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Validation of Unmanned Aircraft Systems Contingency Procedures and Requirements Terminal Human-in-the-Loop Simulation Technical Report

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16. Abstract

Objective: We investigated procedural solutions to Unmanned Aircraft System (UAS) lost link events in the terminal environment. **Background:** UAS are only allowed to fly under a paper-based Certificate of Authorization (COA), which is not intended to deliver lost link information to air traffic control specialists (ATCS) in an effective manner. **Method:** We integrated lost link contingency routes into Instrument Flight Procedures (IFPs) to communicate lost link procedures. We conducted a human-in-the-loop (HITL) simulation to examine using IFPs in this manner. **Results**: Participants rated the lost link procedures as effective. **Conclusion:** We found that modified IFPs do seem to be a viable method for communicating lost link procedures to ATCS and could be useful for UAS integration into the National Airspace System.

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EXECUTIVE SUMMARY

Background

Currently, public Unmanned Aircraft System (UAS) applicants (federal, state, and local agencies) require a Certificate of Authorization (COA) from the Federal Aviation Administration (FAA) to fly outside restricted airspace or warning areas. COAs are required because the unmanned aircraft are not compliant with sections of Title 14 of the Code of Federal Regulations. Without an onboard pilot, there is a significant reliance on the Command and Control data link and a greater emphasis on the loss of functionality associated with off-nominal (contingency) events such as loss of link.

COAs, however, are not intended to provide lost link information such as contingency routes/procedures to air traffic control specialists (ATCS). COAs are also not standardized, so if they do contain lost link information it may not be easily found by ATCS at the time of a lost link event.

Objectives

This research effort examined procedural solutions to UAS lost link events in the terminal environment by determining the operational impact of standardized lost link procedural alternatives on airspace safety and efficiency. It also assessed the impact/risks (e.g., workload, situation awareness) of the contingency procedures on terminal ATCS. Lastly, this research will help determine if Instrument Flight Procedures (IFPs) are a viable method for communicating UAS lost link procedures to ATCS.

Methods

This study assessed loss of C2 link only; pilots maintained normal communication channels with ATCS. Scenarios were divided by conditions based on phase of flight in which the lost link occurred:

- Condition 1: Lost link during Departure Phase
- Condition 2: Lost link during Arrival Phase
- Condition 3: Lost link during En Route/Cruise Phase

The HITL consisted of twelve scenarios as well as one baseline scenario per condition.

Objective and subjective data were collected to evaluate the impact of lost link on ATCS and on operations in the terminal environment. Dependent measures collected during the simulation included safety, efficiency, communication, situation awareness measures, as well as controller workload.

Conclusions and Recommendations

Using standard lost link contingency procedures similar to existing IFPs (SIDs, STARs, IAPs) already in use for manned aircraft is a viable method for communicating lost link procedures to air traffic controllers, and could be useful tools for integrating UAS into the NAS.

Some airports may need customized lost link procedures (e.g., a holding turn or no holding turn before returning to base) depending upon the individual airport characteristics and typical traffic conditions. However, the UAS contingency procedures should be consistent within each airport so that ATCS are aware of the specific UAS flight maneuvers.

1. INTRODUCTION

This document, Validation of Unmanned Aircraft Systems (UAS)[1] Contingency Procedures and Requirements Terminal Human-in-the-Loop (HITL) Simulation Technical Report, describes one of many activities in a portfolio that supports requirements for investigating issues pertaining to the integration of UAS into the National Airspace System (NAS).

Within the aviation community, interest in using UAS for a broad range of purposes is increasing, making UAS access to the NAS a priority. The Federal Aviation Administration (FAA) reached a significant milestone with the implementation of Part 107, which permits small UAS (less than 55 pounds) daytime operations within visual line-of-sight and at or below 400 feet above ground level in uncontrolled airspace. However, outside the limits of Part 107, requests for access to the NAS are subject to technical and operational assessments of the specific UAS operation in question. It has been a growing imperative within the UAS community, including public and civil users, to reduce these restrictions and support more routine access in order to improve and advance integration of UAS into the NAS. Therefore, validated operational standards and policies need to be established.

While the initial focus has been on integrating UAS into today's NAS, it is necessary to maintain awareness of how the NAS will evolve in NextGen. With the increased use of UAS, issues that are unique to these aircraft are likely to arise. Many UAS do not have the same performance characteristics as manned aircraft, communication procedures between air traffic control (ATC) and the UAS operator/pilot-in-command (PIC) are dissimilar, and lost link and other UAS-related off-nominal events can occur. These issues pose new challenges for air traffic control specialists (ATCS) and it is essential that they be addressed in order to maintain NAS safety, efficiency, and capacity, which are cornerstones of NextGen.

1.1. BACKGROUND

In recent years the FAA has conducted a number of studies concerning UAS contingency conditions, such as lost link. In 2014, researchers conducted a HITL simulation intended to be a foundational study, building a baseline for follow-on work that could look for solutions to mitigate the impact of lost link and other contingency conditions. Entitled UAS Operational Assessment: Contingency Operations (Pastakia, et al., 2015), the goal was to determine the effects of specific UAS contingency events on system safety and efficiency in the NAS and on ATCS workload. Study results illustrated the potentially adverse effects that UAS contingency events can have on NAS operations and ATCS. At the same time, the study demonstrated the resiliency and capability of current ATCS in mitigating these effects and maintaining the priority of safety above all other factors. Participants indicated that enhanced predictability of contingency procedures and operations would greatly support integration of UAS into the NAS and minimize the impact on efficiency while maintaining system safety.

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[1] A UAS is the aircraft itself and all of the associated support equipment, control station, data links, telemetry, communications and navigation equipment, etc., necessary to operate the UA. The UA is flown by a pilot via a ground control system or autonomously using an on-board computer, communication links, and any additional equipment that is necessary for the UA to operate safely. A UA operates without the possibility of direct human intervention from within or on the aircraft.

In 2016-2017, a research effort entitled ATC Receipt and Display of Contingency Information (Pastakia et al., 2017) was initiated to explore contingency information and display needs. The objective of this task was to determine information and high-level display requirements for terminal and en route automation systems when an Instrument Flight Rules (IFR) flight plan is required. The main activity in the research was the conduct of two cognitive walkthroughs, one for terminal and one for en route domains. In both cognitive walkthroughs, the participants discussed information and procedural needs for UAS contingency events. Overall results from both the terminal and en route cognitive walkthroughs highlighted that ATCS need time to react after seeing that a UAS is lost link. They are more concerned with their awareness of the UAS lost link procedure rather what the actual procedure is; however, they did feel that the procedure is important.

One of the near-term recommendations from the cognitive walkthroughs that could be addressed today without significant modification to terminal and en route automation systems is that UAS contingency plans should match manned aircraft procedures to the maximum extent possible. Another recommendation that may be placed under some level of scrutiny is that lost link contingency procedures should be standardized in some manner to reduce the potential operational scenarios that ATCS may encounter, thereby enabling predictability. ATCS desire predictability so they would benefit from having only a few, known contingency procedures (e.g., continue on flight plan, divert to a dedicated location). Fewer options would simplify controller search procedures when they need to ascertain or confirm the contingency procedure for a specific operation.

1.2. OBJECTIVE

The objective of the research presented in this document is to consider recommendations from the aforementioned HITL and to validate findings from the Pastakia et al. (2017) research concerning procedural solutions to UAS lost link events in the terminal environment. A real-time HITL simulation allowed us to immerse ATCS in a laboratory setting to test mitigations for UAS contingency operations while assessing specific performance metrics. The HITL also assessed the impact/risks (e.g., workload, situation awareness) of the contingency procedures on terminal ATCS. Lastly, this HITL helped determine if Instrument Flight Procedures (IFPs) are a viable method for communicating UAS lost link procedures to ATCS.

1.3. SCOPE

The Validation of UAS Contingency Procedures and Requirements research supports the NAS Segment Implementation Plan (NSIP). The activities conducted under this research contribute to the Separation Management – UAS Concept Validation and Requirements Development. The research effort includes two HITL simulations, one in the terminal environment (described here) and one in the en route environment (described in a separate report), that are designed to assess the impact of UAS integration into the NAS. The terminal HITL simulation research is a follow-on activity to the Pastakia et al. (2017) research and builds upon previous exploratory studies.

2. METHOD

2.1. PARTICIPANTS

We recruited five groups of two terminal ATCS from TRACON facilities (level 7 and above) across the country to participate in the HITL simulation. The task lead and sponsor from ANG-C2 coordinated with AJV-7, ATO Technical Labor, and NATCA to secure ATCS as simulation participants.

2.2. LABORATORIES AND EQUIPMENT

This research effort made use of the WJHTC's laboratory infrastructure to successfully complete all of the research activities. In particular, we utilized the FAA NIEC laboratory. The NIEC is the FAA's research platform to explore, integrate, and evaluate advanced aviation concepts through simulation activities resulting in concept maturation and requirements definition; it is a flexible and extensible environment that consists of real and simulation systems as well as infrastructure capabilities to support the environment. Characteristics of the NIEC include:

- Representation and integration across multiple NAS domains in one facility
- A real-time, rapid prototyping and simulation environment that simulates the NAS while integrating NextGen concepts
- Voice communications capabilities
- Audio, video, and data recording capabilities
- Flexibility to support multiple concurrent studies

2.2.1 Audio-Video Recording System

We used the NIEC's audio-video recording system to record communication during the simulation. Each controller position had a microphone nearby to record communications and ambient noise. Each position also had an overhead camera to record the scope, the workload assessment keypad (WAK), and controller actions. The audio-video recordings allowed us to review playbacks of the simulation as needed to provide clarity about specific situations (e.g., in cases where the WAK response was missing, we could review the video to determine if a response was attempted).

2.2.2. Communication

A simulated communication environment allowed for realistic air-ground and ground-ground voice communication between simulation participants, simulation pilots, and ghost controllers. Each ghost controller position was equipped with an interphone and the ability to monitor the frequency of the two active (departure and arrival) sectors. Ghost position 1 simulated Oakland Tower and Hayward Tower as well as a Front Line Manager/Controller-in-Charge (FLM/CIC) position. Ghost position 2 simulated Oakland Center (ZOA).

2.3. HARDWARE

Air traffic controller workstations for the participants and ghost sector controllers were located in the NIEC laboratory. The lab configuration is depicted in Figure 1. Note in the figure, the departure participant sat at position 9R and the arrival participant sat at position 9G during the simulation.

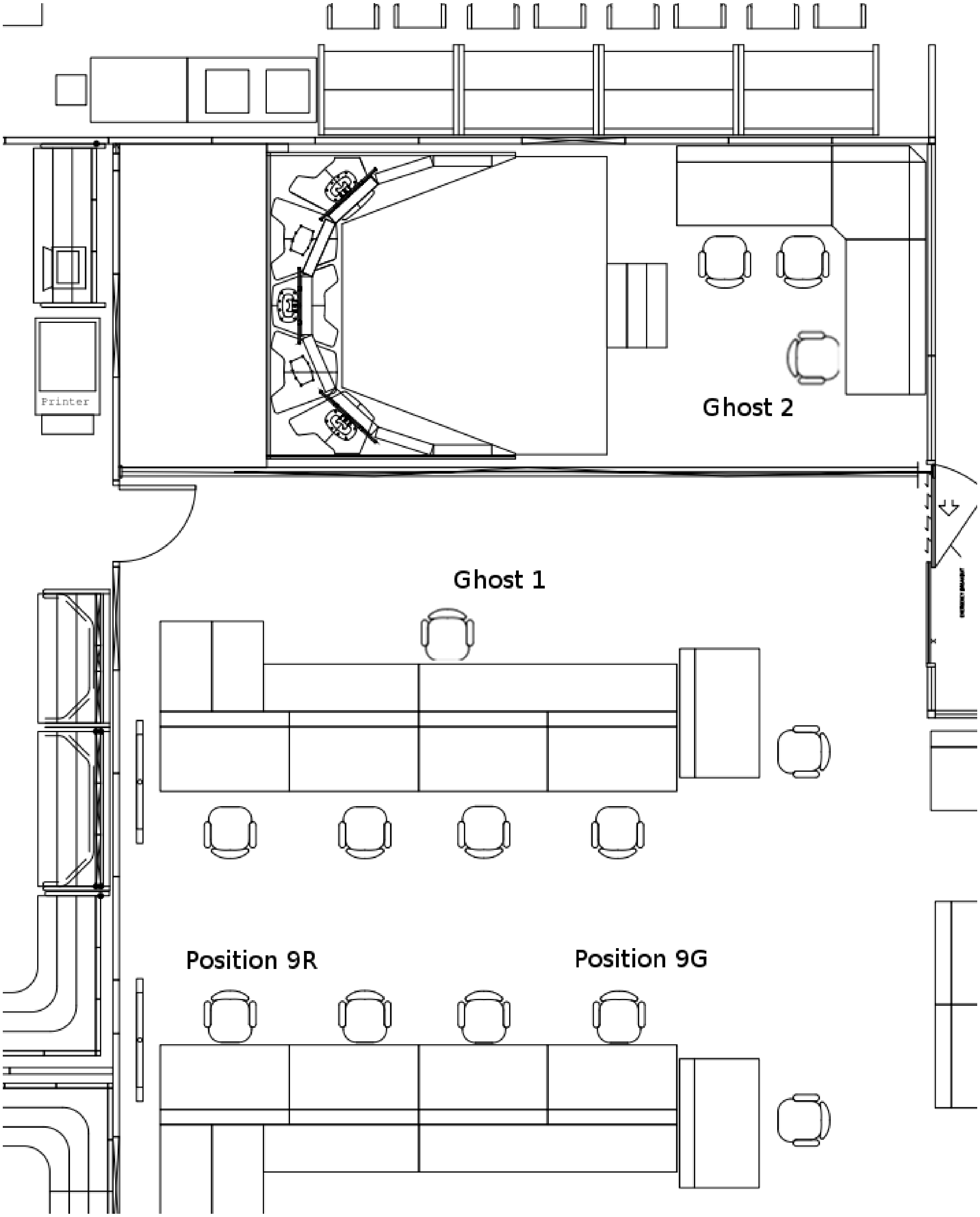

Figure 1. Simulation Participant and Ghost Controller Locations in NIEC Lab.

2.3.1. Air Traffic Control Terminal Workstation Consoles

Each ATCS workstation was equipped with a Barco ISIS 2K x 2K Liquid Crystal Display (LCD), a STAR keyboard and trackball, and an Interim Voice Switch Replacement (IVSR) communications system. The Barco LCD was designed for ATCS use and provided the same resolution (2048 x 2048 pixels) and display size (19.83" x 19.83", 28.05" diagonal) as those used in the field. Each position was also equipped with a simulated Automated Surface Observing System (ASOS) Controller Equipment-Information Display System (ACE-IDS) overhead display, which allowed participants to view information such as maps, published arrival and departure procedures, airport weather and status, and facility operating procedures.

Figure 2. ATCS Workstations

2.3.2. Ghost Sector Air Traffic Control Workstations

Two ghost sector workstations were required during the conduct of the simulation. Each workstation simulated sectors adjacent to the participants'. Like the other ATCS workstations, they included a monitor, keyboard, and trackball. Workstations also included audio communications, the ability to monitor simulated frequencies, and the ability to communicate directly with participants.

2.3.3. Simulation Pilot Workstations

Simulation pilot workstations were located in the TGF sim pilot laboratory, a separate room away from the NIEC. Each workstation consisted of a computer, keyboard, monitor, and communication equipment. Simulation pilots controlled TGF-generated aircraft using commands on their respective workstations. These commands are typically comprised of pre-defined strings of alphanumeric characters that pilots entered using a standard keyboard.

Each simulation pilot workstation provided a plan view (2-D) display of traffic and a list of assigned aircraft. For each assigned aircraft, the workstation provided information regarding the current state and flight plan data.

Figure 3. TGF Sim Pilot Workstations

2.4. SOFTWARE

The simulation utilized the Distributed Environment for Simulation, Rapid Engineering, and Experimentation (DESIREE) and TGF simulation engines. The TGF is a crosscutting infrastructure that drives terminal, en route, and other research laboratories at the WJHTC. DESIREE and TGF work together to immerse the research participant into a realistic environment that can emulate air traffic environments.

DESIREE consists of a series of interchangeable human-machine interfaces. It has the capability to emulate multiple ATC platforms and displays. Its purpose is to enable researchers to modify or add information and functionality to a variety of current ATC environments to allow for the evaluation of new concepts and procedures. DESIREE receives input from TGF that allows it to present information on a radar display (e.g., Standard Terminal Automation Replacement System (STARS), Display System Replacement (DSR), and En Route Automation Modernization (ERAM)), including radar tracks, flight data block (FDB), and sector maps. It also allows ATCS to perform the typical functions that they would perform in the appropriate ATC operational environment (e.g., performing handoffs, entering data into the host computer). DESIREE can also emulate ghost sector operations by providing automation to control these unstaffed sectors. When needed this automation can communicate with TGF to act as a simulation pilot for the aircraft. DESIREE has data collection capabilities and can collect information on all ATCS entries made during a simulation run.

TGF was designed to generate realistic aircraft trajectories and associated digital radar messages for aircraft in a simulated airspace environment. It uses preset flight plans and dynamic flight models to generate simulated surveillance tracks. The TGF algorithms control aircraft maneuvers so that they represent realistic climb, descent, and turn rates. In addition, TGF records information about aircraft trajectories, proximity, and other relevant data, which researchers use in subsequent analyses. Real-time information on each aircraft was output in DIS format to both the DESIREE displays and the Dynamic DSP Simulator (DDS) applications.

Use of a TGF aircraft model in simulation can sometimes be less costly than using simulators; however, it is a lower fidelity method of integrating a UAS into simulation. TGF models of UAS were either created in-house by TGF developers based on data from the UAS lab simulators or were based on NASA Base of Aircraft Data (BADA) models. In cases where a TGF model did not exist, we selected a surrogate aircraft model of a manned aircraft with flight characteristics that closely matched the desired flight characteristics of a particular UAS. TGF models emulated how a UAS flies (e.g., speed, turn rates) but not necessarily how it behaves. The responsiveness of an actual UAS and the TGF models differ; however, for the purposes of shakedown and simulation testing we scripted the scenarios in a manner such that we could fix the behavior of the UAS.

2.5. ASSUMPTIONS AND CONSTRAINTS

The FAA currently restricts how and where UAS can be operated; therefore, rules and procedures for operating outside Warning Areas or Restricted Airspace were defined according to current FAA regulations. Assumptions for this simulation were as follows:

- Single point of failure only: Loss of C2 link only in each scenario (two-way communications still existed)
- UAS squawked 7400 when a lost link occurred
- Standardized lost link procedures were known to ATCS and UAS operators; UAS platforms were programmed to comply
- A UAS lost link was not considered an emergency for the purposes of the HITL; however, ATCS advised the adjacent sector, control tower (ATCT), and/or FLM/CIC as necessary
- UAs were not able to comply with visual clearances or instructions
- UAs were integrated and used the same arrival and departures as manned aircraft
- UAs had auto-land capability
- UAs had certified DAA capabilities
- UAs filed an IFR flight plan with appropriate SIDs and/or STARs which incorporated lost link procedures
- UAS was deemed airworthy and had operational approval
- The expectation of a UAS lost link recovery was to fly the published lost link routing/approach, land, roll to the end of the runway, turn off runway, taxi across the hold line, and shut down
- The IFR flight plan included aircraft designation as a UAS by including a prefix ‘U’ in the aircraft type
- ‘U’ was used to depict UAS on flight progress strips and time shared in the FDB similar to ‘H’ for a heavy jet
- ATCS were familiar with aircraft performance characteristics (e.g., altitude limitations, speed)
- ATCS and UAS operators communicated via voice (air-to-ground)
- UAS PIC and flight crew were appropriately credentialed by the FAA
- UA was transponder and/or ADS-B equipped

- Airports were properly equipped to handle UAS ground operations

2.6. AIRSPACE

The airspace for the HITL was composed of simplified sectors and surrounding airspace based on the Mulford, Grove, Richmond, and Diablo sectors of NCT. These sectors provide air traffic services to the Oakland International Airport (KOAK), Hayward Airport (KHWD), and the surrounding area. The Mulford and Grove secotrs were combined to form the ‘arrival sector’ with delegated airspace of flight level 110 and below. The Richmond and Diablo sectors were combined to form the ‘departure sector’ with delegated airspace of flight level 190 and below in addition to airspace flight level 120-190 above the arrival sector. The traffic flow for KOAK was in a ‘west’ configuration using runways 28L, 28R, and 30. KHWD was in a similar configuration using runways 28L and 28R. We simplified the airspace to reduce the training time needed for ATCS participants to become familiar with the operation in preparation for the simulation.

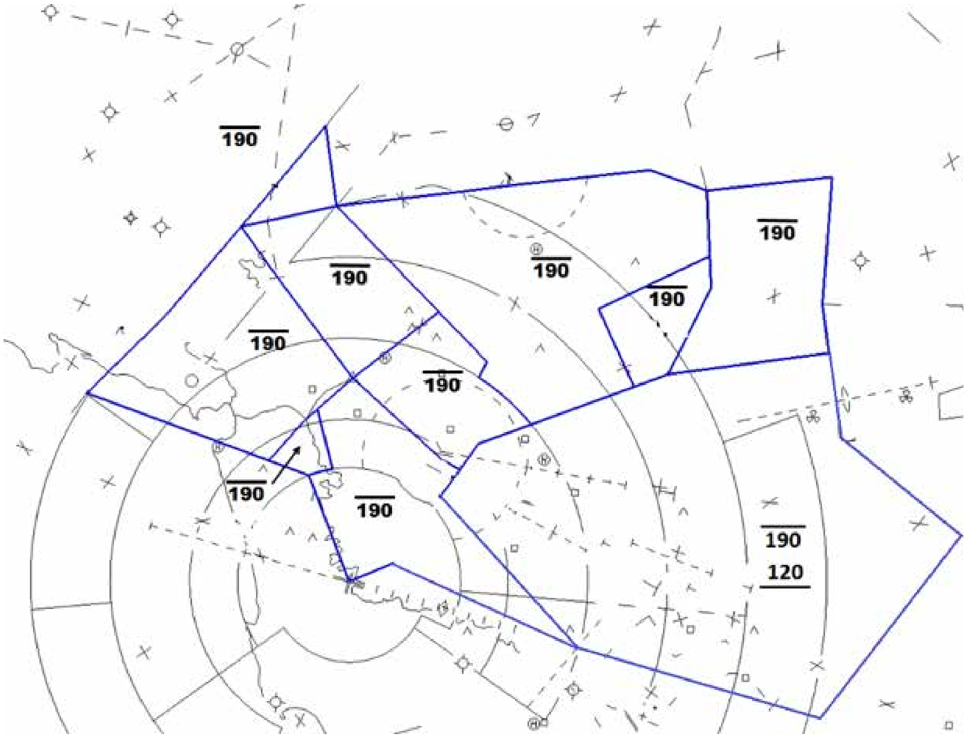

Figure 4. Departure Sector

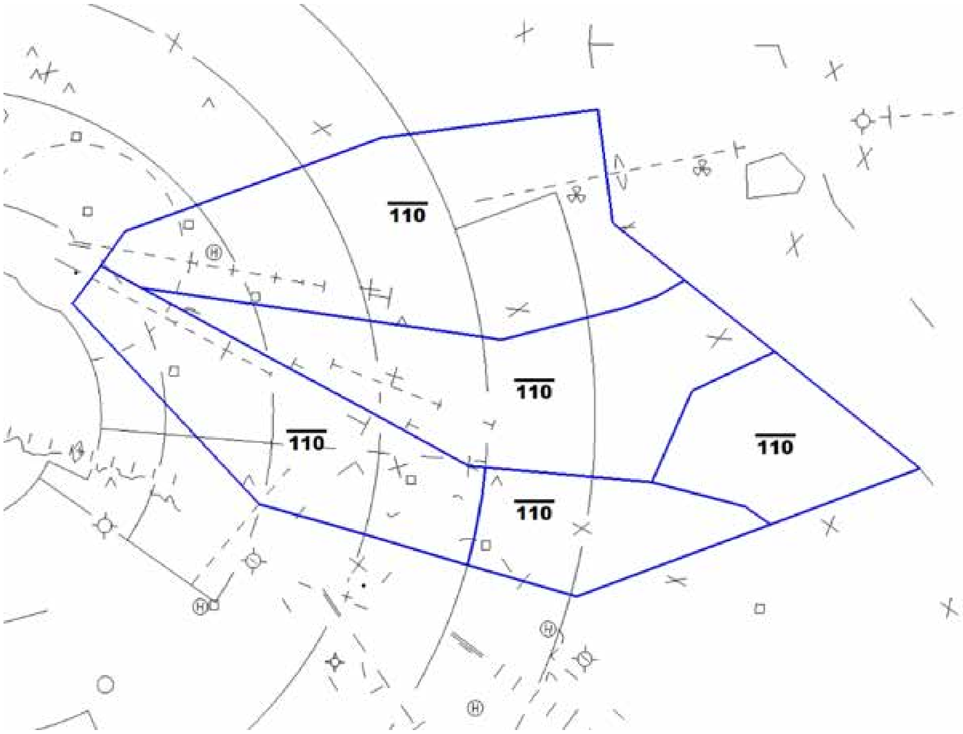

Figure 5. Arrival Sector

2.7. UAS PLATFORMS

Scenarios used two conceptual UAS platforms similar to known airframes:

- Single engine turbo prop; Cessna 208-like with a service ceiling of FL250 and cruise speed of 214 knots
- Single engine jet; Cirrus Vision Jet-like with a service ceiling of FL280 and a cruise speed of 330 knots

For the purposes of the simulation, we referred to each UAS as being 'like' a known aircraft as they had flight characteristics similar to those known platforms; however, the simulation did not evaluate specific aircraft.

These operated in the airspace as the aircraft of interest and were the only types of aircraft that could potentially experience lost link in the simulation. Cessna 208s and Cirrus Vision Jets could be either manned or unmanned.

As UAS become more prevalent with normalized operations in the NAS, the ability to differentiate between manned aircraft and UAS will become increasingly important to ATCS. We therefore prefixed the aircraft type with the character 'U' in the FDB and flight strips, similar to an 'H' for heavy jets (e.g., U/C208/R). The 'U' prefix allowed for increased ATCS situation awareness and potential changes such as lost link routing. We elicited feedback on the UAS designator from participants.

Background traffic included 10-20% unmanned aircraft with the rest of the traffic consisting of manned aircraft. Traffic in each scenario was composed of moderate traffic flows of departing, arriving, and en route/overflight aircraft.

2.8. INSTRUMENT FLIGHT PROCEDURES

Prior to scenario design, ATC SMEs evaluated all existing IFPs for KOAK and KHWD to determine viability for incorporating UAS lost link procedures. The SMEs identified and selected several IFPs for use in the simulation. The SMEs appended the contingency procedures to the IFPs as "NOTES" (see Vincent, et al., 2015 for a similar procedure). This allowed a UAS experiencing a lost link to transition onto a published segment of an arrival route and then execute an instrument approach into the subject airport. All IFPs used in the simulation can be found in Appendices B, C, and D.

2.9. MATERIALS

2.9.1. Informed Consent

Each participant read and signed an informed consent statement (Appendix A-1) before beginning the experiment. The informed consent statement described the study, the foreseeable risks, and the rights and responsibilities of the participants, including that their participation was voluntary. We protected all the information that the participant provided, including personally identifiable information (PII), from release except as may be required by statute. Signing the form indicated that the participant understood their rights as a participant in the study and gave their consent to participate.

The task lead offered to distribute a copy of FAA Order 1280.1B, "Protecting Personally Identifiable Information", to any participant who requested it as well as to answer any questions concerning that order.

2.9.2. Data Collection Instruments

We collected objective and subjective data during the simulation. Objective system data from TGF and DESIREE included safety and efficiency metrics such as the number of operational errors and the number of delays to manned aircraft. These measures provided information regarding what occurred during the different test conditions. The simulation was also video and audio recorded so that the research team could review the scenarios as needed during data analysis.

2.9.3. Background Questionnaire

We collected biographical data from participants via tablet. Before beginning the simulation participants completed a Background Questionnaire (Appendix A-2). The Background Questionnaire included items about age, gender, experience, and attitudes about participating.

2.9.4. Post-Scenario Questionnaire

At the end of each scenario, participants completed a Post-Scenario Questionnaire (PSQ; Appendix A-3), also via tablet, that asked them to provide subjective ratings regarding their performance, workload, and reactions to the test conditions (e.g., easy/difficult). Workload ratings in particular were assessed using a standard 10-point scale where 1 referred to very low workload and 10 referred to very high workload. The 10-point workload scale has been validated on numerous occasions in aviation research (Roscoe & Ellis, 1990; Stein & Rosenberg, 1983; Parasurman, Sheridan, & Wickens, 2008). The first six questions on the PSQ consisted of the NASA Task Load Index.

The NASA Task Load Index (TLX) is a subjective workload assessment tool that allows users to perform subjective workload assessments when working with various human-machine interface systems. Hart and Staveland (1988) originally developed the TLX for the NASA Ames Research Center. The NASA TLX has become the gold standard for measuring subjective workload across a wide range of applications. The NASA TLX asks users to rate their experience on six dimensions:

- Mental Demand
- Physical Demand
- Temporal Demand
- Performance
- Effort
- Frustration

The NASA TLX has been successfully used around the world to assess workload in various environments such as aircraft cockpits; command, control, and communication (C3) workstations; supervisory and process control; and simulations and laboratory tests (So, 2018).

2.9.5. Exit Questionnaire

At the end of the simulation, participants completed an Exit Questionnaire (Appendix A-4) which asked participants to provide ratings about the realism of the ATCS displays, effectiveness of pre-simulation training, and performance compared to actual operations using 10-point scales. It also prompted the participants to provide additional responses about their experience in the simulation and their impressions regarding overall effects on safety, efficiency, workload, and other measures across all of the test conditions.

2.9.6. Workload Assessment Keypad

Participants also provided workload ratings in real time via the WAK (Figure 6). A WAK was present at each ATCS position (excluding the ghost positions) and data was collected and time-stamped by DESIREE. The WAK consisted of a touch panel display with 10 numbered buttons. At three minute intervals, using auditory and visual signals, the WAK prompted the participants to press a button to provide their subjective workload rating. At the onset of the prompt the WAK emitted a brief tone and the background screen flashed yellow for 30 seconds or until the participant responded. The participant indicated their current workload by pressing one of the numbered buttons.

Figure 6. Workload Assessment Keypad (WAK)

2.10. PRE-TESTING

After thoroughly testing all the scenarios and equipment in the weeks prior, we conducted a validation session referred to as shakedown over three days. During shakedown, researchers and lab personnel worked through each of the test conditions and scenarios and collected the data from the system as planned for the simulation. Lab personnel also ensured that the system hardware and software were working correctly and identified any issues or problems for remediation and reevaluation prior to the simulation. During this time, we also ensured all data collection devices were functioning as required and that data files contained the information necessary for later analysis.

3. EXPERIMENTAL DESIGN

3.1. SCENARIOS

This study included 12 scenarios in which lost links occurred plus one baseline scenario per grouping of scenarios (phase of flight). Scenarios were divided by condition which was based on phase of flight in which the lost link occurred:

Table 1. Simulation Experimental Conditions

Condition 1, Lost Link During Departure Phase	
1.1	Baseline Nominal
1.2	Lost Link Return to Airport, No Hold (jet)
1.3	Lost Link Return to Airport, No Hold (prop)
1.4	Lost Link Return to Airport, Hold (jet)
1.5	Lost Link Return to Airport, Hold (prop)
Condition 2, Lost Link During Arrival Phase	
2.1	Baseline Nominal
2.2	Lost Link Continue on Flight Plan (jet)
2.3	Lost Link Continue on Flight Plan (prop)
2.4	Lost Link Land Opposite Direction (jet)
2.5	Lost Link Land Opposite Direction (prop)
2.6	Multiple Lost Link (two jets)
2.7	Multiple Lost Link (two props)
Condition 3, Lost Link During En Route/Cruise Phase	
3.1	Baseline Nominal
3.2	Lost Link Divert to Alternate Airport (jet)
3.3	Lost Link Divert to Alternate Airport (prop)

While the three baseline scenarios were largely similar due to the lack of a lost link UAS, they did vary slightly in traffic level and pattern. We created each lost link scenario by having an aircraft in its respective baseline scenario lose link and follow the appropriate procedure. The following sections described each scenario in detail.

3.1.1 Baseline Scenarios

Scenarios 1.1, 2.1, and 3.1 contained traffic composed of a mix of prop, turbo prop, and jet aircraft; all UAS experienced nominal conditions. The UAS departed, overflew, and arrived in normal sequence mixed with manned aircraft on designated routes for their performance level.

The goal of these scenarios was to demonstrate the handling of the UAS as it transitioned terminal airspace with manned aircraft to tease out any differences between manned and unmanned aircraft, and to provide a comparison point for the lost link conditions.

3.1.2. Condition 1, Lost Link During Departure Phase

In each departure lost link scenario, the UAS departed in normal sequence mixed with manned aircraft on a designated departure route. After airborne on departure, the UA lost control link and squawked 7400. After following the appropriate lost link procedure, the UA landed autonomously on the runway in use. These scenarios in general allow for the examination of any differences between nominal unmanned aircraft operations and a lost link on departure situation.

- Scenarios 1.2 and 1.3 – Lost Link Return to Airport, No Hold (jet or prop)

A Cirrus Vision Jet-like (scenario 1.2) or C208-like (scenario 1.3) UAS experienced lost link. The procedure was for the UA to proceed via the assigned departure route to a designated fix inside the terminal airspace (ALTAM) at the last assigned altitude, turn and fly direct to a designated arrival fix (BBUBB) inside the terminal airspace, then descend and return to the airport via the arrival route and specified IAP.

Comparing these two scenarios to each other allows for the examination of potential differences based on the type of aircraft to go lost link. Comparing these two scenarios to scenarios 1.4 and 1.5 allows for the examination of the impact of using a delaying turn to give ATCS more time to prepare for the return route.

- Scenarios 1.4 and 1.5 – Lost Link Return to Airport, Hold (jet or prop)
  A Cirrus Vision Jet-like (scenario 1.4) or C208-like (scenario 1.5) UAS experienced lost link. The procedure was for the UA to proceed via the assigned departure route to a designated fix inside the terminal airspace (ALTAM) at the last assigned altitude and execute one complete turn in holding. After completing the hold, the UA would fly direct to a designated arrival fix (BBUBB) inside the terminal airspace, then descend and return to the airport via the arrival route and specified IAP. The UA landed autonomously on the runway in use.

3.1.3. Condition 2, Lost Link During Arrival Phase

In each arrival lost link scenario, the UAS flew an arrival procedure in terminal airspace mixed with manned aircraft. At a point in the route, the UA lost control link and squawked 7400. After following the appropriate lost link procedure, the UA landed autonomously on the runway. These scenarios in general allow for the examination of any differences between nominal unmanned aircraft operations and a lost link on arrival situation.

- Scenarios 2.2 and 2.3 – Lost Link Continue on Flight Plan (jet or prop)
  A Cirrus Vision Jet-like (scenario 2.2) or C208-like (scenario 2.3) UAS experienced lost link in the participant’s airspace. The procedure was for the UA to fly the correct arrival and approach procedure for the runway in use.

  Comparing these two scenarios to each other allows for the examination of potential differences based on the type of aircraft to go lost link. Comparing these two scenarios to scenarios 2.4 and 2.5 allows for the examination of the impact of an opposite-direction arrival, and comparing to scenarios 2.6 and 2.7 allows for the examination of the impact of multiple lost links occurring at the same time.

- Scenarios 2.4 and 2.5 – Lost Link Land Opposite Direction (jet or prop)
  A Cirrus Vision Jet-like (scenario 2.4) or C208-like (scenario 2.5) UAS experienced lost link at a point outside the participant’s airspace. Prior to the lost link, the IFR flight plan contained a STAR that was filed based on predicted weather and the expectation of an east flow air traffic operation at KOAK. Subsequent to the lost link event, a wind shift occurred at KOAK that necessitated a change in air traffic operations to a west flow. The UA flew the pre-programmed opposite direction arrival to the runway in use.

- Scenarios 2.6 and 2.7 – Multiple Lost Link (2 jets or 2 props)
  Two lost link events occurred in a partially overlapping period – one on departure and one on arrival.

  A Cirrus Vision Jet-like (scenario 2.6) or C208-like (scenario 2.7) UAS experienced lost link. The lost link arrival had been coordinated ahead of time from the external facility (Oakland ARTCC ZOA, by the ghost controller). The UA flew the correct arrival as in scenarios 2.2 and 2.3.

  After airborne on departure, a second UA lost control link. The procedure was the same as scenarios 1.2 and 1.3 (return to airport with no hold).

3.1.4. Condition 3, Lost Link During En Route/Cruise Phase

In each cruise lost link scenario, the UAS was flying through terminal airspace (neither departing from nor arriving in the participant's airspace) mixed with manned aircraft. At a point in the route, the UA lost control link and squawked 7400. The procedure was for the UA to continue on flight plan at the assigned altitude until the designated divert fix (VINCO). Upon reaching the divert fix the UA would turn onto the arrival route, descend, and execute the designated IAP into the alternate airport (KWHD). The UA landed autonomously on the runway in use. These scenarios in general allow for the examination of any differences between nominal unmanned aircraft operations and a lost link with diversion situation.

- Scenarios 3.2 and 3.3 – Lost Link Divert to Alternate Airport (jet or prop)
  A Cirrus Vision Jet-like (scenario 3.2) or C208-like (scenario 3.3) UAS experienced lost link.

  Comparing these two scenarios to each other allows for the examination of potential differences based on the type of aircraft to go lost link

3.2. INDEPENDENT VARIABLES

We examined the following independent variables:

1. **Phase of Flight for Lost Link Event**
   We examined procedures that took place in one of the departure, arrival, or cruise phases of flight. All scenarios for a specific phase of flight had identical background (non-lost link UAS) traffic with randomized call signs, although the overall level of traffic was kept consistent across the three flight phase conditions.

2. **Type of UAS Involved in Lost Link Event**
   We examined how the type of UAS that experienced lost link affected operations by running two versions of each contingency procedure with one of two different UA in order to evaluate the effects of different performance characteristics. The first aircraft

was a single engine jet (similar to a Cirrus Vision Jet) and the second aircraft was a single engine turbo-prop (similar to a Cessna Caravan C208).

3. **Type of Contingency Procedure for Lost Link Event**
   Contingency procedures were specific to the phase of flight of the lost link aircraft. We evaluated:
   - Return to airport after departure – one variation with a holding delay and one without
   - Continue on flight plan – one variation continuing in on flight plan with other traffic, in the other arriving at the opposite direction runway
   - Divert to alternate airport – in the last contingency procedure the UA flew to an alternate airport and landed
4. **NCT Sector**
   The HITL assessed two sectors in NCT airspace:
   - OAK West, Departures
   - OAK East, Arrivals

3.3. DEPENDENT VARIABLES

We collected the following dependent measures during the simulation:

1. **Safety Measures**
   Number of losses of separation involving manned and UAS aircraft
   Duration of loss of separation
   Closest point of approach during loss of separation

2. **Efficiency Measures**
   Airport acceptance rate
   Number of departures

3. **Communication Measures**
   Number of ATCS-pilot communications
   Duration of communications

4. **ATCS Workload Measures**
   Number of sim pilot commands entered
   WAK
   NASA-Task Load Index

5. **ATCS Situation Awareness Measures**
   Subjective situation awareness on PSQ

6. **ATCS Preference Measures**
   Subjective preferences on various topics on PSQ

3.4. PROCEDURE

3.4.1. Schedule of Events/Timeline

The table below is an example of the weekly schedule of simulation scenarios.

Table 2. Weekly Schedule of Events

Time	Day 1 Tuesday	Time	Day 2 Wednesday	Time	Day 3 Thursday
8:00	Welcome, In Brief	8:00	Scenario 3	8:00	Scenario 10
8:30		8:30		8:30	
9:00		9:00	Scenario 4	9:00	Scenario 11
9:30		9:30		9:30	
10:00	Practice Scenario 1	10:00	Scenario 5	10:00	Scenario 12
10:30		10:30		10:30	
11:00	Practice Scenario 2	11:00	Scenario 6	11:00	Scenario 13
11:30		11:30		11:30	
12:00	LUNCH	12:00	LUNCH	12:00	LUNCH
12:30		12:30		12:30	
1:00	Practice Scenario 3	1:00	Scenario 7	1:00	Scenario 14
1:30		1:30		1:30	
2:00	Practice Scenario 4	2:00	Scenario 8	2:00	Scenario 15
2:30		2:30		2:30	
3:00	Scenario 1	3:00	Scenario 9	3:00	End of Simulation Debrief
3:30		3:30		3:30	
4:00	Scenario 2	4:00	Daily Debrief	4:00	
4:30		4:30		4:30	

3.4.2. In-Brief

On the first day of the study, the research task lead introduced the research team to participants and then briefed them on the background and objectives of the study. An ATCS SME then gave a brief overview of the airspace, procedures, and simulated, laboratory environment the participants would experience. After the briefings the participants completed an informed consent form along with a background questionnaire (see Section 2.9).

3.4.3. Training/Practice Scenarios

Following the in-brief, we gave participants a brief overview of the laboratory equipment. The participants then controlled traffic in practice scenarios as ATCS SMEs observed and were on standby to answer questions. The practice runs served to familiarize participants with the test environment, interactions with the simulation pilots, and usage of the WAK. Practice scenarios used the same airspace as the experimental scenarios and featured arrivals and departures following the same procedures; however, the traffic density was lower. We confirmed with participants that they were sufficiently prepared to begin data collection runs after completing the practice scenarios.

3.4.4. Data Collection Procedure

The simulation ran over a five-week period. Each week consisted of two travel days for the participants and three days of training and simulation. The HITL contained 15 data collection scenarios over the course of the three days. Each scenario lasted approximately 30 minutes.

We collected data in the form of audio and video recordings of ATCS, telemetry data from TGF, questionnaires, workload assessment via the WAK, and other forms of operational and performance data via DESIREE.

4. DATA ANALYSIS METHODOLOGY

We used Bayesian methods to model the impact of the independent variables on the dependent variables (see Sections 3.2 and 3.3). Each dependent variable was modeled separately using a Bayesian multilevel generalized linear regression (see Appendix F for a detailed description of the models). The one exception was loss of separation data, which included the number of losses, the point of closest approach during a loss, and duration of loss of separation. Due to the small number of events, particularly when limited to those losses that involved a UAS, the model provided a poor description of the data. As such, the report provides only summary statistics of the loss of separation results.

4.1. HOW RESULTS ARE REPORTED

Most readers are likely more familiar with frequentist statistical methods that result in a p-value and sometimes a confidence interval (CI). The p-value is the probability of a statistical result given a null hypothesis. The CI (commonly set to 95%, thus termed the 95% CI) gives the probability that a given CI would include the real value of, say, a mean if the experiment were repeated many, many times and the CI calculated for each. A statistical result is commonly termed ‘significant’ if the p-value is less than .05. The CI and level of significance for the p-value are related such that if the p-value is less than .05, the 95% CI will also exclude zero. In contrast, Bayesian methods do not use a p-value and instead of a CI use what is called a high-density interval (HDI). The HDI is interpreted in the way that many people intuitively think a CI should be (but is not) interpreted: a 95% HDI tells us the range of values that we can be 95% certain the actual value falls in.

Following the typical convention but with Bayesian statistics, this report uses 95% HDIs and refers to comparisons as ‘significant’ if the 95% HDI excludes zero. It also reports a single-number ‘confidence’ in a comparison, similar to a p-value, by examining how much of the Bayesian posterior probability falls to one side or the other of a comparison point. For example, say that the distance flown by aircraft in condition A is compared to the distance flown in condition B. The 95% HDI may find that the difference between conditions ranges from 0.5 to 3.1 nautical miles (nm; e.g., condition A’s mean distance flown is higher than condition B’s), but the model also finds a 1% chance that the difference could be negative (i.e., condition B actually has a higher mean than condition A if we had access to the population instead of a sample). This would be reported as a significant difference between A and B with 99% confidence in the difference (the complement of the 1% chance that B is truly higher than A) and a 95% HDI of (0.5, 3.1) nm.

Aside from the description of participant demographic data and sector differences, the results are organized according to condition (i.e., phase of flight). Within each condition, results are broken out for each type of dependent variable (e.g., safety). Only statistically significant results (95% confidence or greater) are reported along with some select results that are consistent with statistically significant results but did not reach significance themselves. An exhaustive summary of results can be found in the appendices. Please note that for non-normally distributed data (e.g., WAK data, survey responses; see Appendices F, G, and H) the HDI values may not be on the same scale as the data.

5. RESULTS

5.1. PARTICIPANT BACKGROUND QUESTIONNAIRE

Participants were active controllers from nine different facilities across the contiguous United States. Participant ages ranged from 29 to 53 years old with a median age of 38. All participants were male. Participants' years of experience as ATCS (including possible military time) ranged from 4 to 31 (median of 10) years with a range of 2 to 21 (median of 9) years specifically in a TRACON facility. Only one participant controlled traffic for less than all of the previous year; that participant reported six months of active work. None of the participants had prior experience working UAS and all reported neutral (neither positive nor negative) feelings as to how UAS impact ATC services.

5.2. ARRIVAL AND DEPARTURE SECTORS

Differences between the arrival and departure sectors were not of primary interest in this HITL. That said, sector was included as a factor in all appropriate analyses (excluding, for example, number of arriving aircraft where there is no need to separate the sectors) in order to control for differences between the two. Many of the dependent variables suggested that participants working traffic in the arrival sector had more difficulty than those working the departure sector. For example, all losses of separation observed during the HITL occurred in the arrival sector. Arrival participants also gave systematically higher WAK responses than departure participants did. The scenarios were not designed for the arrival sector to be more difficult than the departure sector; however, more traffic appeared in the arrival sector by the nature of how the operations in some scenarios played out.

5.3. CONDITION 1 – DEPARTURE PHASE

Only statistically significant results are reported. Please note that for non-normally distributed data (e.g., WAK data, survey responses; see Appendices F, G, and H), the HDI values may not be on the same scale as the data. Recall that there were three scenario types in Condition 1 (see

Section 3.1.2): the baseline where no lost link occurred, the return-without-hold condition where a lost link UAS turned and entered back into the arrival stream, and the return-with-hold condition where a lost link UAS performed one turn in holding in the departure sector before entering the arrival stream.

5.3.1. Safety

5.3.1.1. Loss of Separation (all aircraft)

Recall that statistical analysis of the loss of separation (LOS) data was not plausible. That said, there were more LOS during the return-without-hold condition (eight) than the return-with-hold condition (five). Those LOS also tended to involve UAS, and particularly the lost link UAS, more often (four UAS involved in three separate events, three of them with lost link, in return-without-hold scenarios compared to one non-lost link UAS in return-with-hold scenarios).

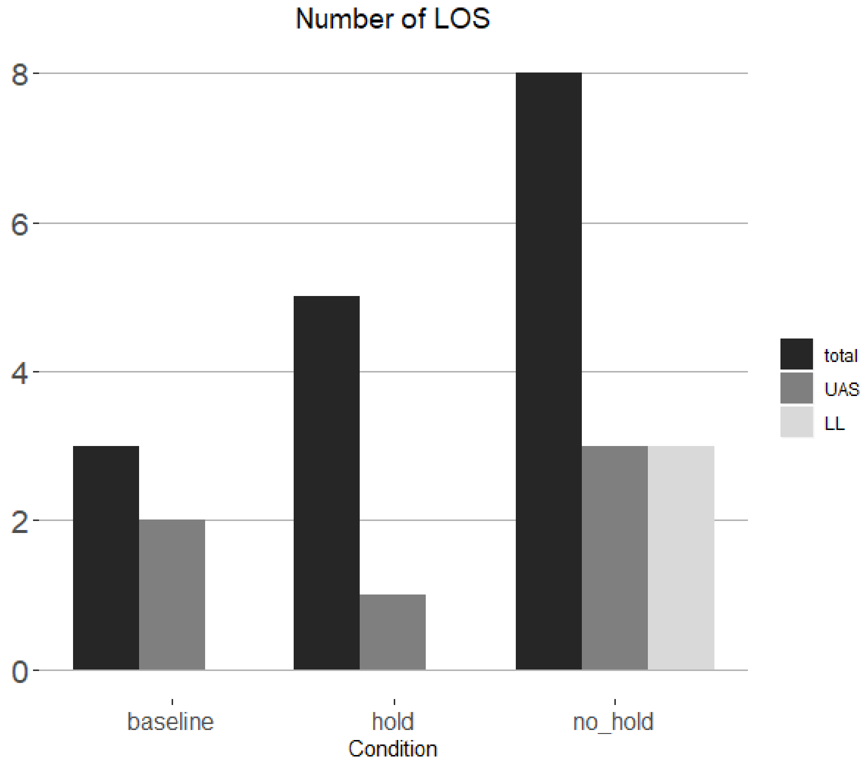

Figure 7. Number of loss of separation events during Condition 1 by scenario type.

In addition to fewer LOS occurring during the return-with-hold scenarios, those that did occur were shorter (median of 140 seconds compared to 218 seconds in the return-without-hold scenarios). There was not a notable difference between the two conditions in closest point of approach. While there were few LOS during baseline scenarios, those that occurred tended to last longer (median of 311 seconds) and involve the aircraft coming closer together (median of 0.95 nm) than those that occurred during the lost link scenarios.

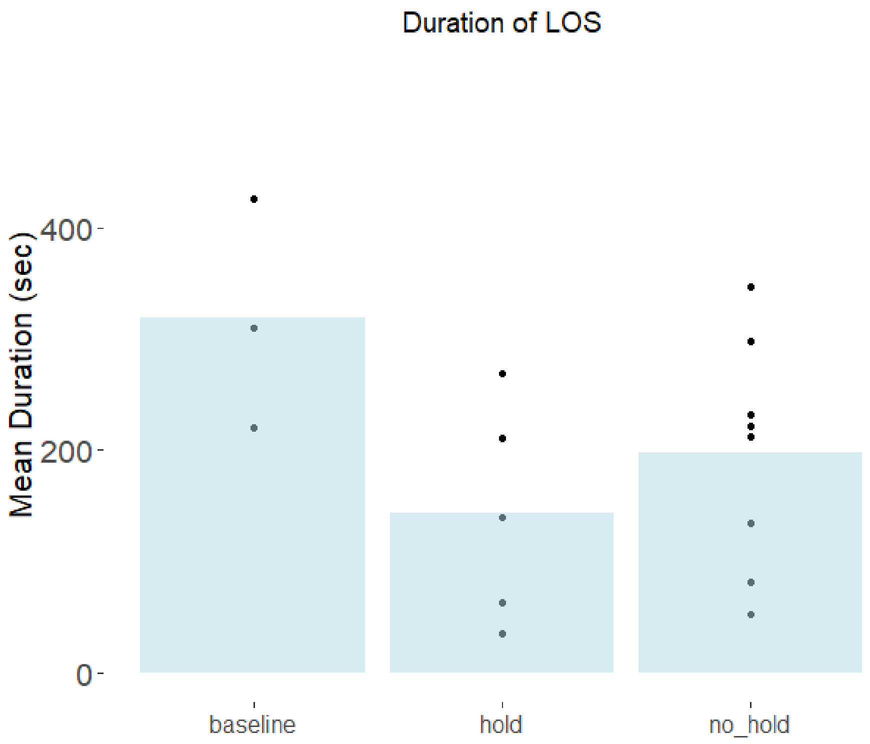

Figure 8. Duration of loss of separation events during Condition 1 by scenario type. Bars indicate scenario mean while dots indicate individual events.

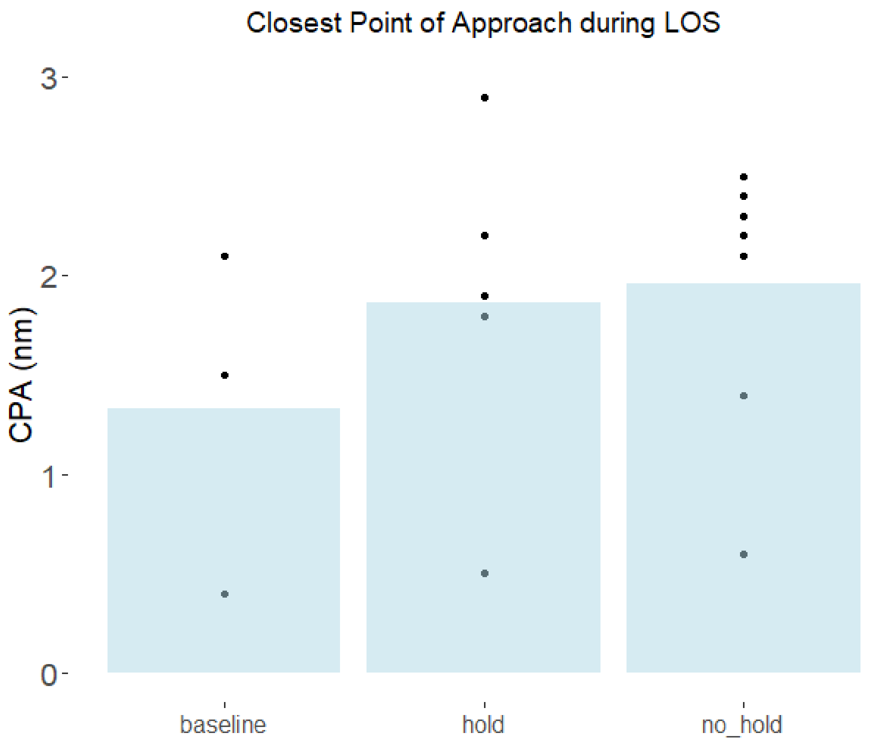

Figure 9. Closest point of approach during loss of separation events during Condition 1 by scenario type. Bars indicate scenario mean while dots indicate individual events.

5.3.1.2 Loss of Separation (UAS only)

When limiting focus to only those LOS that involved a UAS, we observed the same pattern of results as in the all-aircraft data. However, there were very few LOS events involving at least one UAS (two in the baseline condition, three in the return-without-hold, and one in the return-with-hold).

5.3.2. Workload

5.3.2.1. WAK Responses

Participants responded with higher workload ratings to the prompts that immediately followed the entrance of a lost link UAS into their sector (mean response 3.9 vs. 5.2; 95% HDI [0.07, 1.11], 98% confidence).

5.3.2.2. NASA-TLX

There was a significant difference across conditions in response to question 3, Temporal Demand. The mean response after finishing a return-with-hold scenario was 6.0 (on the scale 1 = extremely low to 10 = extremely high) whereas the mean response was lower after finishing either a return-without-hold (5.7; 95% HDI [-0.5, 0.9], 62% confidence) or baseline (4.7; 95%

HDI [0.1, 1.9], 98% confidence) scenario. The difference was only statistically significant in comparison to the baseline but we report all comparisons because the responses fit a pattern.

Overall, there was some evidence for a difference in workload across departure scenarios as reported on the NASA-TLX. There was only a single statistically significant difference, as described above, but the return-with-hold condition also tended to receive the highest ratings on the other questions (Figure 10).

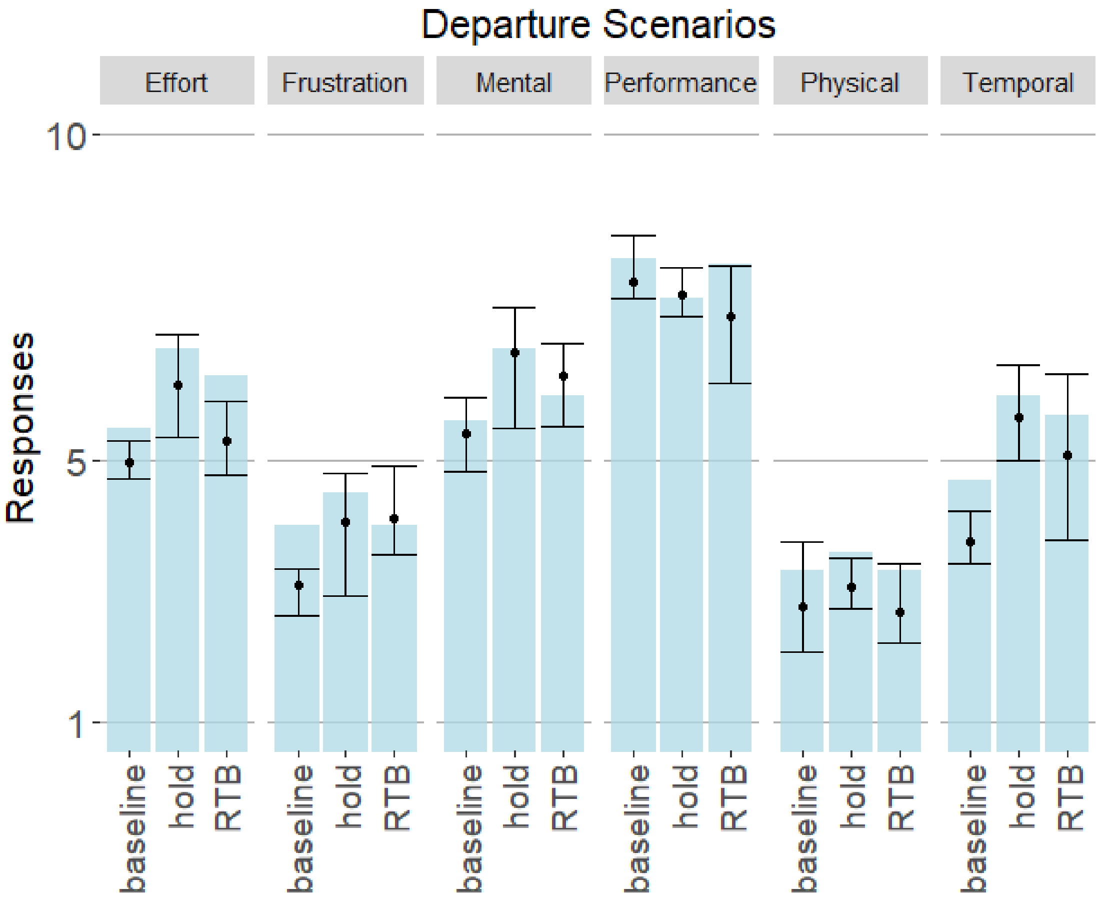

Figure 10. NASA TLX responses for Condition 1. Bars indicate scenario mean while dots and error bars indicate model mean and 95% HDI.

5.4. CONDITION 2 – ARRIVAL PHASE

Only statistically significant results are reported. Recall that there were four scenario types in Condition 2 (see Section 3.1.3): the baseline condition where no lost link occurred, the ‘continue in’ condition where a lost link UAS inbound from the east simply followed its original landing plan; the opposite-direction–landing condition where a lost link UAS inbound from the west lands from the west against current airport operations; and the multiple lost link condition where two UAS experience lost link events, one arrival following the continue-in procedure and one departure following the return-without-hold procedure.

5.4.1. Safety

5.4.1.1. Loss of Separation (all aircraft)

Recall that statistical analysis of the loss of separation (LOS) data was not plausible. There were no LOS during the arrival baseline condition. The number of LOS were similar for the three lost link conditions but we observed a tendency for the duration of LOS to be longest in the multiple lost link condition (median of 200 seconds) and shortest in the continue-in condition (median of 80 seconds).

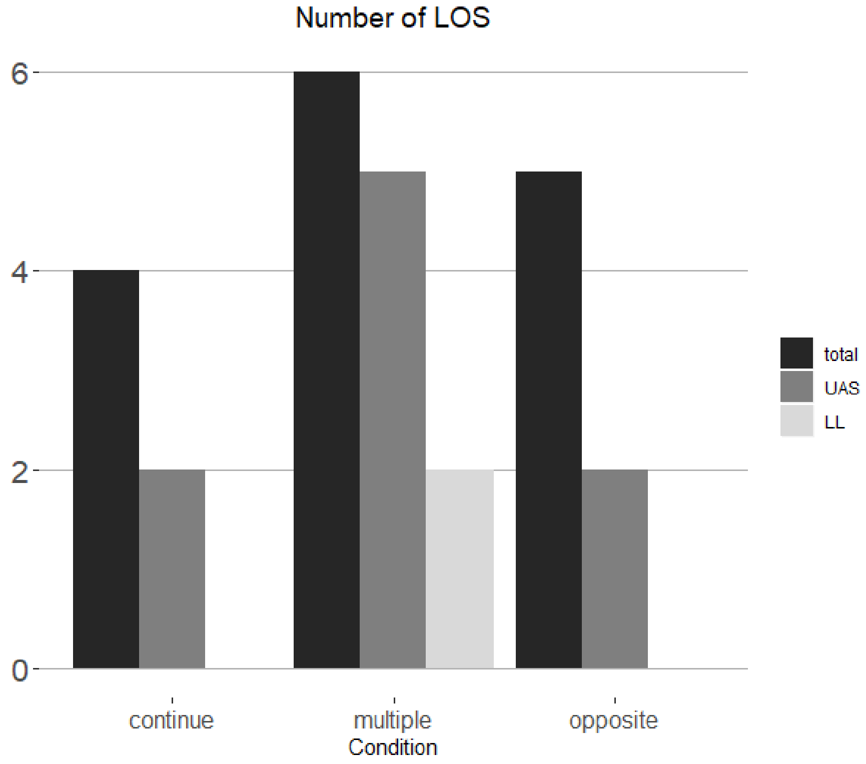

Figure 11. Number of loss of separation events during Condition 2 by scenario type.

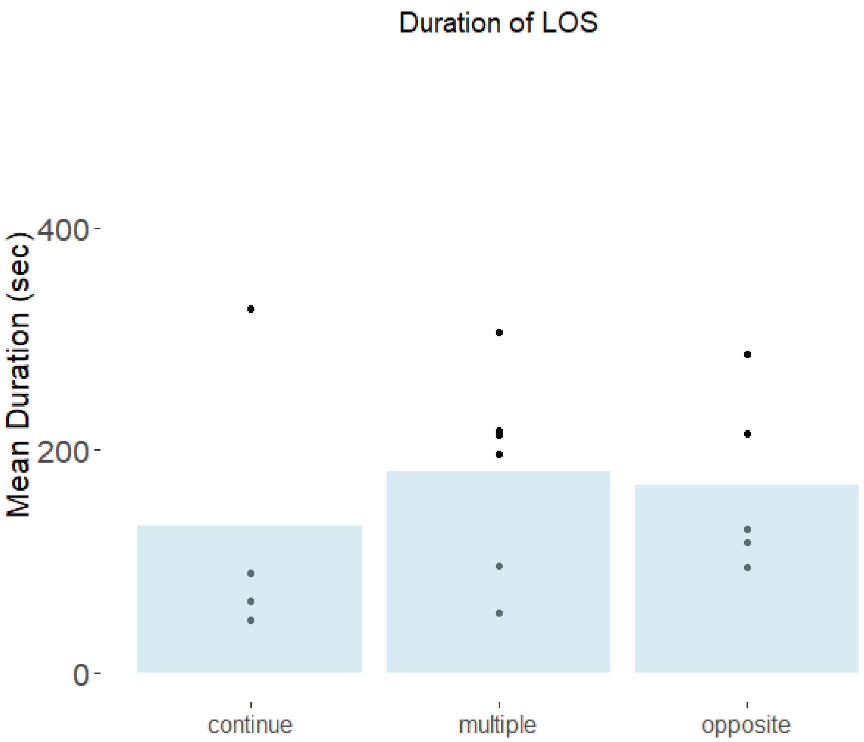

Figure 12. Duration of loss of separation events during Condition 2 by scenario type. Bars indicate scenario mean while dots indicate individual events.

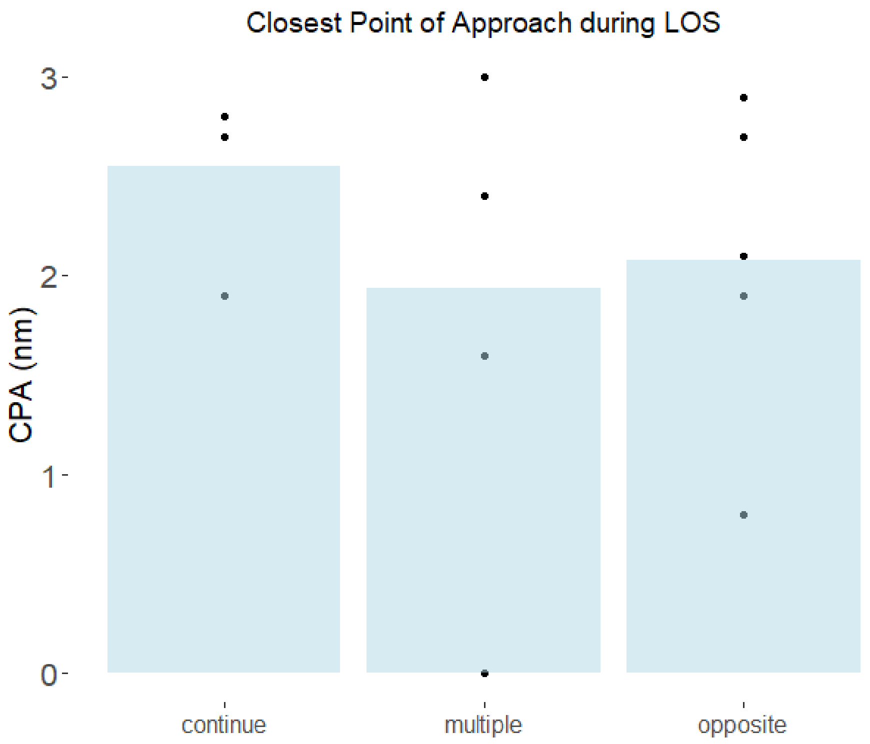

Figure 13. Closest point of approach during loss of separation events during Condition 2 by scenario type. Bars indicate scenario mean while dots indicate individual events.

5.4.1.2. Loss of Separation (UAS only)

While limiting focus to only those LOS that involved a UAS, we observed that more LOS occurred during the multiple lost link condition (five) than the other two lost link conditions (two each). Conversely, it could be said that LOS involving only manned aircraft occurred more often during the continue-in and opposite-direction conditions. Otherwise, there were no notable differences across conditions.

5.4.1.3. Post-Scenario Questionnaires

Question 7 on the PSQ asked participants to rate their performance in safely resolving the lost link (on the scale 1 = extremely low to 10 = extremely high). Participants rated their performance lower on the continue-in (mean rating 6.3) compared to the multiple lost link (8.4; 95% HDI [-2.8, -1.7], 99% confidence) or opposite-direction (7.8; 95% HDI [-2.8, -0.2], 100% confidence) conditions. However, this appears to be because participants at the departure position did not consider the continue-in procedure to be lost link and gave a low response (mean response for arrival participants 9.2, mean response for departure participants 3.1).

Question 9 on the PSQ asked participants to rate the overall safety of the scenario (on the scale 1 = extremely low to 10 = extremely high). Participants rated safety lower on the opposite-direction (mean rating 7.1) compared to the baseline (8.5; 95% HDI [-3.7, -1.0], 99%

confidence) or continue-in (9.0; 95% HDI [-3.5, -1.5], 100% confidence) conditions. The opposite-direction mean rating was also lower than the multiple lost link mean rating (8.4). While the comparison to the multiple lost link condition is lower than the standard 95% (only 75%), we report it as there appears to be a pattern such that the opposite-direction condition received the lowest responses.

5.4.2. Efficiency

5.4.2.1. Number of Departures

We observed fewer departures in the opposite-direction condition (179 across nine scenario runs, or an average of 19.9 departures per scenario) compared to the other conditions (26.8 in baseline, 95% HDI [-0.5, 0.2], 79% confidence; 26.6 in continue-in, 95% HDI [-0.5, -0.1], 99% confidence; 25.9 in multiple, 95% HDI [-0.5, -0.1], 99% confidence). The decrease was likely caused by participants holding departures during the lost link UA's arrival. There tended to be slightly fewer departures in the jet (mean of 18.8) compared to the turboprop (20.8) versions of the opposite-direction scenario.

5.4.2.2. Post-Scenario Questionnaires

Question 8 on the PSQ asked participants to rate their performance in efficiently resolving the lost link (on the scale 1 = extremely low to 10 = extremely high). Participants rated their performance lower on the continue-in (mean rating 6.3) compared to the multiple lost link (8.0; 95% HDI [-2.9, -0.5], 99% confidence) or opposite-direction (7.4; only 85% confidence) conditions. However, this appears to be because participants at the departure position did not consider the continue-in procedure to be lost link and gave a low response (mean response for arrival participants 9.3, mean response for departure participants 2.9).

Question 10 on the PSQ asked participants to rate the overall efficiency of operations (on the scale 1 = extremely low to 10 = extremely high). Participants rated efficiency lower in the opposite-direction (mean rating 7.4) compared to the continue-in (8.7; 95% HDI [-2.2, -0.7], 100% confidence) condition.

5.4.3. Situation Awareness

5.4.3.1. Post-Scenario Questionnaires

Question 13 on the PSQ asked participants to rate their overall situation awareness (on the scale 1 = extremely low to 10 = extremely high). Participants rated their situation awareness higher on the continue-in (mean rating 8.8) compared to the baseline (8.1; 95% HDI [0.1, 2.0], 96% confidence) or multiple lost link (7.8; 95% HDI [-0.1, 2.2], 92% confidence) conditions. The average rating in the opposite-direction condition was 8.1, similar to the latter two conditions, but the comparison to the continue-in condition only had a statistical significance of 80%.

5.4.4. Workload

5.4.4.1. WAK Responses

Participants responded with higher workload ratings to the prompts that immediately followed the entrance of a lost link UAS into their sector (mean response 3.9 vs. 5.2; 95% HDI [0.07, 1.11], 98% confidence). This occurred for arrival sector participants in the multiple lost link scenario (for both lost link UAs) as well as the continue-in scenario, and for the departure sector participants in the multiple lost link scenario (one UA) and the opposite-direction scenario.

5.4.4.2. Communications

We observed a significant difference in the average duration of communications in the opposite-direction condition (5.25 seconds) compared to the multiple lost link (4.94; 95% HDI [0.0, 1.1], 96% confidence) condition. The baseline and continue-in conditions fell in the middle and were not significantly different from any other conditions. There tended to be more communications in the baseline condition (mean 153) than the multiple lost link (149; 95% HDI [-0.2, 0.0], 91% confidence), continue-in (150; 95% HDI [-0.2, 0.1], 90% confidence), or opposite-direction (128, 95% HDI [-0.3, -0.1], 99% confidence) conditions. Additionally, the opposite-direction condition had fewer communications than either of the other two lost link conditions (100% confidence for both comparisons, both 95% HDIs [-0.3, -0.1]). The large decrease in number of communications during the opposite-direction condition was likely due to participants holding departures and thus having fewer aircraft to communicate with.

5.4.4.3. Sim Pilot Commands

We similarly observed fewer sim pilot commands entered in the opposite-direction condition (mean 130 commands per scenario) compared to the other conditions (148 in the baseline, 95% HDI [-0.3, -0.0], 96% confidence; 149 in continue-in, 95% HDI [-0.2, -0.1], 100% confidence; 146 in multiple lost link, 95% HDI [-0.2, -0.1], 100% confidence). The decrease was likely due to participants holding departures during the lost link UA's arrival and thus pilots having fewer aircraft to give commands to.

5.4.4.4. NASA TLX

There was a notable difference across conditions in response to question 4, how successful were you at completing your tasks (Performance). The mean response was highest (on the scale 1 = extremely low to 10 = extremely high) in the continue-in condition (8.4) and lower in the opposite-direction (7.4; 95% HDI [1.0, 2.1], 100% confidence), baseline (7.5; 95% HDI [-0.5, 2.9], 87% confidence), and multiple lost link (7.7; 95% HDI [-0.1, 1.5], 91% confidence) conditions. The difference was only statistically significant in comparison to the opposite-direction condition but we report all the differences because the responses fit a pattern.

Overall, there was some evidence for a difference in workload across arrival scenarios. There was only a single statistically significant difference, described above, but the continue-in condition also tended to receive the lowest ratings (i.e., lower workload) on the other questions.

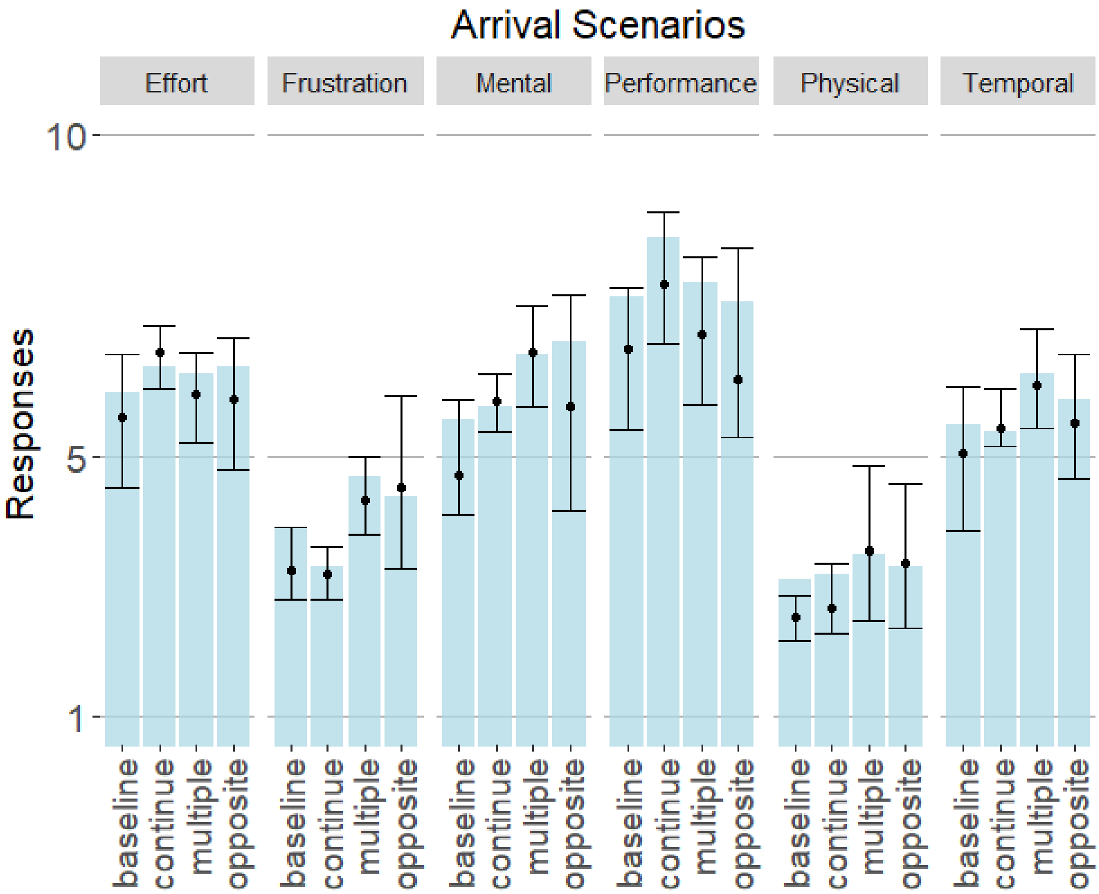

Figure 14. NASA TLX responses for Condition 2. Bars indicate scenario mean while dots and error bars indicate the model mean and 95% HDI.

5.4.4.5. Post-Scenario Questionnaire

Question 11 on the PSQ asked participants to rate their workload due to the lost link event (on the scale 1 = extremely low to 10 = extremely high). Participants rated their workload higher on the opposite-direction (mean rating 6.3) and multiple lost link (6.2) conditions compared to the continue-in (4.1; both 95% HDIs [0.9, 3.1], 100% confidence in both differences) condition. This difference again appeared to be driven by the difference between arrival and departure sector participants, where departure participants gave much lower ratings in the continue-in condition (mean response 1.7 vs. 6.2 for arrival participants).

5.5. CONDITION 3 – CRUISE PHASE

Only statistically significant results are reported here. Recall that there were two scenario types in Condition 3 (see Section 3.1.4): the baseline scenario where no lost link occurred and the divert-to-alternate condition where a lost link UAS overflight diverts to land at KHWD.

5.5.1. Safety

5.5.1.1. Loss of Separation (all aircraft)

Recall that statistical analysis of the loss of separation (LOS) data was not plausible. While there was a similar number of LOS in both the baseline and divert conditions, they differed concerning their durations and closest point of approach. LOS during the baseline condition tended to be shorter in duration (median of 126 seconds compared to 193 in divert) but involve the aircraft coming closer together (median of 0.3 nm compared to 1.4 nm in divert).

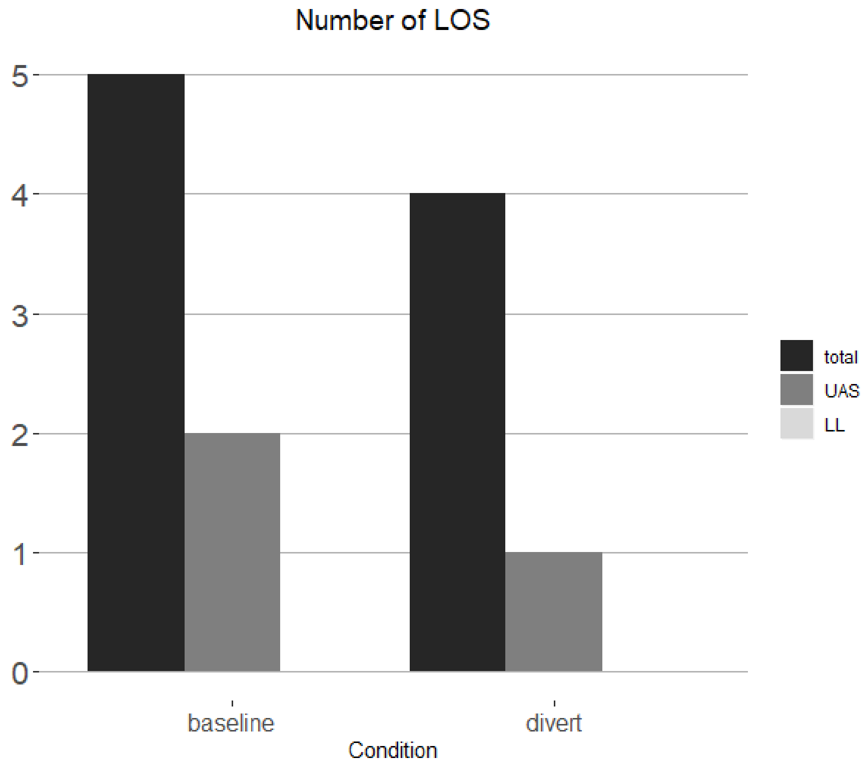

Figure 15. Number of loss of separation events during Condition 3 by scenario type. Note that no loss of separation events involved the lost link UAS in Condition 3.

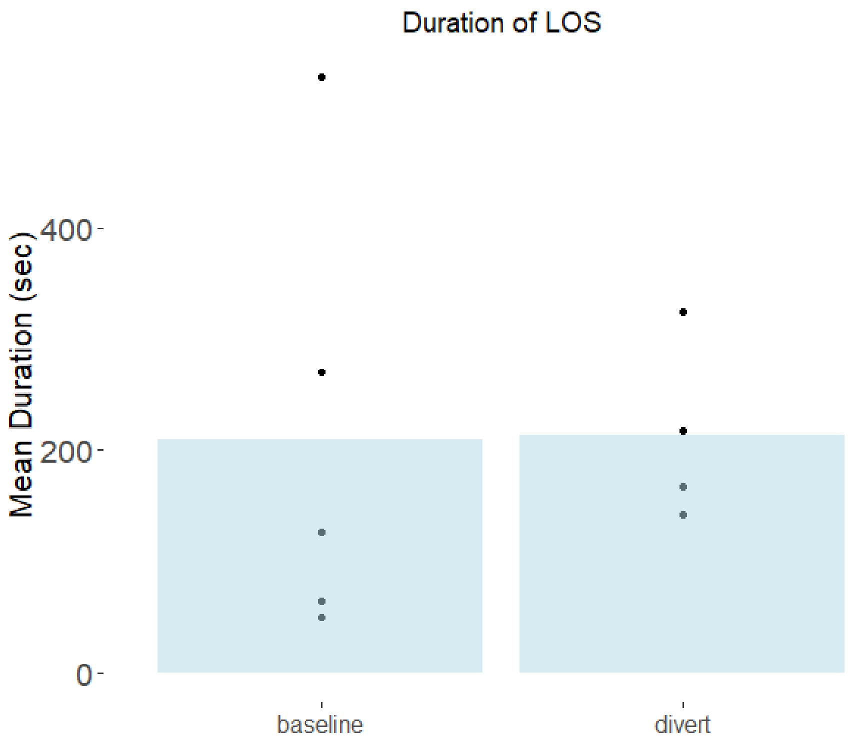

Figure 16. Duration of loss of separation events during Condition 3 by scenario type. Bars indicate scenario mean while dots indicate individual events.

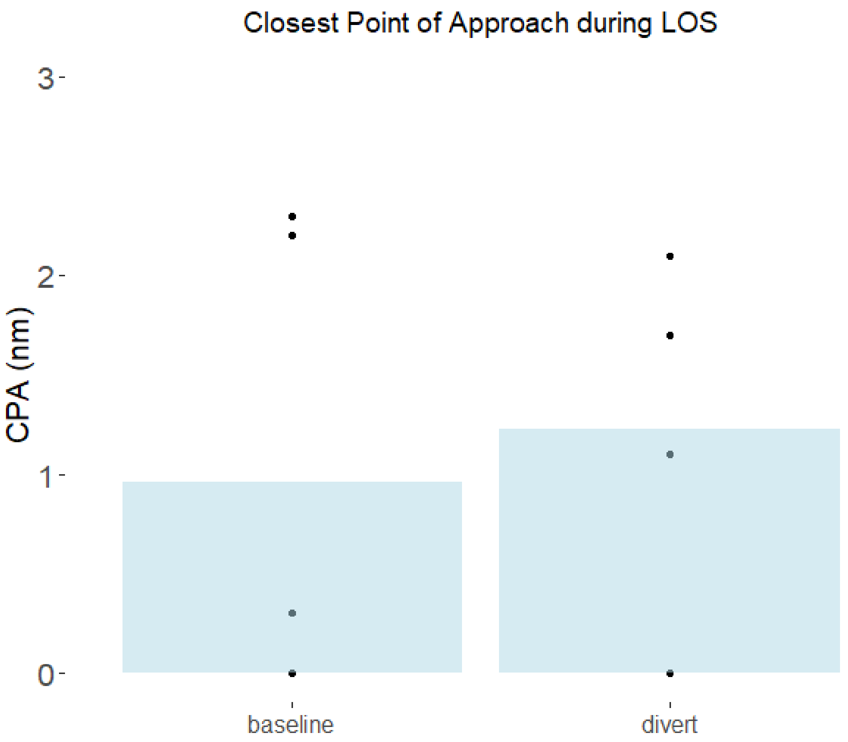

Figure 17. Closest point of approach during loss of separation events during Condition 3 by scenario type. Bars indicate scenario mean while dots indicate individual events.

5.5.1.2. Loss of Separation (UAS only)

When limiting focus to only those LOS that involved a UAS, we observed only three events (two during baseline scenarios and one during divert scenarios). These LOS were not notably different.

5.5.2. Workload

5.5.2.1. WAK Responses

Participants responded with higher workload ratings to the prompts that immediately followed the entrance of a lost link UAS into their sector (mean response 3.9 vs. 5.2; 95% HDI [0.07, 1.11], 98% confidence). This occurred in the divert scenario when a lost link UAS entered the arrival sector.

5.5.2.2. Communications

We observed a significant difference in the number of communications in the divert condition (mean 141) compared to the baseline (158; 95% HDI [-0.3, -0.0], 98% confidence) condition. The mean duration of communications was not significantly different, however.

5.5.2.3. NASA TLX

Overall, there is little evidence for a difference in workload across cruise scenarios; we report this as a departure from the previous two conditions. The lost link scenario received higher mean ratings on two of the six questions but never by more than a point and no differences were statistically significant.

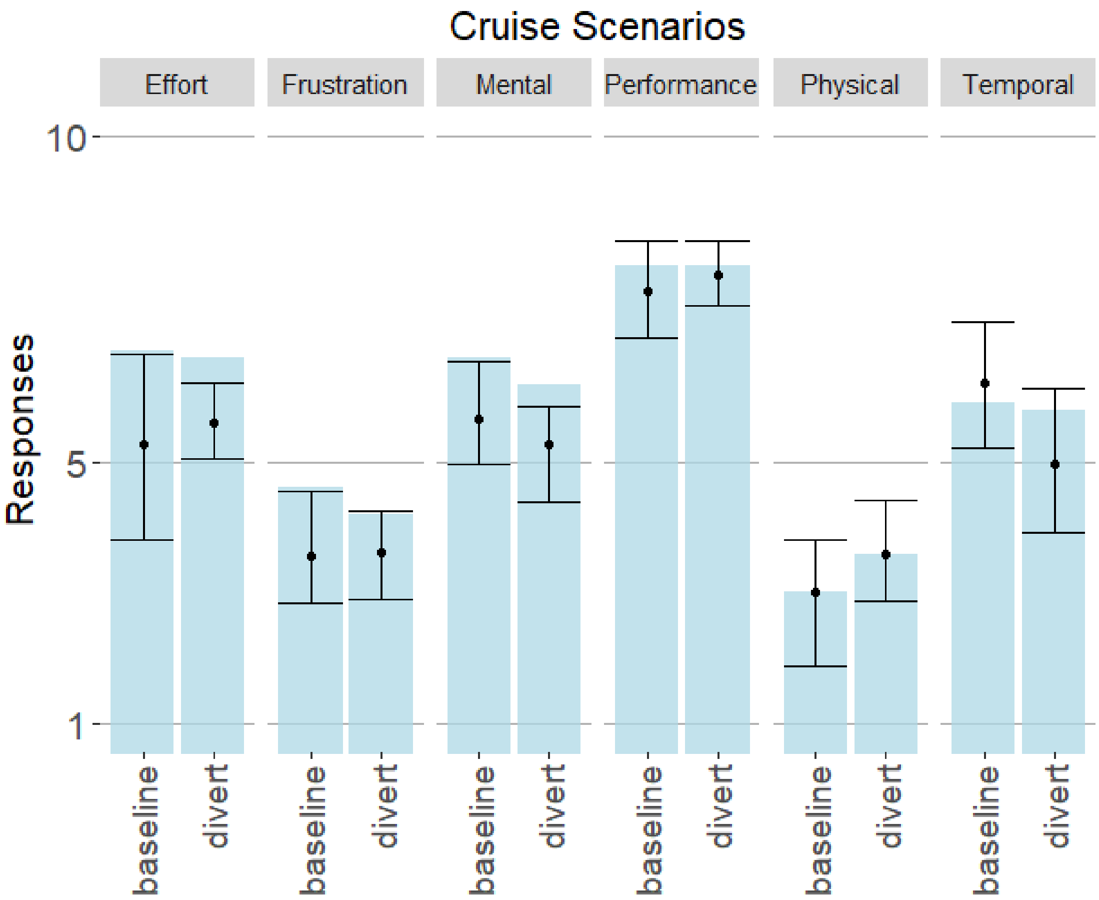

Figure 18. NASA TLX responses for Condition 3. Bars indicate the scenario mean while dots and error bars indicate the model mean and 95% HDI.

5.6. SUMMARY OF RESULTS

5.6.1. Condition 1: Departure

The departure lost link scenarios allowed us to compare the impact of the return-with-hold and return-without-hold contingency procedures on performance and workload. Overall, there were few differences between these two conditions and none were statistically significant.

On the NASA TLX, participants reported that the return-with-hold scenarios had a numerically higher temporal demand than return-without-hold, and this was significantly different from that for the baseline condition. In the exit questionnaires, participants ranked the contingency procedures in order of difficulty. Participants ranked the return-with-hold procedure as being more difficult than the return-without-hold procedure (median rank of 4 vs. 3).

On the other hand, we observed more loss of separation events during the return-without-hold condition and those events tended to last longer.

5.6.2. Condition 2: Arrival

These scenarios allowed us to compare the impact of a landing lost-link aircraft that was flying the same direction as the other traffic to that of an aircraft that was landing in the opposite direction. The overall pattern of results showed that an opposite direction aircraft has a much bigger impact on operations while a same-direction aircraft is little different than baseline.

The opposite direction scenario necessitated stopping departures as reflected by the average number of departures (mean 20 departures vs. ~26 departures in the other three conditions).

Participants rated the overall safety of the opposite direction condition lower; the same pattern held for their ratings of overall efficiency and overall workload. When ranking contingency procedures, participants ranked opposite direction landings as the most difficult while continue-in was the easiest non-baseline scenario. Finally, in the exit questionnaire participants rated the opposite direction scenario as a less effective procedure than the multiple lost link procedure.

The multiple lost link scenario featured a departure aircraft returning to base as well as an arrival; comparing this condition to the continue-in condition is useful for understanding the impact of multiple lost link events. In the PSQ, participants rated their situation awareness lower for the multiple lost link condition compared to continue-in, and their workload higher. On the NASA TLX, participants rated themselves as less successful at completing their tasks for multiple lost link versus continue-in. Participants ranked the multiple lost link scenarios the second most difficult.

5.6.3. Condition 3: Cruise

Participants ranked the divert scenario the third most difficult of all the scenarios. However, objective performance and the other survey results showed little impact of the divert scenario compared to baseline.

5.6.4. Subjective Workload

In addition to the increase in WAK responses we observed when a lost link UAS entered a participant's sector, the number of communications made by the participant also reliably increased WAK ratings (95% HDI [0.09, 0.59], 99% confidence). In the departures sector only, the number of communications made by pilots reliably increased workload (95% HDI [0.07, 0.34], 99% confidence). In the arrival sector, participants reliably reported higher workload as the number of UAS in the sector increased (95% HDI [0.08, 0.36], 99% confidence).

5.6.5. Jets Verses Turboprops

We did not observe many consistent differences between jet and turboprop lost link scenarios. When there were statistically significant differences, they tended to be for a single survey question or in a single condition as opposed to consistently appearing throughout a survey or dependent variable.

We observed two isolated differences between jets and turboprops on the PSQ. However, lost link aircraft type did not have a reliable effect on subjective workload ratings during the scenario (WAK responses). Additionally, there were no significant differences in the other measures (e.g., number of arrivals or departures) when comparing conditions with a lost link jet to conditions with a lost link turboprop. The overall data pattern suggested no difference between the two.

5.6.6. Effectiveness of Lost Link Procedures

Question 12 of the PSQ asked participants to rate the effectiveness of the lost link procedure (on the scale 1 = extremely low to 10 = extremely high). Participants rated effectiveness higher in the multiple lost link (mean rating 7.5) compared to the continue-in (6.2; 95% HDI [0.4, 3.4], 99% confidence) or opposite direction (6.1; 95% HDI [-0.2, 2.9], 88% confidence) conditions. However, this appears to be because participants at the departure position did not consider the continue-in procedure to be lost link and gave a low responses (mean response for arrival participants 8.7, departure participants 3.3).

The final question on the exit questionnaire asked participants to rank order the various lost link conditions that they experienced over the course of the HITL. The results are in Table 3:

Table 3. Mean and median ranking of lost link procedures

Procedure	Mean response	Median response
No lost link (baseline)	1.0	1.0
Arriving aircraft continue-in	2.8	2.5
Departing aircraft return-without-hold	3.5	3.0
Departing aircraft return-with-hold	3.9	4.0
Cruise aircraft divert to alternate airport	5.2	5.0
Multiple aircraft lost link	5.4	5.0
Arriving aircraft opposite direction landing	6.2	7.0

For aircraft that lose link during departure and return to base, we saw no consistent advantage for executing a hold before returning versus returning with no hold. When aircraft lose link during arrival and continue on their flight plan, we saw a stark difference for those going the same direction as other traffic versus those going in the opposite direction. Participants rated the same direction lost link scenarios (continue-in) as being more difficult than only baseline while the opposite direction lost link was consistently the most difficult. Participants rated the scenarios in which an en route aircraft diverted to an alternate airport as difficult though we saw little impact of the procedure on objective or other subjective measures. This suggests that diverting to an alternate airport that is outside of busy airspace may have little effect on operations.

5.6.7. Viability of Instrument Flight Procedures

When asked if IFPs (SIDs, STARs, and IAPs) are viable methods for communicating UAS lost link procedures to ATCS, all 10 participants stated yes. One stated “Yes. Absolutely. It will be one way to make it more consistent. At least having an idea of where they are headed rather than just going to a certain point and holding is probably the best way, at this time, to attempt to control them.”

5.6.8. Identification of UAS

In the exit questionnaire, participants provided ratings regarding the use of the ‘U’ indicator to distinguish UA from manned aircraft. When asked what the overall impact of the U indicator in the data block was, the median response was 7 on a scale of 1 to 10 where 1 is extremely negative and 10 is extremely positive. Based on the statistical model we are 88% confident that their responses were above neutral (a rating of 5), leaning toward the positive end of the scale. Some participants felt that the U was useful in identifying the UAS and quickly learned to scan for all U’s in the data blocks; however, others felt that although it was helpful it was “somewhat hard to recognize during high volume operations.” One participant suggested, “I almost wish there was another type of designator for UAS attached to the data tag as a reminder. Sometimes I actually missed the special U designator. Maybe add another symbol attached to the end of the call sign, like a # or + in addition to the U designator.” Another participant suggested to “change the aircraft type to something different (i.e., U208 instead of C208).”

When asked to rate the influence of the U indicator on their situation awareness, the median response was 8 on the same scale of 1 to 10. Based on the statistical model, we are 99% sure the responses were above neutral. One participant stated, “The indicator was great until the traffic volume was high. Once the volume was high, I began making judgment on the call sign versus the U.” Another stated that it was a reminder that visual separation could not be used with the UAS and that it was limited to only one approach.

Participants also answered an open-ended question as to what they thought about the use of the U indicator in the data block. Most had positive feedback, with one stating, “I thought it was perfect. It doesn’t take up too much room yet identifies the UAS” and another “I liked it. With the rules being slightly different for UAS, I don’t know how you could do without the U.” One participant felt it “didn’t really stand out, but at least it was something.”

Participants also discussed the U indicator during the post-simulation debrief. Again, most provided positive feedback; however, some suggested making it more clear by adding another designator at the end of the call sign, including the U in the call sign (e.g., UPSU, FEDXU), or highlighting it in a different way (e.g., change color to yellow).

6. RECOMMENDATIONS

- Using standardized lost link contingency procedures for UAS is a viable method for communicating lost link procedures to ATCS.
    - In the simulation, participants had access to the lost link contingency procedures via the Information Display System (IDS), but rarely used it because they could use radio communication with pilots. Further research should examine the use of automation or information display systems if communication with pilots is lost.

- UAS contingency procedures should be consistent within each airport.
    - Participants reported that there was little or no difference between a holding turn and no holding turn in the simulation but it was good that the procedure did not change within a scenario. We recommend that airports be allowed to customize their lost link procedures so long as it is consistent within the airport (e.g., the procedure does not vary by carrier). In addition, participants suggested that KHWD should not be assigned as the divert airport given its close location to the main airport and approach patterns.

- Some, but not all, contingency procedures are disruptive and should be avoided when possible.
    - Participants reported that it was not difficult to manage lost link events when the UAS continued on flight plan, but they reported a great deal of difficulty when the UAS landed from the opposite direction.

- UA performance characteristics may not have an impact on ATC operations.
    - Participants did not report any issues with the different UA types (jet or turboprop) in the simulation. However, whether faster UAs cause ATCS to rush their decisions and actions or slower UAs get in the way of typical traffic flow may depend upon the simulation conditions.

- There needs to be a strong indicator that identifies an aircraft as a UAS.
    - In general, participants responded positively to the U indicator and agreed that UAS indicators are necessary. However, some participants had less favorable comments about the specific implementation in the simulation and provided other recommendations for indicators.

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LIST OF ACRONYMS

ATC	Air Traffic Control
ATCS	Air Traffic Control Specialist
C2	Command and Control
CFR	Code of Federal Regulations
CIC	Controller In Charge
COA	Certificate of Authorization
DAA	Detect and Avoid
DSR	Display System Replacement
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
FDB	Flight Data Block
FLM	Front Line Manager
HITL	Human-in-the-Loop
IAP	Instrument Approach Procedure
IFP	Instrument Flight Procedures
IFR	Instrument Flight Rules
JAA	Joint Aviation Authority
KHWD	Hayward Airport
KOAK	Oakland International Airport
NAS	National Airspace System
NATCA	National Air Traffic Controllers Association
NCT	Northern California TRACON
NIEC	NextGen Integration and Evaluation Capability
NM	Nautical Miles
PIC	Pilot-in-Command
PSQ	Post Scenario Questionnaire
RF	Radio Frequency
SID	Standard Instrument Departure
SME	Subject Matter Expert
STAR	Standard Terminal Arrival Route
STARS	Standard Terminal Automation Replacement System
TRACON	Terminal Radar Approach Control (facility)
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
WAK	Workload Assessment Keypad
WJHTC	William J. Hughes Technical Center

APPENDIX A—1. INFORMED CONSENT

Validation of Unmanned Aircraft Systems	**Version**
Contingency Procedures and Requirements	**5-11-2018**
Informed Consent Statement	

I, ______________________________, understand that this study, entitled "Validation of Unmanned Aerial Systems (UAS) Contingency Procedures and Requirements Terminal Human-in-the-Loop (HITL) Simulation" is sponsored by the Federal Aviation Administration (FAA) and is being directed by Lacey Thompson.

Nature and Purpose

I have been recruited to volunteer as a participant in this research study. The purpose of this study is to conduct a HITL simulation to determine how UAS integration may affect air traffic operations in the terminal environment. The results of the study will be used to identify future research and to help the FAA establish Air Traffic Control (ATC) standards and procedures for integrating UAS into the National Airspace System.

Experimental Procedures

On the first day, a group of researchers and ATC subject-matter experts will provide an overview of the project's research goals and familiarize participants with UAS operations. The participants will then complete a Background Questionnaire about their ATC experience. Next, researchers will provide the participants with guidelines of how the simulation will be conducted and participants will have an opportunity to familiarize themselves with the airspace and handle traffic in practice scenarios. Over the following three days of simulation, participants will work traffic scenarios, in which they will provide ratings of subjective workload. An automated data collection system will record system operations and generate a set of standard measures related to safety, efficiency, and communications. Scenarios will be audio-video recorded so that researchers can derive additional measures and reexamine any important events. At the end of each scenario, the participants will be asked to complete a Post-Scenario Questionnaire that will be used to gather their thoughts on the scenario just presented. Finally, after all the scenarios have been presented and discussed, participants will complete an Exit Questionnaire to gather their overall thoughts about their simulation experience.

Discomfort and Risks

I understand that I will not be exposed to any foreseeable risks or intrusive measurement techniques. I understand that I will not be exposed to any foreseeable risks beyond what I usually experience in my every day job.

Anonymity and Confidentiality

My participation in this study is strictly confidential. All information that I provide will be anonymized by the experimenters. All data collected in the study will be used for scientific purposes only and no names or identities will be released in any reports. Laboratory personnel will not disclose or release any Personally Identifiable Information (PII), except as may be required by statute. I understand that any Personally Identifiable Information [PII] will be protected according to FAA Order 1370.121 – FAA Information Security and Privacy Program & Policy.

Benefits

I understand that the only benefit to me is that I will be able to provide the researchers with valuable feedback and insight regarding UAS integration into the NAS. My data will help the FAA to identify the human factors issues with UAS integration and help the FAA to establish ATC standards and procedures for UAS integration.

Participant Responsibilities

I am aware that to participate in this study I must be an ATC professional. I will answer any questions asked during the study to the best of my ability. I will not discuss the content of the experiment with other potential participants until the study is completed.

Participant Assurances

I understand that my participation in this study is completely voluntary and I can withdraw at any time without penalty. I also understand that the researchers in this study may terminate my participation if they believe it is in my best interest. I understand that if new findings develop during the course of this research that may relate to my decision to continue participation, I will be informed. I have not given up any of my legal rights or released any individual or institution from liability for negligence.

Lacey Thompson has adequately answered all the questions I have asked about this study, my participation, and the procedures involved. I understand that Lacey Thompson or another member of the research team will be available to answer any questions concerning procedures throughout this study. If I have questions about this study or need to report any adverse effects from the research procedures, I will contact Lacey Thompson at (609) 485-8429.

Compensation and Injury

I agree to immediately report any injury or suspected adverse effect to Lacey Thompson at (609) 485-8429.

Audio-Video Recording

The entire simulation will be audio-video recorded in case the researchers need to review any events for data evaluation purposes. The researchers may show the simulation recordings to our study sponsors, but only with the explicit consent of the participants.

☐ Yes, I agree to allow my simulation recordings to be shown to sponsors.

☐ No, I do **not** agree to allow my simulation recordings to be shown to sponsors.

Signature Lines

I have read this informed consent statement. I understand its contents, and I freely consent to participate in this study under the conditions described. I understand that, if I want to, I may have a copy of this form.

Research Participant: ______________________________ Date: __________

Investigator: ______________________________ Date: __________

Witness: ______________________________ Date: __________

Appendix A – 2. Background Questionnaire

Validation of Unmanned Aircraft Systems Contingency Procedures and Requirements	**Version 5-11-2018**
Background Questionnaire	

Instructions

The Background Questionnaire is designed to obtain information about your background and experience as an air traffic control specialist. The researchers will only use this information to describe the participants in this study as a group. Your identity will remain anonymous.

1. What is your **gender**?	☐ Male ☐ Female
2. What is your **age**?	______ years
3. What is the **TRACON facility** where you work?	______ facility
4. How many **years of experience** do you have in ATC? (include all FAA and military experience)	______ years
5. How many **years of experience** do you have in **the TRACON environment**?	______ years
6. How many of the **past 12 months** have you actively controlled traffic at your facility?	______ months
7. How **frequently do you work UAS** at your facility?	☐ I have **never** worked any UAS ☐ About 1 UAS every **year** ☐ About 1 UAS every **month** ☐ About 1 UAS every **week** ☐ About 1 UAS every **day** ☐ About 1 UAS every **hour** ☐ More than 1 UAS every **hour** How many? ____

8. Please list the **UAS types** that operate at your facility, if any
e.g., RQ-4 Global Hawk, MQ-1 Predator

____

____

____

9. In your experience, **how do UAS operations affect ATC services in your sector?**	Negative Effect	①②③④ ⑤ ⑥⑦⑧⑨ | None	Positive Effect

Comments:

Appendix A – 3. Post-Scenario Questionnaire

Validation of Unmanned Aircraft Systems	**Version**
Contingency Procedures and Requirements	**5-11-2018**
Post-Scenario Questionnaire	

Instructions

The Post-Scenario Questionnaire is designed to draw upon your thoughts about the specific events presented in the scenario you just completed.

1. **Mental Demand** – How much mental and perceptual activity was required? (Did the scenario require a lot of thinking, deciding, calculating, remembering, looking, searching, etc.? Was the task easy or demanding, simple or complex, exacting or forgiving?)	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High
2. **Physical Demand** – How much physical activity was required? (Did the scenario require any pushing, pulling, turning, controlling, activating, etc.? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?)	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High
3. **Temporal Demand** – 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?)	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High
4. **Performance** – How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)?	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High
5. **Effort** – How hard did you have to work (mentally and physically) to accomplish your level of performance?	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High
6. **Frustration** – How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the scenario?	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

7. Rate your **performance for safely resolving the lost link event**(s) during this scenario.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

8. Rate your **performance for efficiently resolving the lost link event**(s) during this scenario.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

9. Rate the **overall safety of operations** during this scenario.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

10. Rate the **overall efficiency of operations** during this scenario.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

11. Rate your **workload due to the lost link event**(s) during this scenario.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

12. Rate the **effectiveness of the lost link contingency procedure** for the lost link event(s) during this scenario.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

13. Rate your **overall level of situation awareness** during this scenario.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

14. Rate your **situation awareness for UAS progress along the lost link contingency procedure** during this scenario.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

15. Rate the **overall performance of the simulation pilots** in terms of responding to control instructions, phraseology, and providing readbacks.	Extremely Low	①②③④⑤⑥⑦⑧⑨⑩	Extremely High

Comments:

16. What aspects of this scenario were hardest to work with? Why?

Comments:

17. Are there any display features or functions that could be provided to make this scenario more manageable? Please explain.

Comments:

18. Are there any procedures that could be provided to make this scenario more manageable? Please explain.

Comments:

19. Do you have any additional comments about the scenario just completed?

Comments:

Appendix A – 4. Exit Questionnaire

Validation of Unmanned Aircraft Systems	**Version**
Contingency Procedures and Requirements	**5-11-2018**
Exit Questionnaire	

Instructions

Please answer the following questions with regard to the entire series of UAS scenarios presented in this study.

1. Rate the **overall realism of the simulation experience** compared to actual ATC operations.	Extremely Low	①②③④⑤⑥⑦⑧⑨	Extremely High

Comments:

2. Rate the **realism of the simulation hardware** compared to actual equipment.	Extremely Low	①②③④⑤⑥⑦⑧⑨	Extremely High

Comments:

3. Rate the **realism of the simulation software** compared to actual functionality.	Extremely Low	①②③④⑤⑥⑦⑧⑨	Extremely High

Comments:

4. Rate the **realism of the airspace** compared to actual NAS airspace.	Extremely Low	①②③④⑤⑥⑦⑧⑨	Extremely High

Comments:

5. Rate the **realism of the simulation traffic scenarios** compared to actual NAS traffic.	Extremely Low	①②③④⑤⑥⑦⑧⑨	Extremely High

Comments:

6. To what extent did the **WAK online workload rating technique interfere** with your ATC performance?	Not at All	①②③④⑤⑥⑦⑧⑨	A Great Deal

Comments:

7. How effective was the **airspace training**?	Extremely Ineffective	①②③④⑤⑥⑦⑧⑨	Extremely Effective

Comments:

8. How effective was the **UAS training**?	Extremely Ineffective	①②③④⑤⑥⑦⑧⑨	Extremely Effective

Comments:

9. How effective were the **procedures used to manage UAS operations**?	Extremely Ineffective	①②③④⑤⑥⑦⑧⑨	Extremely Effective

Comments:

10. How effective was the **display system for managing UAS operations**?	Extremely Ineffective	①②③④⑤⑥⑦⑧⑨	Extremely Effective

Comments:

11. What was the impact of having a **lost link aircraft land on the opposite runway**?	Extremely Negative	①②③④⑤⑥⑦⑧⑨	Extremely Positive

Comments:

12. What was the impact of having **multiple lost link aircraft** in the airspace at the same time **compared to a single lost link**?	Extremely Negative	①②③④⑤⑥⑦⑧⑨	Extremely Positive

Comments:

13. What was the **overall impact** of the U indicator in the data block for UAS?	Extremely Negative	①②③④⑤⑥⑦⑧⑨	Extremely Positive

Comments:

14. Rate the **influence of the U indicator on your situation awareness**.	Extremely Negative	①②③④⑤⑥⑦⑧⑨	Extremely Positive

Comments:

15. What did you think about the use of the **U indicator** in the data block for UAS?

Comments:

16. Do you have any suggestions for alternative information for the **UAS data block**?

Comments:

17. What suggestions do you have for effectively integrating UAS in the NAS?

Comments:

18. Are IFPs (Standard Instrument Departures (SIDs), Standard Terminal Approach Routes (STARs), and Instrument Approach Procedures (IAPs)) viable methods for communicating UAS lost link procedures to air traffic controllers?

Comments:

19. What was your procedure preference for a lost link **during departure**: immediate return to base or return after a hold?

Comments:

20. Do you have any suggestions for alternative contingency procedures **on departure**?

Comments:

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21. Do you have any suggestions for alternative contingency procedures **on arrival** besides continuing on route?

Comments:

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22. Do you have any suggestions for alternative contingency procedures **for en route aircraft** besides diverting to an alternative airport?

Comments:

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____

____

23. What was the impact of a lost link for a **turboprop-style** UAS versus a **jet-style** UAS? Was one easier or more manageable than the other?

Comments:

____

____

____

____

____

RANK ORDER PREFERENCE

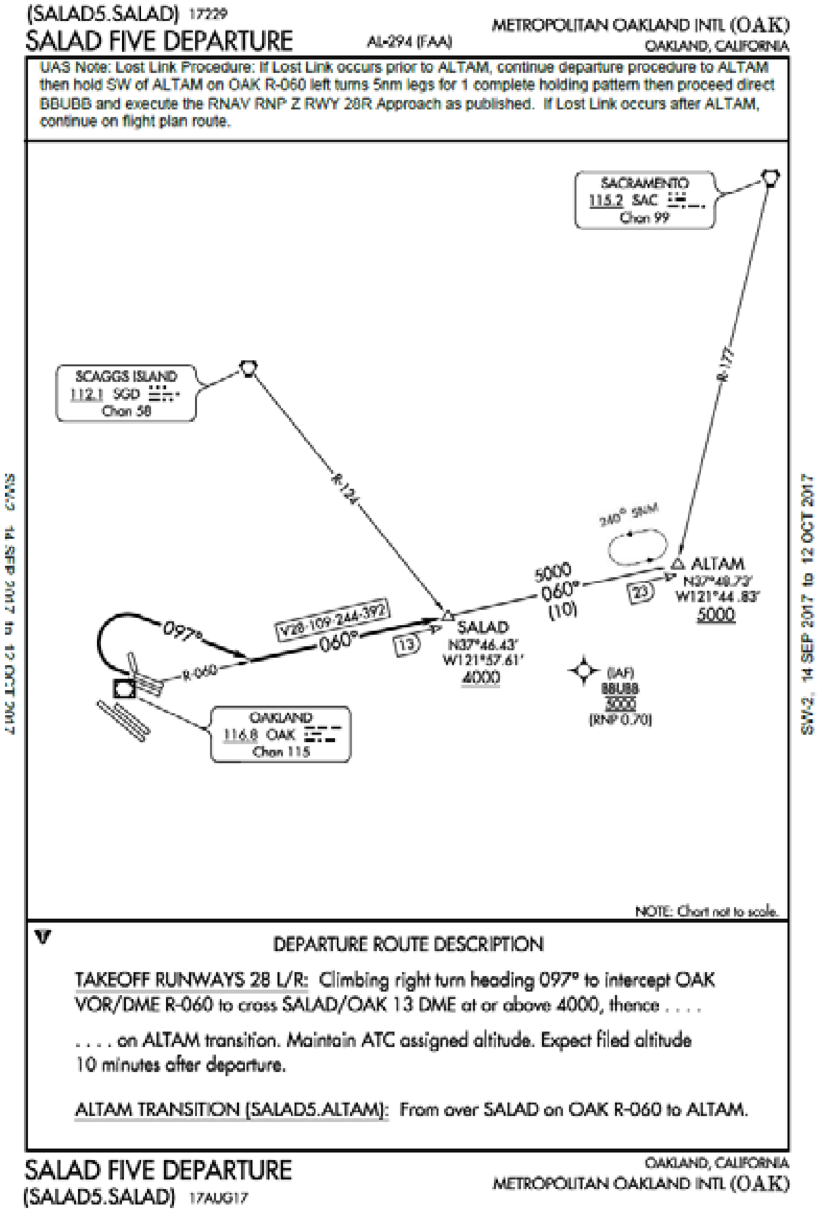
How would you rank the relative difficulty of these scenarios? Please start from 1 = easiest to manage.

☐ No lost link occurs
☐ Departing aircraft loses link, returns directly to airport
☐ Departing aircraft loses link, returns to airport after a hold
☐ Arriving aircraft loses link, lands normally
☐ Arriving aircraft loses link, lands in opposite direction
☐ Multiple aircraft lose link at same time
☐ En route aircraft loses link, diverts to airport in your airspace

APPENDIX B—. STANDARD INSTRUMENT DEPARTURES (SIDS)

The SALAD FIVE DEPARTURE was used by all UAS departing KOAK during the simulation. A specific fix (ALTAM) was identified on the SID, as the point where if a lost link were to occur prior to the fix, the UAS would return to KOAK via the specified lost link route. The specified lost link route was defined as ALTAM direct BBUBB and then the transition onto the RNAV (RNP) Z RWY 28R approach into KOAK. If the lost link were to occur after ALTAM, the UAS would continue on flight plan route. Two versions of the SALAD FIVE DEPARTURE were created. One version included a turn in holding at ALTAM, the other did not include holding.

SALAD FIVE DEPARTURE with HOLD



(SALAD5.SALAD) 17229
SALAD FIVE DEPARTURE
AL-294 (FAA)
METROPOLITAN OAKLAND INTL (OAK)
OAKLAND, CALIFORNIA

UAS Note: Lost Link Procedure: If Lost Link occurs prior to ALTAM, continue departure procedure to ALTAM then hold SW of ALTAM on OAK R-060 left turns 5nm legs for 1 complete holding pattern then proceed direct BBUBB and execute the RNAV RNP Z RWY 28R Approach as published. If Lost Link occurs after ALTAM, continue on flight plan route.

NOTE: Chart not to scale.

DEPARTURE ROUTE DESCRIPTION

TAKEOFF RUNWAYS 28 L/R: Climbing right turn heading 097° to intercept OAK VOR/DME R-060 to cross SALAD/OAK 13 DME at or above 4000, thence . . . .

. . . . on ALTAM transition. Maintain ATC assigned altitude. Expect filed altitude 10 minutes after departure.

ALTAM TRANSITION (SALAD5.ALTAM): From over SALAD on OAK R-060 to ALTAM.

SALAD FIVE DEPARTURE
(SALAD5.SALAD) 17AUG17
OAKLAND, CALIFORNIA
METROPOLITAN OAKLAND INTL (OAK)

SALAD FIVE DEPARTURE with NO Hold

(SALAD5.SALAD) 17229

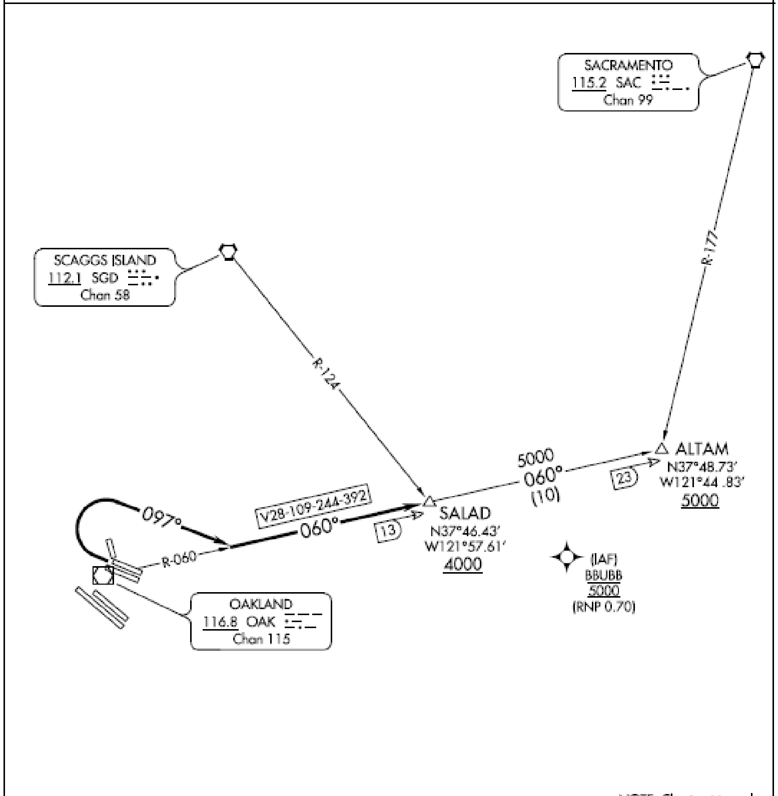
SALAD FIVE DEPARTURE

AL-294 (FAA)

METROPOLITAN OAKLAND INTL (OAK)
OAKLAND, CALIFORNIA

UAS Note: Lost Link Procedure: If Lost Link occurs prior to ALTAM, continue departure procedure to ALTAM then proceed direct BBUBB and execute RNAV RNP Z RWY 28R Approach as published. If Lost Link occurs after crossing ALTAM, continue on flight plan route.

SW-2, 14 SEP 2017 to 12 OCT 2017



NOTE: Chart not to scale.

SW-2, 14 SEP 2017 to 12 OCT 2017

DEPARTURE ROUTE DESCRIPTION

TAKEOFF RUNWAYS 28 L/R: Climbing right turn heading 097° to intercept OAK VOR/DME R-060 to cross SALAD/OAK 13 DME at or above 4000, thence . . . .

. . . . on ALTAM transition. Maintain ATC assigned altitude. Expect filed altitude 10 minutes after departure.

ALTAM TRANSITION (SALAD5.ALTAM): From over SALAD on OAK R-060 to ALTAM.

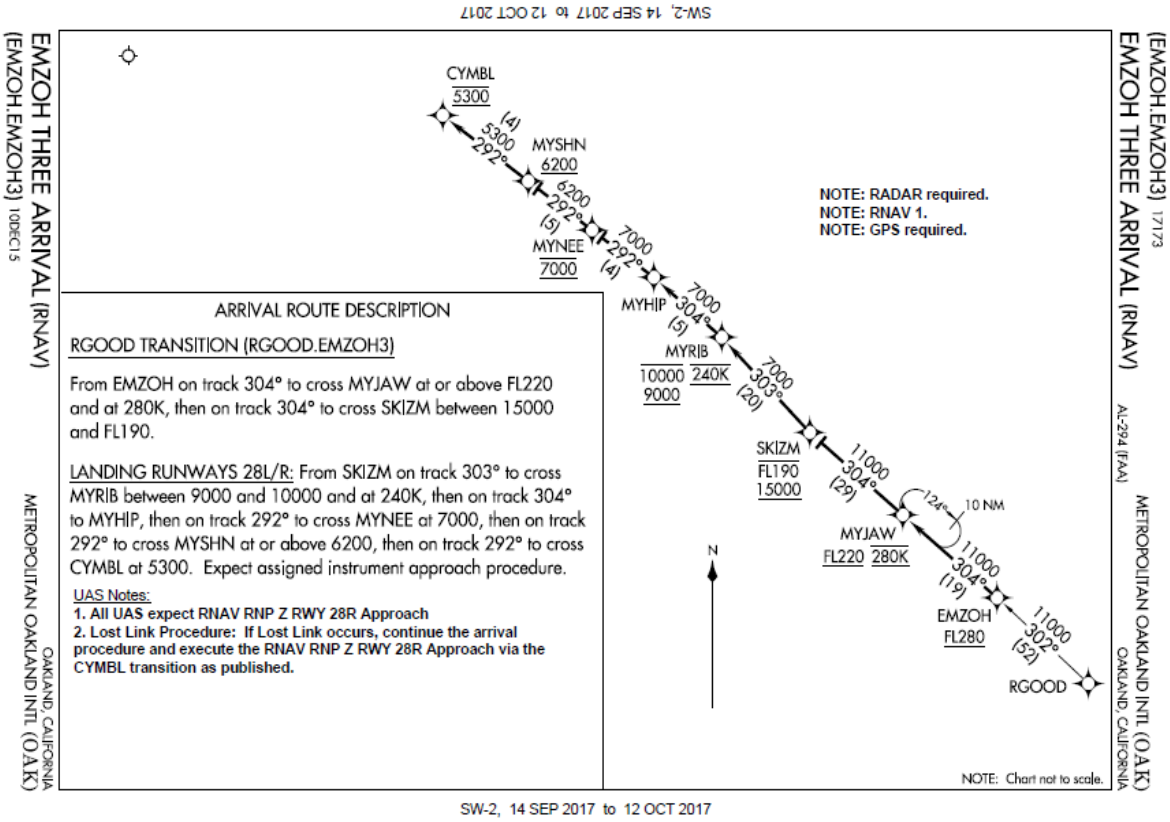
SALAD FIVE DEPARTURE
(SALAD5.SALAD) 17AUG17

OAKLAND, CALIFORNIA
METROPOLITAN OAKLAND INTL (OAK)

APPENDIX C—STANDARD TERMINAL ARRIVAL ROUTES (STARS)

The EMZOH THREE ARRIVAL, OAKES TWO ARRIVAL, and AANET ONE ARRIVAL were KOAK STARs used in the development of UAS lost link contingency procedures to be available during the en route and arrival phase of flight. In the event of a lost link, the defined procedure was to continue on the STAR and then transition onto the specified Instrument Approach Procedure (IAP).

EMZOH THREE ARRIVAL



NOTE: RADAR required.
NOTE: RNAV 1.
NOTE: GPS required.

ARRIVAL ROUTE DESCRIPTION

RGOOD TRANSITION (RGOOD.EMZOH3)

From EMZOH on track 304° to cross MYJAW at or above FL220 and at 280K, then on track 304° to cross SKIZM between 15000 and FL190.

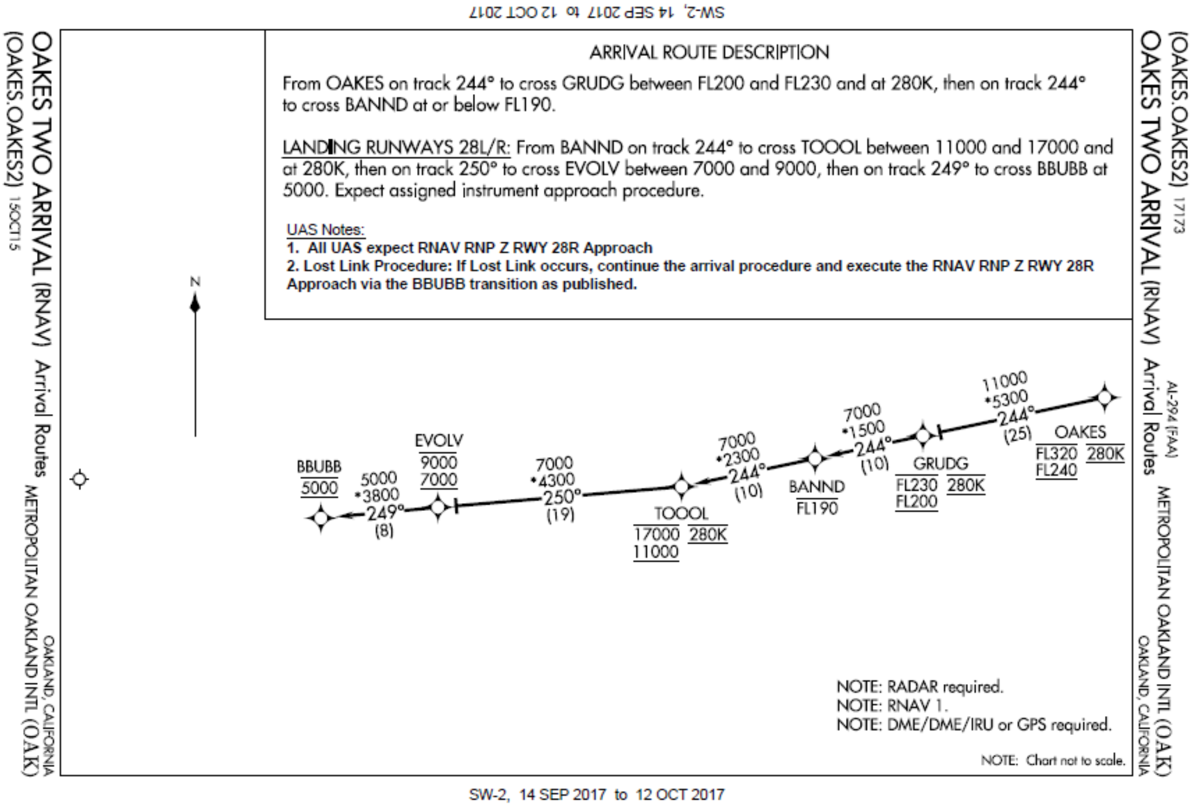
LANDING RUNWAYS 28L/R: From SKIZM on track 303° to cross MYRIB between 9000 and 10000 and at 240K, then on track 304° to MYHIP, then on track 292° to cross MYNEE at 7000, then on track 292° to cross MYSHN at or above 6200, then on track 292° to cross CYMBL at 5300. Expect assigned instrument approach procedure.

UAS Notes:

1. All UAS expect RNAV RNP Z RWY 28R Approach
2. Lost Link Procedure: If Lost Link occurs, continue the arrival procedure and execute the RNAV RNP Z RWY 28R Approach via the CYMBL transition as published.

SW-2, 14 SEP 2017 to 12 OCT 2017

OAKES TWO ARRIVAL



ARRIVAL ROUTE DESCRIPTION

From OAKES on track 244° to cross GRUDG between FL200 and FL230 and at 280K, then on track 244° to cross BANND at or below FL190.

LANDING RUNWAYS 28L/R: From BANND on track 244° to cross TOOOL between 11000 and 17000 and at 280K, then on track 250° to cross EVOLV between 7000 and 9000, then on track 249° to cross BBUBB at 5000. Expect assigned instrument approach procedure.

UAS Notes:

1. All UAS expect RNAV RNP Z RWY 28R Approach

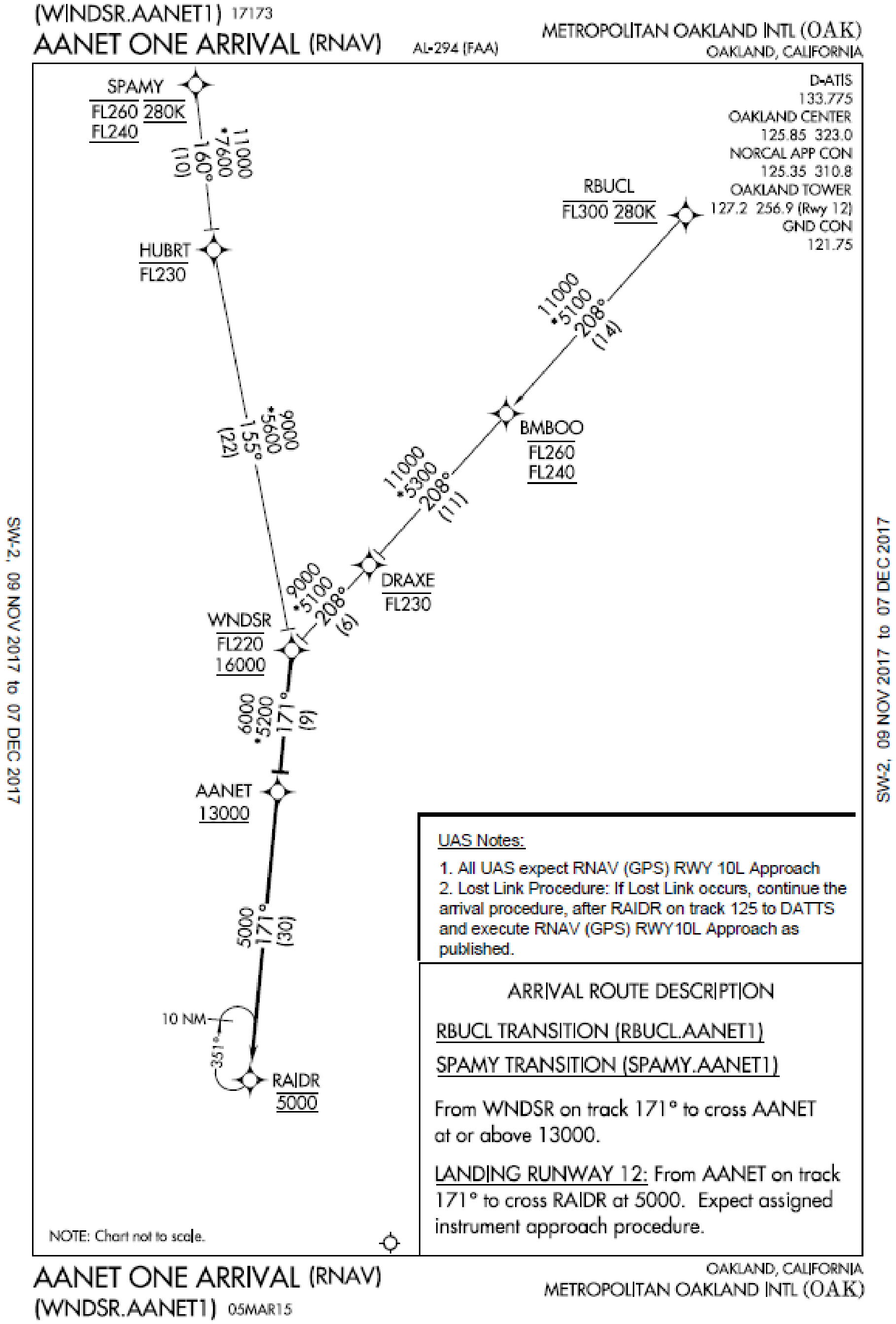
2. Lost Link Procedure: If Lost Link occurs, continue the arrival procedure and execute the RNAV RNP Z RWY 28R Approach via the BBUBB transition as published.

NOTE: RADAR required.
NOTE: RNAV 1.
NOTE: DME/DME/IRU or GPS required.

NOTE: Chart not to scale.

AANET ONE ARRIVAL

(WINDSR.AANET1) 17173
AANET ONE ARRIVAL (RNAV) AL-294 (FAA)
METROPOLITAN OAKLAND INTL (OAK)
OAKLAND, CALIFORNIA



D-ATIS
133.775
OAKLAND CENTER
125.85 323.0
NORCAL APP CON
125.35 310.8
OAKLAND TOWER
127.2 256.9 (Rwy 12)
GND CON
121.75

UAS Notes:

1. All UAS expect RNAV (GPS) RWY 10L Approach
2. Lost Link Procedure: If Lost Link occurs, continue the arrival procedure, after RAIDR on track 125 to DATTS and execute RNAV (GPS) RWY10L Approach as published.

ARRIVAL ROUTE DESCRIPTION

RBUCL TRANSITION (RBUCL.AANET1)

SPAMY TRANSITION (SPAMY.AANET1)

From WNDSR on track 171° to cross AANET at or above 13000.

LANDING RUNWAY 12: From AANET on track 171° to cross RAIDR at 5000. Expect assigned instrument approach procedure.

NOTE: Chart not to scale.

SW-2, 09 NOV 2017 to 07 DEC 2017

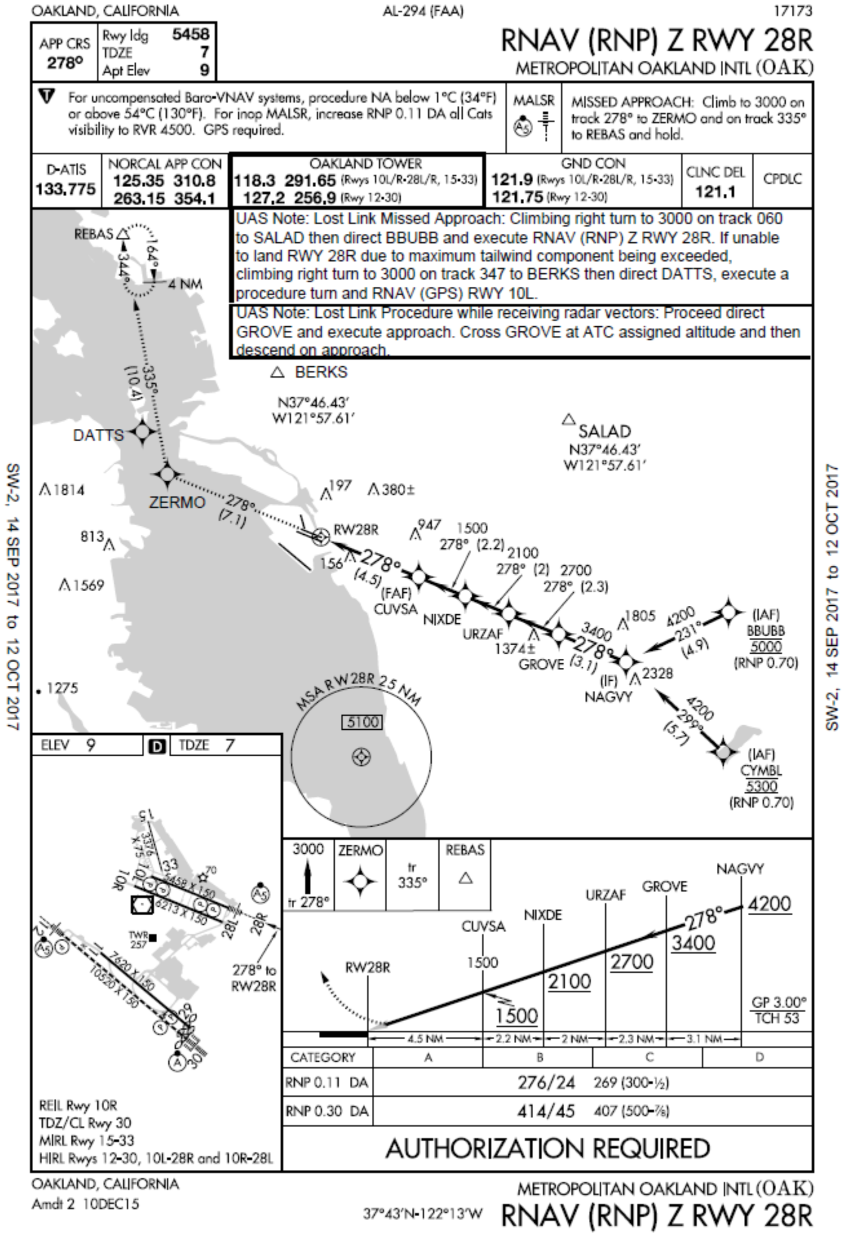
SW-2, 09 NOV 2017 to 07 DEC 2017

AANET ONE ARRIVAL (RNAV)
(WNDSR.AANET1) 05MAR15
OAKLAND, CALIFORNIA
METROPOLITAN OAKLAND INTL (OAK)

APPENDIX D—INSTRUMENT APPROACH PROCEDURES (IAPS)

The three IAPs used for UAS arrivals included the RNAV (RNP) Z RWY 28R (KOAK), RNAV (GPS) RWY 10L (KOAK), and RNAV (GPS) RWY 28L (HWD). The RNAV (RNP) Z RWY 28R into KOAK was the predominant IAP used for UAS arrivals. The SALAD FIVE DEPARTURE, EMZOH THREE ARRIVAL, and OAKES TWO ARRIVAL all used this procedure as the final published segment of the UAS lost link contingency routing. The RNAV (RNP) Z RWY 28R also contained a lost link procedure in the event the UAS experienced a lost link while receiving radar vectors for sequencing to the airport. The RNAV (GPS) RWY 10L (KOAK) was used to test the 2 scenarios which featured an opposite direction arrival of a UAS experiencing a lost link. During these 2 scenarios the lost link UAS landed opposite direction to the airport traffic flow while experiencing a light tailwind. The 2 IAPs for KOAK also included a lost link procedure in the event the maximum tailwind component of the UAS was exceeded. These procedures were published on the two approach plates, but not tested during the simulation. The RNAV (GPS) RWY 28L (HWD) was used to test a UAS lost link diversion to an alternate airport during the enroute/cruise phase of flight. UAS aircraft transitioning the airspace northwest bound on V107 were able to utilize the VINCO transition for the approach if the lost link event occurred prior to VINCO intersection.

RNAV (RNP) Z RWY 28R



OAKLAND, CALIFORNIA AL-294 (FAA) 17173

RNAV (RNP) Z RWY 28R
METROPOLITAN OAKLAND INTL (OAK)

APP CRS	Rwy ldg	5458
278°	TDZE	7
	Apt Elev	9

For uncompensated Baro-VNAV systems, procedure NA below 1°C (34°F) or above 54°C (130°F). For inop MALSR, increase RNP 0.11 DA all Cats visibility to RVR 4500. GPS required.

MALSR

MISSED APPROACH: Climb to 3000 on track 278° to ZERMO and on track 335° to REBAS and hold.

D-ATIS	NORCAL APP CON	OAKLAND TOWER	GND CON	CLNC DEL	CPDLC
133.775	125.35 310.8 263.15 354.1	118.3 291.65 (Rwys 10L/R-28L/R, 15-33) 127.2 256.9 (Rwy 12-30)	121.9 (Rwys 10L/R-28L/R, 15-33) 121.75 (Rwy 12-30)	121.1	

UAS Note: Lost Link Missed Approach: Climbing right turn to 3000 on track 060 to SALAD then direct BBUBB and execute RNAV (RNP) Z RWY 28R. If unable to land RWY 28R due to maximum tailwind component being exceeded, climbing right turn to 3000 on track 347 to BERKS then direct DATTS, execute a procedure turn and RNAV (GPS) RWY 10L.

UAS Note: Lost Link Procedure while receiving radar vectors: Proceed direct GROVE and execute approach. Cross GROVE at ATC assigned altitude and then descend on approach.

CATEGORY	A	B	C	D
RNP 0.11 DA	276/24 269 (300-½)			
RNP 0.30 DA	414/45 407 (500-⅞)			

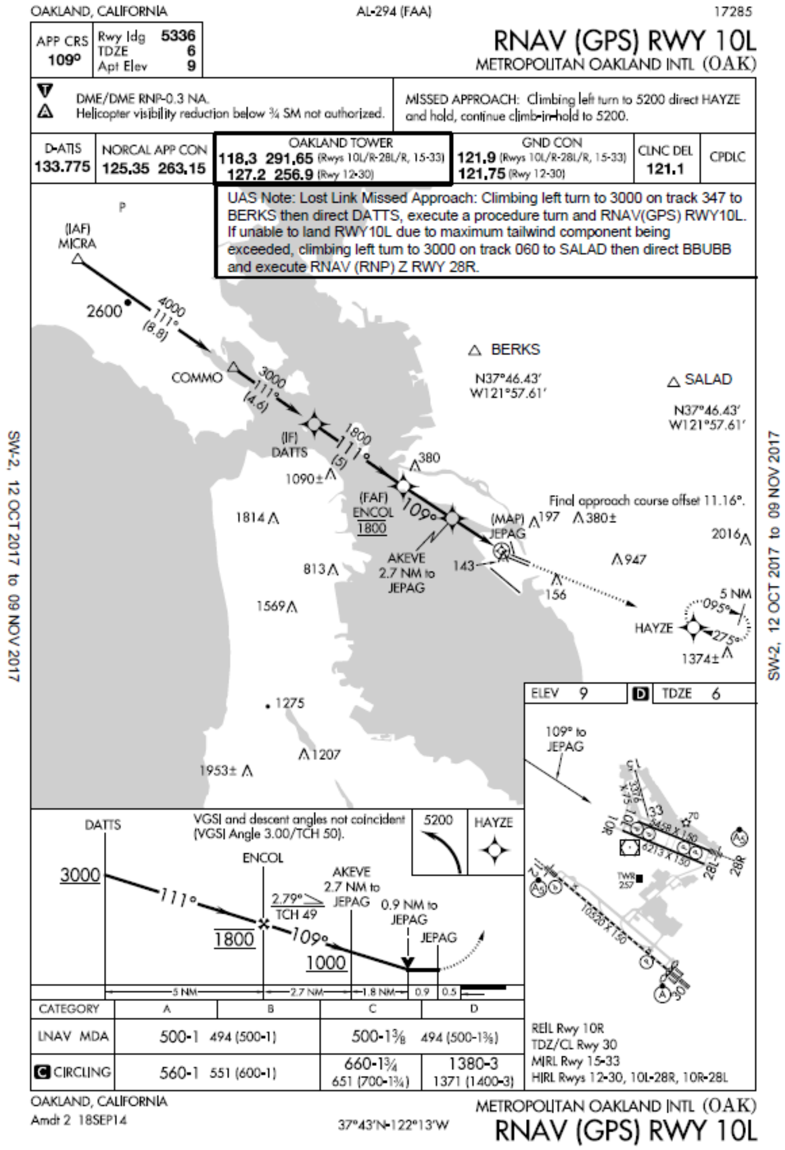
AUTHORIZATION REQUIRED

REIL Rwy 10R
TDZ/CL Rwy 30
MIRL Rwy 15-33
HIRL Rwys 12-30, 10L-28R and 10R-28L

OAKLAND, CALIFORNIA
Amdt 2 10DEC15

METROPOLITAN OAKLAND INTL (OAK)
37°43′N-122°13′W RNAV (RNP) Z RWY 28R

RNAV (GPS) RWY 10L



OAKLAND, CALIFORNIA AL-294 (FAA) 17285

APP CRS	Rwy ldg	5336
109°	TDZE	6
	Apt Elev	9

RNAV (GPS) RWY 10L
METROPOLITAN OAKLAND INTL (OAK)

DME/DME RNP-0.3 NA.
Helicopter visibility reduction below ¾ SM not authorized.

MISSED APPROACH: Climbing left turn to 5200 direct HAYZE and hold, continue climb-in-hold to 5200.

D-ATIS	NORCAL APP CON	OAKLAND TOWER	GND CON	CLNC DEL	CPDLC
133.775	125.35 263.15	118.3 291.65 (Rwys 10L/R-28L/R, 15-33) 127.2 256.9 (Rwy 12-30)	121.9 (Rwys 10L/R-28L/R, 15-33) 121.75 (Rwy 12-30)	121.1	

UAS Note: Lost Link Missed Approach: Climbing left turn to 3000 on track 347 to BERKS then direct DATTS, execute a procedure turn and RNAV(GPS) RWY10L. If unable to land RWY10L due to maximum tailwind component being exceeded, climbing left turn to 3000 on track 060 to SALAD then direct BBUBB and execute RNAV (RNP) Z RWY 28R.

Final approach course offset 11.16°.

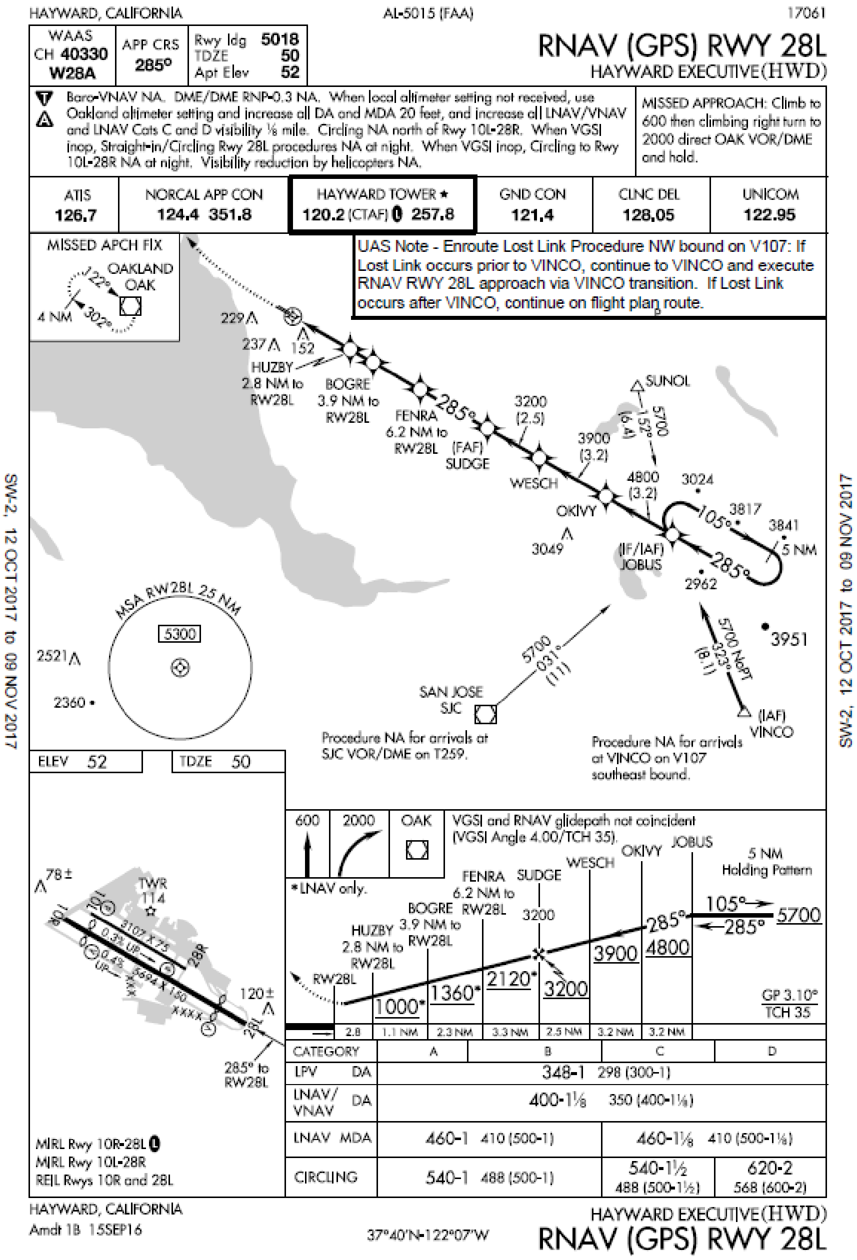
VGSI and descent angles not coincident (VGSI Angle 3.00/TCH 50).

CATEGORY	A	B	C	D
LNAV MDA	500-1 494 (500-1)		500-1⅜ 494 (500-1⅜)	
CIRCLING	560-1 551 (600-1)		660-1¾ 651 (700-1¾)	1380-3 1371 (1400-3)

REIL Rwy 10R
TDZ/CL Rwy 30
MIRL Rwy 15-33
HIRL Rwys 12-30, 10L-28R, 10R-28L

OAKLAND, CALIFORNIA
Amdt 2 18SEP14
37°43'N-122°13'W
METROPOLITAN OAKLAND INTL (OAK)
RNAV (GPS) RWY 10L

RNAV (GPS) RWY 28L (HWD)



HAYWARD, CALIFORNIA AL-5015 (FAA) 17061

RNAV (GPS) RWY 28L
HAYWARD EXECUTIVE(HWD)

WAAS CH **40330** **W28A**	APP CRS **285°**	Rwy ldg TDZE Apt Elev	**5018** **50** **52**

Baro-VNAV NA. DME/DME RNP-0.3 NA. When local altimeter setting not received, use Oakland altimeter setting and increase all DA and MDA 20 feet, and increase all LNAV/VNAV and LNAV Cats C and D visibility ⅛ mile. Circling NA north of Rwy 10L-28R. When VGSI inop, Straight-in/Circling Rwy 28L procedures NA at night. When VGSI inop, Circling to Rwy 10L-28R NA at night. Visibility reduction by helicopters NA.

MISSED APPROACH: Climb to 600 then climbing right turn to 2000 direct OAK VOR/DME and hold.

ATIS	NORCAL APP CON	HAYWARD TOWER ★	GND CON	CLNC DEL	UNICOM
126.7	**124.4 351.8**	**120.2** (CTAF) ● **257.8**	**121.4**	**128.05**	**122.95**

UAS Note - Enroute Lost Link Procedure NW bound on V107: If Lost Link occurs prior to VINCO, continue to VINCO and execute RNAV RWY 28L approach via VINCO transition. If Lost Link occurs after VINCO, continue on flight plan route.

Procedure NA for arrivals at SJC VOR/DME on T259.

Procedure NA for arrivals at VINCO on V107 southeast bound.

VGSI and RNAV glidepath not coincident (VGSI Angle 4.00/TCH 35).

*LNAV only.

CATEGORY	A	B	C	D
LPV DA	348-1 298 (300-1)			
LNAV/ VNAV DA	400-1⅛ 350 (400-1⅛)			
LNAV MDA	460-1 410 (500-1)		460-1⅛ 410 (500-1⅛)	
CIRCLING	540-1 488 (500-1)		540-1½ 488 (500-1½)	620-2 568 (600-2)

MIRL Rwy 10R-28L ●
MIRL Rwy 10L-28R
REIL Rwys 10R and 28L

HAYWARD, CALIFORNIA
Amdt 1B 15SEP16

37°40'N-122°07'W

HAYWARD EXECUTIVE(HWD)
RNAV (GPS) RWY 28L

SW-2, 12 OCT 2017 to 09 NOV 2017

SW-2, 12 OCT 2017 to 09 NOV 2017

APPENDIX E—WHY BAYESIAN STATISTICS AND GENERALIZED LINEAR MODELS

Takeaway points of this appendix:

- Various data collected during the HITL (e.g., survey responses, WAK responses, number of arrivals) are not normally distributed, so they should not be summarized or analyzed under the assumption of a normal distribution
- Generalized linear models, such as implemented in R or other statistical software, properly model non-normal data
- The output from Bayesian analyses better map onto researchers' expectations about significance and confidence values
- The practitioner faces overhead in learning software and better statistical techniques but is rewarded with better, more valid results

Human factors experimenters typically use frequentist statistical methods (t-tests, ANOVAs, etc.) to analyze data. In this report we have used different (but still frequentist) statistical methods, namely generalized linear models, in a Bayesian framework. Both of these choices provide a better description of the data and more intuitive results for decision-makers. Since statistical analysis exists as a way to assist decision making, we believe that this choice is the proper one.

Generalized Linear Models

The general linear model is a statistical model that says that outcome/dependent variable(s), **Y**, can be described as a combination of input/independent variables, **X**, and 'weights', **B**, along with some error term, **E**. Common statistical analyses such as multiple regressions, correlations, ANOVAs, and t-tests are examples of a general linear model where there is a single dependent variable and one or more independent variables. These models are 'linear' because Y is taken to be a linear combination of the Xs: if there are two independent variables, for example, the regression equation would be written as $Y = X0 + B1*X1 + B2*X2 + e$. B1 and B2 are the weights that are statistically tested to see if independent variables X1 and/or X2 affect the value of Y (X0 is an intercept term that is rarely of experimental interest and e is the error that helps describe how well the regression describes the data). These models are 'general' because they assume Y is normally distributed, or roughly shaped like a bell curve. General linear models are perfectly adequate for data like human heights or weights or, in the case of air traffic control experiments, variables like aircraft distance and time flown in sector.

However, not all data are normally distributed. Counts of events, such as airport arrivals or the number of losses of separation, tend to be log distributed: they can only be positive and tend to be positively skewed such that most events are bunched together at some counts but there are fewer events at higher counts. These kinds of variables are not necessarily well-described by a general linear model. Instead we can use generalized linear models, which still assume a linear association between Y and X but pass it through a distribution other than the normal (thus, the general linear model is an example of a generalized linear model where the distribution happens to be normal). By respecting the kind of data being described, generalized linear models provide a better description and more appropriate statistical analysis of the data.

Bayesian Statistics

Frequentist statistics, at a conceptual level, takes the view that experiments can (or hypothetically will be) repeated many/infinite times. The frequentist description of a coin having a 50% probability of coming up heads, for example, means that if you were to flip the coin a high number of times, you would observe equal numbers of heads and tails. When applied to experiment analysis, frequentist statistics are typically summarized with p values and, sometimes, confidence intervals. However, p values and frequentist confidence intervals are not intuitive to interpret and have a number of drawbacks.

The p value for a statistical test, such as the t value in a t-test, is defined as the probability of obtaining a result (t value) of the observed value or more extreme assuming that a null hypothesis is true (in the case of a t-test, usually that the difference in two means is zero). Rewording the definition slightly, the p value is the probability that the experimental data occurred given the null hypothesis. Reading the definition likely makes a couple of observations stick out: first, it relies on potential outcomes that are never actually observed (e.g. the 'more extreme' t values), and second, it assumes a null hypothesis that researchers rarely believe (e.g. that two conditions we are testing, likely because we expect them to differ, are actually the same). P values are involved in the creation of frequentist confidence intervals, which means that confidence intervals inherit their problems. Confidence intervals also have a non-intuitive meaning: a 95% confidence interval, for example, does not mean that there is a 95% chance that the 'real' (i.e., in the entire population) value falls within the interval. Instead, a 95% confidence interval means that if one were to conduct a large number of the exact same experiment and create a confidence interval for each, 95% of those confidence intervals would contain the 'real' value.

Bayesian statistics come from Bayes' rule, which connects the probability of an event to prior knowledge about that event. For example, one would think that the probability that it is going to rain is different depending on if it is cloudy or not. As it relates to statistical analysis Bayesian inference happens by multiplying a statistical model (such as a t-test or generalized linear model) by prior probabilities on the various elements of the model (such as the **B** weights) to provide an outcome. Practically speaking, this multiplication is carried out by software which provides many possible results via Monte Carlo random sampling. By looking at the outcomes of the random samples the analyst can decide how likely a particular outcome is. For example, if all of the random samples have a positive difference in means between two conditions, the analyst can assume that it is unlikely that the two conditions are the same. The results of frequentist analyses are an example of Bayesian analyses that use certain priors, in the same way that the general linear model is an example of a generalized linear model that uses a certain distribution.

The outcome of a Bayesian analysis is essentially the opposite of a p value: instead of the probability of data given a hypothesis, a Bayesian analysis provides the probability of the hypothesis given the data. This is what an analyst actually wants to know: given the data I've observed in my experiment, how likely is it that these two conditions differ? Additionally, the Monte Carlo random samples used in conducting a Bayesian analysis provide probabilities and confidence intervals that can be intuitively interpreted. If a Bayesian analysis results in 95% of the samples for some parameter (such as the difference of means between two conditions) being above zero, then the analysis says that there is a 95% chance that the 'real' difference is above zero. There is no need for considering infinite exact versions of the experiment or convoluted definitions; Bayesian outcomes align with what people typically expect statistical outcomes to mean.

It is important to note that Bayesian analysis is not a panacea. Bayesian methods can be used for simple procedures like correlations or t-tests; if these procedures are poorly chosen, such as when a generalized linear model would be more appropriate, then the outcome will still be less than optimal. Additionally, any statistical analysis is limited by the quality and quantity of the data available. If there is little data or it was collected in a haphazard way, the best statistical analysis could still be a poor, or just noisy, description of the real world. However, we believe that using generalized linear models and Bayesian inference provides the best opportunity for an accurate description of the data collected, and that the results will be more intuitive and suitable for assisting decision making on the study outcomes.

APPENDIX F—MODELING APPROACH

Modeling trial-level outcomes

For outcomes that are measured at the trial level (e.g., the number of departures), we will use a generalized multilevel model. We model the distribution for measure Y for trial i from participant j as:

$$Y_{ij} \sim g^{-1}(\eta_j + \boldsymbol{\beta} \cdot \mathbf{X_{ij}})$$

g is the link function, which will be chosen based on the support of Y; i.e., the type (integer vs. real) and range of values that the outcome can take on. Examples include the *identity* function for metric outcomes, and the *log* function for count outcomes.

$\mathbf{X_{ij}}$ is row i from the model matrix for participant j.

$\boldsymbol{\beta}$ is a vector of coefficients for "fixed" effects.

η_j is the second-level model for participant effects, which are modeled using the distribution:

$$\eta_j \sim \gamma_0 + \gamma_1 W_j + \mu_j$$

γ_0 is the overall intercept.

W_j codes whether participant j was controlling the arrival ($W = 0$) vs. departure ($W = 1$) sector.

γ_1 is a coefficient that provides an estimate of the "sector effect".

μ_j is the random error component for participant j. I.e., it estimates the extent to which a given participant differs from the "average" participant after accounting for the sector.

Model matrix

The model matrix is designed to make use of baseline scenarios to estimate the effects of the sector traffic, the type of aircraft that goes lost link, and the specific lost link procedure.

Phase of flight effects

Here, the departure scenarios serve as a baseline.

Trial	phase_arrival	phase_cruise
1.1 Baseline Nominal	0	0
1.2 Lost Link Return to Airport, No hold (Jet)	0	0
1.3 Lost Link Return to Airport, No hold (Turboprop)	0	0
1.4 Lost Link Return to Airport, Holding (Jet)	0	0
1.5 Lost Link Return to Airport, Holding (Turboprop)	0	0
2.1 Baseline Nominal	1	0
2.2 Lost Link Continue on Flight Plan (Jet)	1	0
2.3 Lost Link Continue on Flight Plan (Turboprop)	1	0
2.4 Lost Link Continue on Flight Plan land opposite direction (Jet)	1	0
2.5 Lost Link Continue on Flight Plan land opposite direction (Turboprop)	1	0
2.6 Multiple Lost Link 1 arrival 1 departure (2 Jets)	1	0
2.7 Multiple Lost Link 1 arrival 1 departure (2 Turboprops)	1	0
3.1 Baseline Nominal	0	1
3.2 Lost Link Divert to Alternate Airport, No hold (Jet)	0	1
3.3 Lost Link Divert to Alternate Airport, No hold (Turboprop)	0	1

Aircraft effects

Trial	turboprop_lostlink	jet_lostlink
1.1 Baseline Nominal	0	0
1.2 Lost Link Return to Airport, No hold (Jet)	0	1
1.3 Lost Link Return to Airport, No hold (Turboprop)	1	0
1.4 Lost Link Return to Airport, Holding (Jet)	0	1
1.5 Lost Link Return to Airport, Holding (Turboprop)	1	0
2.1 Baseline Nominal	0	0
2.2 Lost Link Continue on Flight Plan (Jet)	0	1
2.3 Lost Link Continue on Flight Plan (Turboprop)	1	0
2.4 Lost Link Continue on Flight Plan land opposite direction (Jet)	0	1
2.5 Lost Link Continue on Flight Plan land opposite direction (Turboprop)	1	0
2.6 Multiple Lost Link 1 arrival 1 departure (2 Jets)	0	1
2.7 Multiple Lost Link 1 arrival 1 departure (2 Turboprops)	1	0
3.1 Baseline Nominal	0	0
3.2 Lost Link Divert to Alternate Airport, No hold (Jet)	0	1
3.3 Lost Link Divert to Alternate Airport, No hold (Turboprop)	1	0

Procedure effects

The baseline scenario for each phase of flight serve as the baseline for measuring procedure effects.

trial	return_no hold	return_ hold	continue_flight_ plan	continue_land_ opposite	multi_lostlink	divert_ airport
1.1	0	0	0	0	0	0
1.2	1	0	0	0	0	0
1.3	1	0	0	0	0	0
1.4	0	1	0	0	0	0
1.5	0	1	0	0	0	0
2.1	0	0	0	0	0	0
2.2	0	0	1	0	0	0
2.3	0	0	1	0	0	0
2.4	0	0	0	1	0	0
2.5	0	0	0	1	0	0
2.6	0	0	0	0	1	0
2.7	0	0	0	0	1	0
3.1	0	0	0	0	0	0
3.2	0	0	0	0	0	1
3.3	0	0	0	0	0	1

Post-hoc comparisons

The model fitting procedure allows us to make *post-hoc* comparisons between specific types of trials. In addition to estimating the effect of each procedure vs. the baseline, compared the following procedures:

- *Lost Link Return to Airport, Holding* vs. *Lost Link Return to Airport, No hold*
- *Lost Link Continue on Flight Plan* vs. *Lost Link Continue on Flight Plan land opposite direction*

Link functions

Measure	**Link Function**
Airport acceptance rate	Log
Average distance in sector (all aircraft)	Identity
Average distance in sector (UAS)	Identity
Average time in sector (all aircraft)	Identity
Average time in sector (UAS)	Identity
Number of departures	Log
Number of conflict alerts (all aircraft)	Log
Number of conflict alerts (UAS)	Log
Closest point of approach during separation loss (all aircraft)	Inverse
Closest point of approach during separation loss (UAS)	Inverse
Duration of separation loss (all aircraft)	Inverse
Duration of separation loss (UAS)	Inverse
Number of losses of separation (all aircraft)	Log
Number of losses of separation (UAS)	Log
Number of misidentified aircraft	Log
Duration of communications (average)	Identity
Number of communications (landline)	Log
Number of communications (total)	Log
Number of repeat clearances	Log
Number of transposed call signs	Log
Number of sim pilot commands entered	Log

APPENDIX G—SURVEY ANALYSIS DETAILS

The survey data were modeled somewhat differently than the measures listed Appendix F. This choice was made because survey responses are considered ordinal data and are relatively different from the other measures. Ordinal data means that while the response options are ordered (e.g. 3 is greater than 2 which is greater than 1), there is no reason to think that the difference between 1 and 2 is the same as the difference between 2 and 3, or that options 1 and 2 mean the same thing to different participants. Research shows that, while being common practice, it is a mistake to model ordinal data with methods that assume a normal distribution because those methods lead to increased erroneous results.

We modeled the survey data using a Bayesian ordered probit regression. The ordinal probit model assumes an underlying normally distributed variable that is then binned into the Likert-style response. For example, the model assumes that people have a continuous, normally distributed property called ‘happiness’, which they have to put into discrete bins when asked to rate how happy they are on a 1 to 7 scale. The model uses a mean response for each question and thresholds for dividing the response into each category (the point at which participants switch from responding ‘1’ to ‘2’ or ‘3’ to ‘4’). That is to say, each survey question is allowed to have its own mean and standard deviation for the underlying distribution as well as its own thresholds for binning that distribution into a response. However, every question on a survey (either the exit survey or the post-scenario surveys taken as a whole) is fit by the model simultaneously, which allows them to be compared in the Bayesian framework. Participants are grouped into a single set of responses for each question, which is different from the model for the other data where participants were included as a second-level factor. Once the posterior probability has been calculated (the model has been fit to the data), statistical hypotheses are answered in a manner similar to bootstrapping. RStan creates a number of Monte Carlo draws of parameter estimates that fit the posterior probability distribution. If responses change for a question across scenarios, we can pull the Monte Carlo draws for those questions and compare the mean parameters. If, say, 95% of them exclude a 0 difference, then we can conclude with 95% confidence that the response changed.

After the model is fit to the data, comparisons of interest were made by creating an expected response for each question and then comparing the expected responses. We will walk through a result reported in the results section (see section 7.4.4, NASA TLX) as an example. Question 4 on the post scenario questionnaire asked participants to rate how successful they were at accomplishing their task goals. In the turboprop version of the continue-in arrival scenario, 3 participants each responded with a 9 or 10 rating and 2 participants each responded with a 7 or 8 rating. The ordered probit model was fit to those data and provided a range of probabilities for any given rating (1 through 10) if the experiment were to be run again. It predicts virtually no chance of a 1 through 5 rating, a small range of probabilities of a 6 rating (around 0 to 5%), anywhere from ~5% to ~40% each of a 7 or 8 rating, and anywhere from ~10% to 50% each of a 9 or 10 rating. These probabilities are then used to generate plausible response sets, each of which is then averaged to find an expected response. The model predicts that the expected response, were additional data to be collected, would likely be between 8 and 9. This prediction meshes with the actual expected response, which is the average of the responses from our participants (8.7).

In order to compare the continue-in and multiple lost link conditions, this process is carried out for each question that contributes to that comparison: the jet and turboprop versions of the continue-in scenarios as well as the multiple lost link scenarios. The range of expected responses for both versions of the continue-in scenarios are then averaged together, as are the expected responses for both versions of the multiple lost link scenarios, and then they are subtracted from each other. We observed that 96% of the expected responses were higher in the continue-in condition than the multiple lost link condition. Thus we report 96% confidence that participants gave a higher rating in that condition.

This process is carried out for each comparison of interest in both the exit and post scenario questionnaires. One exception is for some questions which are not meant to be compared to another but instead to provide its own direct answer. For example, Question 17 of the exit questionnaire asked participants to rate the effectiveness of the procedures used to manage UAS operations. This is a self-contained question where participants provided a rating from 1, meaning very ineffective, to 10, meaning very effective, with 5 being a neutral response. We are interested in knowing what rating we would expect participants to give in general (i.e., if we were to collect more data) and if they believed the procedures were effective (i.e., if the response is greater than 5 on average). For questions like these, we simply take the various expected responses and see how often they fall above 5. The model predicts an expected response anywhere from around 6 to 9, although likely between 7 and 8 (which fits with our observed data, which had an average of 8). 99.8% of the Monte Carlo draws of the expected response are above 5, so we say that we are 99% confident that participants rated the procedures as effective.

APPENDIX H—WAK ANALYSIS

There are several challenges to modelling data from the workload assessment keypad (WAK), which are taken into account by our current approach:

- WAK responses are made on an ordinal scale, while most statistical tests (e.g., ANOVA) assume metric data
- Some responses are missing, and we can't assume that the misses are random (i.e., higher workload might make a miss more likely)
- The responses form a time series, and data from past studies exhibit autocorrelation in the responses; these data violate the assumption made by most tests that they are "independent and identically distributed"

Modeling workload

We modelled the *workload* construct using a two-level model.

Level 1

The first level of the model predicts that workload at time t on trial i for participant p will be:

$$y_{itp} = \mathbf{x}_{\mathbf{itp}}^{\mathbf{T}} \boldsymbol{\beta}_{\mathbf{p}} + \varphi y_{i,t-1,p}$$

Response-level explanatory variables ($\mathbf{x}_{\mathbf{itp}}$) are described below.

This model captures the lag-1 autoregressive effect of the response variable, (φ). The inclusion of this term corrects for the violation of independence of samples over time, motivated by an analysis of WAK data from a previous study.

Level 1 Predictors

Each run is partitioned into 10 s *epochs* in which various objects and events are counted (i.e., the number of aircraft in the sector, the number of communications made by the participant). E.g., the first epoch will cover the time period $(0,10]s$, the second $(10,20]s$, etc.

The vector of response-level variables $\mathbf{x}_{\mathbf{itp}}$ is composed of the following elements. Some variables will be normalized to a mean of 0 and standard deviation of 1, and others will be centered to have a mean of 0; these are indicated below.

1. Run number: linear component {1, 2, 3, …, 15} (normalized)
2. Run number: quadratic component {1, 4, 9, …, 225} (normalized)
3. Number of communications by the participant during the prompt epoch {0, 1, 2, …} (normalized)
4. Number of communications from pilots to the participant during the prompt epoch {0, 1, 3, …} (normalized)
5. Total number of aircraft in the sector during the prompt epoch (including UAS) {0, 1, 2, …} (normalized)
6. Number of UAS in the sector during the prompt epoch {0, 1, 2, …} (normalized)
7. Whether a UAS went LL in the participant's sector since the last WAK prompt {0, 1}

8. Whether a UAS went LL in a neighboring sector since the last WAK prompt {0, 1}
9. Whether a LL UAS entered the participant's sector since the last WAK prompt {0, 1}
10. Whether a LL UAS is in sector and currently executing a RTB with no hold {0, 1}
11. Whether a LL UAS is in sector and currently executing a RTB with a hold {0, 1}
12. Whether a LL UAS is in sector and currently continuing its flight plan: same direction {0, 1}
13. Whether a LL UAS is in sector and currently continuing its flight plan: opposite direction {0, 1}
14. Whether a LL UAS is in sector and diverting to an alternate airport {0, 1}
15. Whether a Caravan-like aircraft is LL in arrivals or departures {0, 1} (centered)
16. Whether a Global Hawk-like aircraft is LL in arrivals or departures {0, 1} (centered)

Level 2

The second level of the model predicts effects for each participant, p. Each element n in the vector $\boldsymbol{\beta}_\mathbf{p}$ is distributed as:

$$\beta_{pn} \sim \mathcal{N}(\gamma_{0n} + w_p\gamma_{1n}, \sigma^2_{\beta n})$$

The variable w_p is an indicator for the participant sector, taking on the values {-1/2, 1/2} (negative for arrivals).

This form allows the parameters γ_{0n} to estimate the average coefficient across all arrival and departure controllers, and γ_{1n} to estimate the arrival vs. departure difference for each β_{pn}.

For example, $\gamma_{0,3}$ is estimates the effect of increasing pilot communications on workload, and $\gamma_{1,3}$ estimates the difference of this effect for the arrivals vs. departures sectors.

No interactions

This model leaves out potentially interesting interactions (e.g., are the effects of different LL procedures different for Caravan vs. Global Hawk?). There are already quite a few parameters to estimate for the amount of data available, so any interaction coefficients will be too noisy to be meaningful.

Responses

We cannot directly observe the "true" workload of a participant; we see the numeric WAK response (and whether the participant made one at all) and can measure the response time.

Numeric response

The numeric response π_{itp} is modeled with a cumulative link model:

$$\pi_{itp} = \begin{cases} 1 \; if \; y_{itp} \leq \theta_1 \\ 2 \; if \; \theta_1 < y_{itp} \leq \theta_2 \\ 3 \; if \; \theta_2 < y_{itp} \leq \theta_3 \\ \vdots \\ 10 \; if \; \theta_9 < y_{itp} \end{cases}$$

We will use a probit link function for this model; therefore:

$$P(\pi_{itp} = k) = \Phi(\theta_k - y_{itp}) - \Phi(\theta_{k-1} - y_{itp})$$

Where $\theta_1, \dots, \theta_9$ are estimated from the data.

Missing responses

The probability that no response was made on a given trial, ε_{itp}, is modeled by:

$$E(\varepsilon_{itp}) = logit^{-1}(\alpha_0 + \alpha_1 y_{itp})$$

Both α_0 and α_1 are estimated from the data. This is motivated by the assumption that higher workload may increase the probability of missing a prompt.

Response time

We make no predictions about the relationship between workload and response time here; inspection of previous results showed a weak relationship between WAK values and RT.

Priors

Priors on the effects of interest ($\boldsymbol{\gamma}, \boldsymbol{\alpha}$) will generally have a Cauchy prior distribution with location 0 and scale 1, e.g.:

$$\alpha \sim Cauchy(0,1)$$

Autoregression

The prior for the autoregressive effect on workload is a truncated normal in the range [-1, 1]:

$$\varphi \sim \mathcal{N}(0,1), -1 \leq \varphi \leq 1$$

Thresholds

Thresholds $\theta_1, \theta_2, \dots, \theta_9$ are constrained to be monotonically increasing. Each has the prior:

$$\theta_k \sim \mathcal{N}(k - 0.5, 2)$$

Variance

Variance for the participant-level model on the elements of $\boldsymbol{\beta}$ will have a half-normal prior distribution:

$$\sigma_{\beta n} \sim \mathcal{N}(0, 10^2)$$

Parameter estimates

We fit a multilevel model to the WAK data. This allows for us to account for variation between participants (sometimes called "random effects") and obtain estimates for the effects of our within-subjects manipulations (e.g., contingency procedure). For each of these effects, we also estimate an effect for our between-subjects manipulation, sector (arrival vs. departure). This allows us to calculate, for each model parameter, four things:

1. The average effect across sectors
2. The effect of sector on that parameter
3. The effect for controllers in the arrival sector only
4. The same for departure controllers

Since this is a Bayesian model, we estimate a distribution of credible parameter values instead of a single point value. For each of the effects of interest, the table below gives the boundaries of the 95% highest density interval (HDI) and the median. If the HDI excludes zero, we take that effect to be statistically significant.

HDI and median for each parameter (continued below)

	All Sectors	**Sector Effect**
1. Run number: linear component	-0.14, 0, 0.14	-0.47, -0.21, 0.07
2. Run number: quadratic component	-0.2, -0.08, 0.03	-0.1, 0.12, 0.34
3. Number of communications by the participant during the prompt epoch	**0.09, 0.35, 0.59**	-0.81, -0.34, 0.13
4. Number of communications from pilots to the participant during the prompt epoch	-0.02, 0.07, 0.17	**0.07, 0.26, 0.45**
5. Total number of aircraft in the sector during the prompt epoch (including UAS)	-0.32, -0.07, 0.2	-0.3, 0.23, 0.73
6. Number of UAS in the sector during the prompt epoch	-0.03, 0.07, 0.17	-0.51, -0.3, -0.12
7. Whether a UAS went LL in the participant's sector since the last WAK prompt	-0.46, 0.44, 1.3	-2.28, -0.6, 0.93
8. Whether a UAS went LL in a neighboring sector since the last WAK prompt	-0.76, 0.22, 1.15	-2.86, -0.94, 0.78
9. Whether a LL UAS entered the participant's sector since the last WAK prompt	**0.07, 0.57, 1.11**	-0.68, 0.24, 1.2
10. Whether a LL UAS is in sector and currently executing a RTB with no hold	-0.62, -0.13, 0.36	-0.76, 0.14, 0.99
11. Whether a LL UAS is in sector and currently executing a RTB with a hold	-0.63, 0.15, 0.91	-1.17, 0.11, 1.44
12. Whether a LL UAS is in sector and currently continuing its flight plan: same direction	-1.32, -0.04, 1.42	-2.7, 0.02, 2.59

13. Whether a LL UAS is in sector and currently continuing its flight plan: opposite direction	-1.41, -0.06, 1.36	-2.79, -0.05, 2.52
14. Whether a LL UAS is in sector and diverting to an alternate airport	-0.52, 0.19, 0.91	-0.66, 0.71, 2.09
15. Whether a Caravan-like aircraft is LL in arrivals or departures	-0.44, -0.11, 0.22	-0.46, 0.15, 0.76
16. Whether a Global Hawk-like aircraft is LL in arrivals or departures	-0.59, -0.12, 0.39	-0.5, 0.41, 1.3

	Arrivals	**Departures**
1. Run number: linear component	-0.08, 0.1, 0.3	-0.3, -0.1, 0.09
2. Run number: quadratic component	-0.3, -0.15, 0.02	-0.19, -0.02, 0.13
3. Number of communications by the participant during the prompt epoch	**0.18, 0.52, 0.88**	-0.17, 0.18, 0.53
4. Number of communications from pilots to the participant during the prompt epoch	-0.19, -0.06, 0.09	**0.07, 0.2, 0.34**
5. Total number of aircraft in the sector during the prompt epoch (including UAS)	-0.56, -0.18, 0.18	-0.33, 0.04, 0.41
6. Number of UAS in the sector during the prompt epoch	**0.08, 0.22, 0.36**	-0.22, -0.08, 0.06
7. Whether a UAS went LL in the participant's sector since the last WAK prompt	-0.44, 0.76, 1.98	-1.02, 0.13, 1.35
8. Whether a UAS went LL in a neighboring sector since the last WAK prompt	-0.62, 0.73, 1.97	-1.62, -0.27, 1.06
9. Whether a LL UAS entered the participant's sector since the last WAK prompt	-0.01, 0.45, 0.92	-0.16, 0.69, 1.58
10. Whether a LL UAS is in sector and currently executing a RTB with no hold	-0.78, -0.21, 0.41	-0.77, -0.06, 0.65
11. Whether a LL UAS is in sector and currently executing a RTB with a hold	-0.92, 0.09, 1.12	-0.79, 0.21, 1.18
12. Whether a LL UAS is in sector and currently continuing its flight plan: same direction	-0.45, -0.05, 0.35	-2.6, -0.03, 2.67
13. Whether a LL UAS is in sector and currently continuing its flight plan: opposite direction	-2.64, -0.03, 2.68	-0.73, -0.08, 0.48
14. Whether a LL UAS is in sector and diverting to an alternate airport	-1.14, -0.17, 0.7	-0.5, 0.56, 1.63
15. Whether a Caravan-like aircraft is LL in arrivals or departures	-0.64, -0.19, 0.26	-0.48, -0.04, 0.41
16. Whether a Global Hawk-like aircraft is LL in arrivals or departures	-0.99, -0.33, 0.32	-0.59, 0.1, 0.75

Other model parameters

Missing responses

Our model accounted for the possibility that workload influenced the likelihood of a participant missing a response. However, we found no reliable effect of (modeled) workload on whether a response was missing (95% HDI [-0.17, 0.42]).

Autoregressive effect

Because WAK responses form a time series, our model accounted for an autoregressive effect on workload. We found that responses were highly autocorrelated (95% HDI [0.79, 0.86]). Analyses that assume independence of responses with have inflated degrees of freedom.

APPENDIX I—POST-SCENARIO QUESTIONNAIRE COMPLETE RESULTS

Departure

question	procedure	sector	mean_resp	median_resp
1. Mental Demand	baseline	arrivals	6.6	6
		departures	4.6	4
	hold	arrivals	7.4	8
		departures	6	6
	RTB	arrivals	7.4	8
		departures	4.7	5
2. Physical Demand	baseline	arrivals	2.8	2.5
		departures	3.8	2
	hold	arrivals	3.9	3
		departures	3.5	3
	RTB	arrivals	3.3	3
		departures	3.3	2
3. Temporal Demand	baseline	arrivals	5.2	6
		departures	4.2	4
	hold	arrivals	7.1	7
		departures	5.1	5
	RTB	arrivals	7.4	8
		departures	3.9	4
4. Performance	baseline	arrivals	8.4	8
		departures	7.8	8
	hold	arrivals	7.4	7
		departures	7.6	8
	RTB	arrivals	8.1	8.5
		departures	7.9	8
5. Effort	baseline	arrivals	6.6	6
		departures	4.4	3
	hold	arrivals	7.6	7
		departures	6	6
	RTB	arrivals	7.5	8
		departures	4.9	6
6. Frustration	baseline	arrivals	4.2	4
		departures	3.8	2
	hold	arrivals	5.6	6
		departures	3.7	4
	RTB	arrivals	5	6
		departures	3.1	2.5

7. Rate your performance for safely resolving the lost link event(s) during this scenario.	baseline	arrivals	5.5	5.5
		departures	3.6	1
	hold	arrivals	8	9
		departures	7.9	8
	RTB	arrivals	8.2	9
		departures	7.3	7.5
8. Rate your performance for efficiently resolving the lost link event(s) during this scenario.	baseline	arrivals	7	10
		departures	4.2	3
	hold	arrivals	7.2	7
		departures	7.7	8
	RTB	arrivals	8.1	8.5
		departures	7.3	7.5
9. Rate the overall safety of operations during this scenario.	baseline	arrivals	8.8	9
		departures	8.2	9
	hold	arrivals	8.4	9
		departures	8.1	8
	RTB	arrivals	8.2	9
		departures	8.5	8.5
10. Rate the overall efficiency of operations during this scenario.	baseline	arrivals	7.6	7
		departures	8.2	9
	hold	arrivals	7.1	7
		departures	7.8	8
	RTB	arrivals	8.2	8.5
		departures	8.3	8.5
11. Rate your workload due to the lost link event(s) during this scenario.	baseline	arrivals	3.2	1
		departures	3.8	3
	hold	arrivals	7	7
		departures	5.3	5
	RTB	arrivals	7.7	8
		departures	4.3	4
12. Rate the effectiveness of the lost link contingency procedure for the lost link event(s) during this scenario.	baseline	arrivals	5.5	5.5
		departures	3.4	1
	hold	arrivals	6.4	7
		departures	7.7	8
	RTB	arrivals	7.7	8.5
		departures	7.5	8
13. Rate your overall level of situation awareness during this scenario.	baseline	arrivals	8.2	8
		departures	8.8	9
	hold	arrivals	8	8
		departures	7.8	8
	RTB	arrivals	8.2	9

		departures	8.5	8.5
14. Rate your situation awareness for UAS progress along the lost link contingency procedure during this scenario.	baseline	arrivals	5.5	5.5
		departures	3.6	1
	hold	arrivals	8.1	9
		departures	7.5	8
	RTB	arrivals	7.9	8.5
		departures	8.9	9
15. Rate the overall performance of the simulation pilots in terms of responding to control instructions, phraseology, and providing readbacks.	baseline	arrivals	9.2	10
		departures	9.6	10
	hold	arrivals	8.8	9
		departures	8.8	9
	RTB	arrivals	9.1	9
		departures	9	10

Arrival

question	procedure	sector	mean_resp	median_resp
1. Mental Demand	baseline	arrivals	6.2	6
		departures	5	5
	continue	arrivals	6.6	7
		departures	4.9	5
	multiple	arrivals	7.4	8
		departures	5.8	5.5
	opposite	arrivals	7.5	7
		departures	6.2	6
2. Physical Demand	baseline	arrivals	2.4	2
		departures	3.8	5
	continue	arrivals	3.2	2.5
		departures	3.2	2
	multiple	arrivals	3.7	3
		departures	3.3	3
	opposite	arrivals	2.6	2
		departures	3.9	3.5
3. Temporal Demand	baseline	arrivals	6.4	7
		departures	4.6	5
	continue	arrivals	6.5	7
		departures	4.2	4
	multiple	arrivals	7.2	7.5
		departures	5.4	5
	opposite	arrivals	6.8	7
		departures	5.3	5

4. Performance	baseline	arrivals	7.2	9
		departures	7.8	7
	continue	arrivals	8.6	9
		departures	8.2	8
	multiple	arrivals	7.7	8.5
		departures	7.6	8
	opposite	arrivals	8	8
		departures	6.9	7.5
5. Effort	baseline	arrivals	6.4	7
		departures	5.6	5
	continue	arrivals	6.8	7
		departures	6	7
	multiple	arrivals	6.8	7
		departures	5.9	6
	opposite	arrivals	7.1	7
		departures	5.9	5.5
6. Frustration	baseline	arrivals	4.6	5
		departures	3.2	2
	continue	arrivals	4.1	4.5
		departures	2.4	2
	multiple	arrivals	5.7	5.5
		departures	3.7	3
	opposite	arrivals	4.9	5.5
		departures	4	3
7. Rate your performance for safely resolving the lost link event(s) during this scenario.	baseline	arrivals	6.4	10
		departures	4	1
	continue	arrivals	9.2	10
		departures	3.1	1
	multiple	arrivals	8.6	9
		departures	8.3	8
	opposite	arrivals	8.6	9
		departures	7.2	7
8. Rate your performance for efficiently resolving the lost link event(s) during this scenario.	baseline	arrivals	4.6	1
		departures	2.8	1
	continue	arrivals	9.3	10
		departures	2.9	1
	multiple	arrivals	7.5	8
		departures	8.5	8
	opposite	arrivals	7.2	8
		departures	7.6	8
	baseline	arrivals	7.6	10

9. Rate the overall safety of operations during this scenario.		departures	9.4	9
	continue	arrivals	9	9.5
		departures	9	9
	multiple	arrivals	7.9	9
		departures	8.8	9
	opposite	arrivals	7.8	8
		departures	6.6	7.5
10. Rate the overall efficiency of operations during this scenario.	baseline	arrivals	8	10
		departures	8.2	8
	continue	arrivals	8.4	8.5
		departures	9	9
	multiple	arrivals	7.1	8
		departures	8.4	9
	opposite	arrivals	7.4	8
		departures	7.5	7
11. Rate your workload due to the lost link event(s) during this scenario.	baseline	arrivals	5	3
		departures	1	1
	continue	arrivals	6.2	6
		departures	1.7	1
	multiple	arrivals	7.5	7.5
		departures	4.8	5
	opposite	arrivals	7.5	8
		departures	5.4	6
12. Rate the effectiveness of the lost link contingency procedure for the lost link event(s) during this scenario.	baseline	arrivals	4.6	1
		departures	2.8	1
	continue	arrivals	8.7	9
		departures	3.3	1
	multiple	arrivals	7.3	8.5
		departures	7.8	8
	opposite	arrivals	6.6	8
		departures	5.7	6
13. Rate your overall level of situation awareness during this scenario.	baseline	arrivals	7.6	10
		departures	8.6	9
	continue	arrivals	9	10
		departures	8.7	8
	multiple	arrivals	7.9	9
		departures	7.7	8
	opposite	arrivals	7.8	7
		departures	8.3	8
	baseline	arrivals	6.5	7.5
		departures	4.2	3

14. Rate your situation awareness for UAS progress along the lost link contingency procedure during this scenario.	continue	arrivals	9	9.5
		departures	5.9	7
	multiple	arrivals	8	8
		departures	7.4	9
	opposite	arrivals	6.6	6.5
		departures	8.4	8.5
15. Rate the overall performance of the simulation pilots in terms of responding to control instructions, phraseology, and providing readbacks.	baseline	arrivals	7.6	7
		departures	8.4	9
	continue	arrivals	8.9	9.5
		departures	9.6	10
	multiple	arrivals	9.2	9
		departures	9.6	10
	opposite	arrivals	9.1	9.5
		departures	9	9.5

Cruise/Overflight

question	procedure	sector	mean_resp	median_resp
1. Mental Demand	baseline	arrivals	8	8
		departures	5.4	6
	divert	arrivals	7.7	8
		departures	4.6	4.5
2. Physical Demand	baseline	arrivals	2.8	2
		departures	3.2	3
	divert	arrivals	3.7	3
		departures	3.5	2.5
3. Temporal Demand	baseline	arrivals	8	8
		departures	4.2	4
	divert	arrivals	7.4	8
		departures	4.2	4
4. Performance	baseline	arrivals	6.8	7
		departures	9	9
	divert	arrivals	7.7	7.5
		departures	8.3	8
5. Effort	baseline	arrivals	8.8	8.5
		departures	5	5
	divert	arrivals	7.8	8
		departures	5.4	5
6. Frustration	baseline	arrivals	7	7.5
		departures	2.6	2
	divert	arrivals	5.6	6
		departures	2.7	2

7. Rate your performance for safely resolving the lost link event(s) during this scenario.	baseline	arrivals	1	1
		departures	1	1
	divert	arrivals	7.1	7
		departures	7.1	7.5
8. Rate your performance for efficiently resolving the lost link event(s) during this scenario.	baseline	arrivals	1	1
		departures	1.8	1
	divert	arrivals	6.9	8
		departures	7.8	7.5
9. Rate the overall safety of operations during this scenario.	baseline	arrivals	5.8	6
		departures	9.6	10
	divert	arrivals	7.5	8.5
		departures	8.3	8
10. Rate the overall efficiency of operations during this scenario.	baseline	arrivals	6	6
		departures	8.8	9
	divert	arrivals	7	8
		departures	8.6	8
11. Rate your workload due to the lost link event(s) during this scenario.	baseline	arrivals	3.3	1
		departures	1.8	1
	divert	arrivals	8.3	8.5
		departures	4.5	4
12. Rate the effectiveness of the lost link contingency procedure for the lost link event(s) during this scenario.	baseline	arrivals	1	1
		departures	3	1
	divert	arrivals	6.2	8
		departures	7.9	9
13. Rate your overall level of situation awareness during this scenario.	baseline	arrivals	6.5	6.5
		departures	9.2	9
	divert	arrivals	7.5	8.5
		departures	8.4	8
14. Rate your situation awareness for UAS progress along the lost link contingency procedure during this scenario.	baseline	arrivals	1	1
		departures	1.8	1
	divert	arrivals	6.8	7.5
		departures	7.6	8.5
15. Rate the overall performance of the simulation pilots in terms of responding to control instructions, phraseology, and providing readbacks.	baseline	arrivals	7.8	7.5
		departures	8.8	10
	divert	arrivals	9.2	10
		departures	9.7	10

APPENDIX J—EXIT QUESTIONNAIRE COMPLETE RESULTS

Rating Questions

question	sector	mean_resp	median_resp
1. Rate the overall realism of the simulation experience compared to actual ATC operations.	arrivals	7	7
	departures	6.6	6
2. Rate the realism of the simulation hardware compared to actual equipment.	arrivals	8.4	8
	departures	8.6	8
3. Rate the realism of the simulation software compared to actual functionality.	arrivals	9	9
	departures	8	8
4. Rate the realism of the airspace compared to actual NAS airspace.	arrivals	8.6	8
	departures	8	8
5. Rate the realism of the simulation traffic scenarios compared to actual NAS traffic.	arrivals	7.6	8
	departures	7.2	7
6. To what extent did the WAK online workload rating technique interfere with your ATC performance?	arrivals	4.6	5
	departures	2	2
7. How effective was the airspace training?	arrivals	8.8	10
	departures	8.2	8
8. How effective was the UAS training?	arrivals	9.4	10
	departures	8.8	9
9. How effective were the procedures used to manage UAS operations?	arrivals	8	8
	departures	8	8
10. How effective was the display system for managing UAS operations?	arrivals	8.6	9
	departures	7.4	8
11. What was the impact of having a lost link aircraft land on the opposite runway?	arrivals	4.4	3
	departures	2	2
12. What was the impact of having multiple lost link aircraft in the airspace at the same time compared to a single lost link?	arrivals	5.2	5
	departures	3.2	3
	arrivals	8.4	10

13. What was the overall impact of the U indicator in the data block for UAS?	departures	5.8	5
14. Rate the influence of the U indicator on your situation awareness.	arrivals	9	10
	departures	6.6	7

LL Procedure Ranking Question, ordered by median response.

question	sector	mean_resp	median_resp
No lost link occurs	arrivals	1	1
No lost link occurs	departures	1	1
Arriving aircraft loses link, lands normally	arrivals	2.2	2
Arriving aircraft loses link, lands normally	departures	3.4	3
Departing aircraft loses link, returns directly to airport	arrivals	4	3
Departing aircraft loses link, returns directly to airport	departures	3	3
Departing aircraft loses link, returns to airport after a hold	arrivals	4	4
Departing aircraft loses link, returns to airport after a hold	departures	3.8	4
Multiple aircraft lose link at same time	arrivals	4.8	5
Overflight aircraft loses link, diverts to airport in your airspace	departures	5	5
Multiple aircraft lose link at same time	departures	6	6
Overflight aircraft loses link, diverts to airport in your airspace	arrivals	5.4	6
Arriving aircraft loses link, lands in opposite direction	arrivals	6.6	7
Arriving aircraft loses link, lands in opposite direction	departures	5.8	7