerts shall have priority over cautions.	Warnings require immediate attention whereas cautions are just awareness/monitoring
A-0049	AE-Alerts-Visual	The RPIC shall receive a visual alert for automatic abnormal mode transitions (e.g. low C2/battery resulting in RTH, descents due to Intruding_Aircraft or loss of GNSS/GPS, etc.).	
A-7026	AE-Alerts-Aural-Warning	Aural alerts should be easily deactivated (but not easily deactivated inadvertently).	Per FAA Guidance: Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls Version 2.0" and AC 20-138D
A-7027	AE-Alerts-Aural-Warning	Audible alerts shall be sufficiently loud and of appropriate pitch quality, duration and pattern.	Per FAA Guidance: Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls Version 2.0" and AC 20-138D
A-0003	AE-Alerts-Visual-Caution	Visual Caution_Alerts shall be displayed in yellow or amber.	Yellow or amber are standard aviation colors for alerts.
A-0040	AE-Alerts-Visual-Caution	Visual Caution_Alerts shall be provided to RPIC for safety conditions needing increased awareness (e.g. low battery, loss of C2, ADS-B detections, invalid parameters, etc.)	Cautions for automatic in-flight contingencies; warning to prevent take-off Full list of alerts in UFM, including: - C2/Telemetry link deterioration - ADS-B information - Battery voltage - GNSS/GPS deterioration - automatic mode changes
A-4025	AE-Alerts-Visual-Warning	The use of blinking should be limited because it can be distracting, and excessive use reduces the attention getting effectiveness. Blinking rates between 0.8 and 4.0 Hertz should be used, depending on the display technology and the compromise between urgency and distraction.	Guidance from: DOT/FAA/TC-16/56 Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls Version 2.0
A-4026	AE-Alerts-Visual-Warning	If flash coding is used on text, the flash rate should be 0.3 to 1 Hz with an on/off cycle of 70 percent	Guidance from FAA-HF-STD-003 STANDARD PRACTICE ALARMS AND ALERTS IN THE TECHNICAL OPERATIONS ENVIRONMENT section 5.4.3.7
A-0005	AE-Alerts-Visual-Warnings	Visual Warning_Alerts shall be displayed in red.	Red is the standard aviation color for warning alerts. International Commission on Illumination chromaticity coordinates for Aviation Red—y is not greater than 0.335; and z is not 309 greater than 0.002

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
A-0027	AE-Alert-Visual	The RPIC shall be alerted if the detected altitude error is greater than 50'.	Threshold set to ensure a UA operating at 400' is less than 450'
A-0104	AE-Comm	All voice communications shall be via hands-free headsets.	
A-0101	AE-Control	The RPIC shall be able to command all UA to return to the launch location (Return_To_Launch) within 5 seconds.	
A-0103	AE-Control	The RPIC shall be able to control each UA individually to: hold, descend to Safe_Altitude, Return_To_Launch, resume, and Land.	
A-0106	AE-Control	The RPIC shall be able to command affected UA to land within 5 seconds.	
A-0105	AE-Control	The RPIC shall be able to command all UA descend to the site specific Safe_Altitude within 5 seconds.	
A-4105	AE-Control	The RPIC shall be able to activate the mode to descend to the Safe_Altitude by a single action (e.g. button or icon) within 1 second.	This is to address the potential for a delay in response if the pilot must "find" their cursor and then move across many fields.
A-7001	AE-DAA General	The DAA system and corresponding BVLOS operations shall be previously approved by the FAA (e.g. 91.113(b) with 44807 exemption or 107.31 waiver)	High level requirement for BVLOS operations approved before advance to m:N
A-7014	AE-DAA-Alert	The RPIC shall receive visual and aural alerts if the onboard-UA DAA triggers a controlled descent.	
A-7015	AE-DAA-Alert	The border around the DAA display shall indicate a visual Caution_Alert if an Intruding_Aircraft is within the DAA_Caution_Threshold, but greater than the DAA_Warning_Threshold.	Makes it easier to identify the problem area on the display, especially when multiple UA
A-7016	AE-DAA-Alert	The border around the DAA display shall indicate a visual Warning_Alert if an Intruding_Aircraft is within the DAA_Warning_Threshold.	Makes it easier to identify the problem area on the display.
A-7012	AE-DAA-Alert-caution	An aural Caution_Alert shall be provided to the RPIC in the presence of an Intruding_Aircraft.	
A-7013	AE-DAA-Alert-warning	A DAA aural Warning_Alert shall be provided to the RPIC when any of the DAA sensors indicates an Intruding_Aircraft is within the DAA_Warning_Threshold.	
A-0206	AE-DH-data	Valid communications (e.g. Internet) connectivity between ROC and on-site GCS shall be operational for all phases of operations.	
A-0209	AE-DH-Data	Information transmitted between the ROC and on-site GCS shall be cryptographically authenticated before being used by the receiver.	Ensures that new messages cannot be fabricated and sent to the GCS by an attacker.

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
A-0210	AE-DH-Data	Information transmitted between the on-site GCS and UA shall be cryptographically authenticated before being used by the receiver.	Ensures that new messages cannot be fabricated and sent to the UA by an attacker
A-0211	AE-DH-Data	All messages shall include a monotonically increasing index. Messages including any index earlier than the most recently received and authenticated message shall be ignored.	Ensures that an attacker cannot replay messages.
A-0026	AE-Display	Each UA independent altitude sensor shall be continuously displayed to the RPIC, or the GCS shall provide a warning if altitude signals disagree by more than 100' AGL.	
A-3997	AE-Display	The ROC_Supervisor shall be able to see the safety related displays of a RPIC within 5 seconds.	In emergency situations, the supervisor promptly needs information
A-3998	AE-Display	Each RPIC station shall be able to withstand the loss of a single display.	This can be done by either aggregating the information on the remaining displays, or a spare display. The number of displays during normal operation will be determined during the human factors assessment.
A-3999	AE-Display	If only one of the RPIC displays is operational, it shall display the minimum safety information required for flight. (e.g. attitude, position, DAA alerting areas, altitude, etc.).	Suggest same content as the ROC_Supervisor screen
A-4019	AE-Display	The displays and alerts shall meet the intent of the FAA human factors standards (invokes requirements A-4020 through A-4039).	
A-4020	AE-Display	Color shall be used only when it is associated with a purpose that aids task performance. The use of color in ATC displays is typically associated with one of the following three purposes: attention, identification, or segmentation.	Guidance from FAA-HF-STD-002 Standard Practice BASELINE REQUIREMENTS FOR COLOR USE IN AIR TRAFFIC CONTROL DISPLAYS section 3.1.1
A-4021	AE-Display	The number of distractor colors shall be fewer than five. For the best effect, the number of distractor colors should be minimized to no more than two or three	Guidance from FAA-HF-STD-002 Standard Practice BASELINE REQUIREMENTS FOR COLOR USE IN AIR TRAFFIC CONTROL DISPLAYS section 3.2.1.3

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
A-4022	AE-Display	The following is a list of conventions for color usage in ATC displays: • Red is reserved to draw attention to emergency or alert messages. • Yellow is reserved to identify a target or data category that needs caution. • Orange, purple or magenta, and cyan or turquoise are reserved to identify data categories. • Green, white, and black are reserved to identify the normal status category. • Non-basic colors, especially those in the green-blue domain (e.g., green-blue, gray-blue, and yellowish-green), are the typical choices for segmentation.	Guidance from FAA-HF-STD-002 Standard Practice BASELINE REQUIREMENTS FOR COLOR USE IN AIR TRAFFIC CONTROL DISPLAYS section 3.3.5
A-4023	AE-Display	The colors used to identify data categories shall be reliably and consistently named. Basic colors should be chosen for the purpose of identification. Color research has found that 11 basic colors (red, green, yellow, blue, pink, brown, purple, and orange; as well as three achromatic terms: black, white, and gray) can be named reliably and consistently across populations of different geographic regions and cultures (Boynton & Olson, 1990). In addition, magenta and cyan are among the consistently namable colors. These colors are maximally separated in the color space.	Guidance from FAA-HF-STD-002 Standard Practice BASELINE REQUIREMENTS FOR COLOR USE IN AIR TRAFFIC CONTROL DISPLAYS section 3.2.2.1
A-4024	AE-Display	The luminance contrast between the text and background shall be greater than the threshold Michelson contrast (30%) for error-free reading. Low text readability increases reading difficulty and may cause reading errors.	Guidance from FAA-HF-STD-002 Standard Practice BASELINE REQUIREMENTS FOR COLOR USE IN AIR TRAFFIC CONTROL DISPLAYS section 3.3.1
A-4033	AE-Display	When task performance requires or implies the need to assess the timeliness of information, the display should include time and date information associated with the data.	Guidance from FAA-HF-STD-001 Human Factors Design Standard section 5.6.1.1.8
A-4034	AE-Display	When a user is performing an operation on a selected object in a display, that object shall be highlighted. Discussion. In many applications, at least two different methods of selection highlighting can be provided. The first of these highlighting methods occurs when the pointer comes to rest for a predetermined time on a selected object. This is sometimes referred to as dwell emphasis, and it tells the user which object the computer perceives the user is about to select. This highlighting is normally dim white. The second type of highlighting occurs when an actual selection has been made and is normally a bright white.	Guidance from FAA-HF-STD-001 Human Factors Design Standard section 5.6.1.2.3

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
A-4035	AE-Display	When an application provides different operational modes, the current mode shall be continuously indicated to a user.	Guidance from FAA-HF-STD-001 Human Factors Design Standard section 5.6.1.2.6
A-4036	AE-Display	Every screen shall have a title or header at the top that is separate and distinguishable from the body of the screen and describes briefly the contents or purpose of the screen.	Guidance from FAA-HF-STD-001 Human Factors Design Standard section 5.6.1.3.1
A-4037	AE-Display	Information that is particularly important or that requires immediate user response shall be displayed in the user's primary viewing area.	Guidance from FAA-HF-STD-001 Human Factors Design Standard section 5.6.1.3.13
A-4038	AE-Display	Screens throughout a system or application shall have a consistent structure that is evident to users.	Guidance from FAA-HF-STD-001 Human Factors Design Standard section 5.6.1.4.1
A-4039	AE-Display	The design should incorporate error prevention and management to the extent practicable so that: 1 the design enables the flight crew to detect and/or recover from errors resulting from their interaction with the equipment; or 2 the design makes the effects of such flight crew errors on the airplane functions or capabilities evident to them and enables them to continue a safe flight and landing; or 3 the design discourages flight crew errors by switch guards, interlocks, confirmation actions, or other effective means; or 4 the effects of errors with potential safety consequences should be precluded by system logic or other aspects of system design that will detect and correct such errors.	Guidance from FAA 25.1302 for human error prevention
A-3908	AE-GCS	The cloud software shall be able to transmit and receive data to/from at least 1 RPIC computer, 1 RPIC Cellular_Control device, and 1 ROC_Supervisor computer.	
A-3909	AE-GCS-control	The RPIC shall be able to shut down the Cellular_Control device when needed.	
A-3910	AE-GCS-control	The RPIC shall be able to shut down his control station when needed and use the Cellular_Control device.	
A-3911	AE-GCS-control	The ROC_Supervisor shall be able to request RPIC control of an operation from the RO.	
A-3912	AE-GCS-control	The RO shall be able to request transfer of control to the ROC_Supervisor	

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
A-3913	AE-GCS-control	If the ROC_Supervisor does not acknowledge acceptance of control of an operation within 15 seconds, the RPIC shall receive a red alert and remain the RPIC responsible for the operation.	
A-3914	AE-GCS-control	If the RPIC does not acknowledge acceptance of control from the ROC_Supervisor for an operation within 15 seconds, the ROC_Supervisor shall receive a red alert and remain the RPIC responsible for the operation.	
A-3915	AE-GCS-control	In order to force transfer control from the RPIC, multiple dissimilar actions shall be required by the ROC_Supervisor.	A second dissimilar confirmation is to ensure the ROC_Supervisor can't accidentally assume control of an operation.
A-3916	AE-GCS-control	If control hasn't been acknowledge/accepted, the RPIC and ROC_Supervisor shall be able to cancel their request to transfer control.	
A-3917	AE-GCS-control	When the RPIC or ROC_Supervisor do not have control of a UA, the control buttons on their display shall show as inactive/unavailable	
A-3918	AE-GCS-control	When a UA is in flight, either the RPIC or the ROC_Supervisor (but not both) shall be in control with the control buttons on their display showing active/available	
A-3919	AE-GCS-control	When the ROC_Supervisor assumes control of a UA, the UAS control and status information shall be shown on the ROC_Supervisor display and removed from the RPIC display.	
A-3920	AE-GCS-control	Flights that the ROC_Supervisor controls shall be shown at the top of the ROC_Supervisor display list.	This increases the ROC_Supervisor's attention on the flights they control
A-3922	AE-GCS-alerts-aural	Regardless of control status, the ROC_Supervisor shall be able to hear the aural warnings for an RO within 5 seconds.	This allows the supervisor to monitor RPIC alerts and smoothly transfer control when needed.
A-3923	AE-GCS-control	The ROC_Supervisor shall be able to request transfer of control to the RO.	
A-3924	AE-GCS-comm	Regardless of control status, the ROC_Supervisor shall be able to verbally communicate with an RO and the SPs (if used) within 5 seconds.	This allows the supervisor to monitor RPIC verbal communications, smoothly transfer control when needed, and return from break-out rooms.
A-3500	AE-GCS-ROC	The RPIC shall be able to control and monitor the UA using a commercially available Cellular_Control device.	ASY implementation: RPIC tablet with cellular services to the Cloud application provides dissimilarity and redundancy
A-0001	AE-General	All changes to the AE baseline configuration shall go through the change management process.	

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
A-3900	AE-ROC	Even when ROC power is lost, the ROC computers, displays, internet, and comms shall remain powered for the duration of flight.	
A-3901	AE-ROC	Physical access to the ROC shall be controlled.	
A-3902	AE-ROC	User authentication shall be required prior to the use of ROC computers.	
A-3903	AE-ROC	Use of the ROC computers shall be limited to approved personnel.	Approved personnel typically just RPIC, ROC_Supervisor, and IT.
A-3904	AE-ROC	The ROC computers shall provide the UA with a freshness (e.g. heartbeat) indication at least every second.	This covers the case of a frozen computer or intermediate stage causing a loss of control that may not be immediately detected by the RPIC.
A-3906	AE-ROC	RPIC stations shall ensure the aural warnings for one RPIC do not impede the ability of other RPICs in the ROC from performing their required activities.	
A-3907	AE-ROC	RPIC Cellular_Control device shall detect if data is not refreshed (frozen or stale data) from GCS or UA and alert the RPIC.	
O-1040	Comm, Train-Crew	For safety alerts, the communications standards shall include RPIC and/or SP/ROC_Supervisor confirmation of the alert.	
L-0009	Location	Operations shall be conducted in areas with previous, successful service history, including C2 coverage.	
L-1000	Location-m:N	Operating_Areas shall be geographically separated by at least the air risk buffer (Buffer_Distance).	Prevents UA from flying into each other; else need UTM for time partitioning
O-2000	Op-Annual	At least annually, the flight crew shall be required to demonstrate proficiency on both normal and abnormal operations.	
O-0018	Op-General	There shall be a fatigue policy in place that addresses breaks and minimum rest periods.	Safe management of multiple UAS BVLOS requires more focus
O-0020	Op-General	The Flight Crew shall perform flight operations in a "Sterile" environment.	
O-0444	Op-in-flight-Supervisor	Transfers of control between the RPIC and ROC_Supervisor shall have both voice and computer confirmations.	
O-0445	Op-in-flight-Supervisor	The ROC_Supervisor shall control no more than two UA in a contingency or emergency.	

ID #	Allocation	BVLOS m:N Mitigation and HF Requirements	Comments/Rationale
O-0750	Op-in-flight-Supervisor	The ROC_Supervisor shall assume control of the UA if the RPIC is unable to perform their duties.	
O-0220	Op-Preflight	The Preflight checklist shall include confirmation of valid communications (e.g. internet, cellular, Comm, etc.) operations between the Ops Center and on-site GCS.	
O-0302	Op-Preflight	As part of Preflight checks, the RPIC shall confirm the aural warnings can be easily heard given the ambient noise.	
O-0350	Op-Preflight	Daily and preflight checklist shall include an IMSAFE evaluation for the Flight Crew.	Applicable to both daily and pre-flight checklists since fatigue and illness can occur throughout the day.
O-0300	Op-Preflight-DAA	Take-off shall not be allowed (no-go) if an Intruding_Aircraft is within the caution threshold.	This is desirable for BVLOS but becomes a requirement for m:N as safe operation relies on automated flight with less RPIC oversight.
T-0500	Train-Crew	The ROC_Supervisor shall pass RPIC training annually.	
T-1020	Train-Crew	The ROC_Supervisor training shall include recognition of RPIC behaviors inconsistent with IMSAFE.	
T-1030	Train-Crew	The annual Crew Resource Management training shall include the coordination and transfer of control procedures for the RPIC and ROC_Supervisor.	
T-1060	Train-Crew	The RPIC shall be trained to correctly respond to all red/Warning_Alerts within 1 second.	
T-2010	Train-Crew	The RPIC and SP/ROC_Supervisor shall receive annual training on Crew Resource Management (CRM).	
T-1000	Train-Crew-Qual	Any person acting as an RPIC shall have a valid Part 107 RPIC certificate.	
T-1070	Train-Crew-Qual	Flight crew shall be trained and shown proficient on aircraft, all approved operations (normal and abnormal), communications standards, and air/ground surveillance techniques.	

Appendix C – m:N Lessons Learned Table

Area	Lessons observed	Recommended change/learning	Comments/disposition
Airport	UA and manned aircraft can operate together at airport locations not under normal flight paths	With on-UA ADS-B-in DAA and another DAA for uncooperatives (i.e. ground radar or ATC services)	RME ATC was helpful to let know incoming helicopter landing in area and fixed-wings were on taxiway and runway
Alerts	Alarms in ROC made it hard to hear on-site SPs	Caution alerts should be less intrusive, and RO should be able to acknowledge/silence. Warnings can also be acknowledged and silenced but retriggered for new aircraft or if advanced from caution.	Added requirements: A-7023 - The RPIC shall be able to acknowledge aural cautions and warnings, which results in the current aural being muted. A-7024 - New caution or warning alerts shall result in unmuted aural alerts. A-7025 - Warning_Alerts shall have priority over cautions.
DAA	Automatic avoidance before the RO sees it on their display	UA ADS-B automated avoidances needs to align with RO display alerts	ArduPilot parameter for avoidance maneuver was inadvertently set to trigger earlier than display; set to proper value
DAA	Extraneous warning from SP that weren't really needed (e.g. traffic 5 minutes out given there are 5 other UA flying)	SP (and DAA) should only provide alerts when approaching caution thresholds	Included in final report
DAA	2 Uncooperative aircraft even at an ATC controlled airport	Radar DAA would have detected the uncooperatives and minimize the need for on-site SP	Included in final report
DAA	On-UA ADS-B-in with automated responses was ~5 seconds faster than relying on the RO human-in-the-loop. The automated, reliable, prompt ADS-B-in UA response minimized RO workload.	Require on-UA ADS-B automated response for BVLOS operations	Baseline assumption/requirement for the project and in the final report
DAA	Phased descent for ADS-B-in avoidance maneuvers effective	Include in final report the fast descent until reaches safe altitude	Included in final report
Display	Supervisor didn't open all the simulated UA (only 3 real UAs)	Key is to be able to quickly access information at all transitions; recommend additional automation to set-up displays	Added requirements: A-3997 The ROC_Supervisor shall be able to see the safety related displays of a RPIC within 5 seconds. A-3922 Regardless of control status, the ROC_Supervisor shall be able to hear the aural warnings for an RO within 5 seconds.
Display	The location/UA information needs to be obvious for the RPIC to quickly associate issues with a site.	Add to hazard that the RPIC does a contingency at the wrong location the mitigation/requirement that	Included in flight test software and in final safety analysis

Area	Lessons observed	Recommended change/learning	Comments/disposition
		the location/UA must be prominently displayed	
Display-DIB	The SP detected weather conditions that weren't displayed to the RPIC.	For BVLOS without a SP/VO, additional weather information should be displayed to the RPIC: ceiling, visibility, winds, site temperature	BVLOS requirement
Display-DIB	The operating area was not marked on the weather map display, so the RPIC couldn't easily tell relative distances.	For BVLOS without an SP/VO, add to the weather radar display the: operating area, distance scale, location of the FAA weather info, and ideally predictive weather info.	BVLOS requirement
Displays	Invoking a subset of the FAA manned/ATC Human Factors requirements provided easy to understand displays, which minimized human errors	Provide the m:N HF requirements to the SDO	Included in recommendations section of final report
Human Factors	The NASA TLX workload assessment was a viable method to assess the RO workload, although there is no standard for what is "too much"	Recommend in final report that additional research is needed to determine the maximum TLX workload that should be deemed acceptable.	Include in final report
ROs	Remote m:N is more like ATC operations and fast-action video gaming that traditional part 61 pilot skills	Recommend to FAA that future commercial UAS RO standards be tailored. Include in the final report to include the recommended simulator training and performance scenarios	Include in final report
Safety Analysis	Using the safety analysis to identify the minimum displays, alerts and operational requirements was effective	Provide the m:N Operational Hazard and Risk Assessment with the safety derived requirements to the SDO.	Included in final report to be provided to the SDO
Simulator	The ArduPilot open-source repository required minimal updates to enable the automation needed for m:N operations.		Included in final report
Simulator	The same ArduPilot open-source software and simulator are effective RO training and testing environment.	Recommend m:N testing and training be initially done on a simulator before any flight testing	Included in final report
Simulator	Since the simulator used the actual UA and GCS software, ROs learned and began to trust the automation while doing the testing/training.	Include simulator training in the recommendations	Included in final report

Area	Lessons observed	Recommended change/learning	Comments/disposition
SOP	Physical break from workstation is needed after ~2 hours. Sloppier communications towards end of operations due to suspected fatigue.	Following fatigue policy is important, even for flight test.	Added: O-0018 The organization shall have a fatigue policy that addresses the maximum on-duty time and required rest period.
SOP	Supervisor was also doing other tasks (intentional which is OK as long as can respond to situations quickly) so took a few seconds for Supervisor to respond and get displays loaded	Add new requirement – The Supervisor shall be able to see the safety related displays of an RO within 5 seconds.	Added: A-3997
SOP	Supervisor boredom	Identify non-critical tasks that supervisor can do when not needed for contingencies	Included in final report as recommendation for further study
SOP/Comm	In Google Meets, once SUP used a break-out room couldn't go back into main room. This affected the loss of internet scenarios.	--Investigate alternatives to Google Meets, so no acceptance of transfer required (e.g. Discord) --New requirement that the Supervisor can join RO's communications	Used cell phone Google Meets to pick up communications Added: A-3924 Regardless of control status, the ROC_Supervisor shall be able to verbally communicate with an RO and the SPs (if used) within 5 seconds.
SOP/Comm	SP used shortcut communications for preflight	If used, how ensure RO can easily confirm the pre-flight tests were all completed and passes, e.g. standard format in the same order as the RO checklist?	Included in final report
SOP/Comm	During UA landing, several RO/SP back/forth that seem extraneous. Are they really needed or just confirmation landed?	If on-site SP used, consider streamlining landing process to minimize extraneous communications	Future investigation
SOP/Comm	Inconsistent terms used between RO/SP	Add to verbal communications standard and training: aircraft designators, DAA instead of radar display, "Charlie Mike" or equivalent, etc.)	See communication section in final report
SOP/Comm	Ambient airport noise from SP headsets made comms sometimes hard to hear	For sites where an on-site SP/VO is used, they should be able to mute their microphone to ensure the multiple sites noise does not overwhelm critical communications and not increase pilot distraction. RO and SUP mics should never be muted.	Add a requirement that the on-site SP can mute their mic, and during the calm times the RO confirms the comms are still viable. The RO should not be mutable

Area	Lessons observed	Recommended change/learning	Comments/disposition
Task Analysis	Static task analysis can effectively predict the number of UAs to be flown given the level of automation and attention required to support the mission	Include in the recommendations to the SDO that a task analysis (with the proposed priorities) be done by operators to determine the number of theoretical UAs per RO	Included in final report
Weather	Hard to tell if weather nearby	Weather range/scale needed on displays	BVLOS requirement
Weather	No indication of winds aloft and forecasted winds	Investigate feasibility of receiving winds aloft info and displaying (as well as trend/forecast info)	BVLOS requirement