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TCL4 UTM (UAS Traffic Management) Texas 2019 Flight Tests, Airspace Operations Laboratory (AOL) Report

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Acronyms and Definitions

2D	Two Dimensional
3D	Three Dimensional
3DR	3D Robotics
AOL	Airspace Operations Lab, HSI division at NASA Ames
ANOVA	Analysis of Variance
App	(software) application
AR	Air Robot
BVLOS	Beyond visual line of sight
C2	Command and control
CH	Characteristic
CNS	Communication, navigation and surveillance
DJI	Da-Jiang Innovation
DMP	Data management plan
FIMS	Flight Information Management System
GCS	Ground control station
GCSO	Ground control station operator
GUFI	Globally unique flight identifier
HSI	Human-systems interactions
LSUASC	Lone Star UAS Center of Excellence & Innovation
M	Matrice
MOE	Measure of effectiveness
MOP	Measure of performance
NASA	National Aeronautics and Space Administration
PIC	Pilot in command
RC	Radio controlled
RID	Remote identification
RTK	Real time kinematic
RTL	Return to launch
SA	Situation awareness
SDSP	Supplemental data service provider
sim	Simulated operations
SOW	Statement of work
sUAS	Small unmanned aerial system
TCL	Technical capability level
TE	Test event
TX	Texas
UAS	Unmanned aerial system or unmanned aircraft system
UAV	Unmanned aerial vehicle
USA	United States of America
USS	Unmanned aerial system service supplier
USS Rep	Unmanned aerial system software developer
UTM	Unmanned aerial system traffic management
UVR	Unmanned aerial system volume restriction
V2V	Vehicle-to-vehicle
VO	Visual observer

TCL4 UTM (UAS Traffic Management) Texas Flight Tests, Airspace Operations Laboratory (AOL) Report

Lynne Martin[1], Cynthia Wolter[2], Kimberly Jobe[2], Madison Goodyear[2], Mariah Manzano[2], Michele Cencetti[3], Joey Mercer[1], Jeffrey Homola[1]

Executive Summary

For the last five years (2015-2019), the Unmanned Aircraft Systems (UAS) Traffic Management (UTM) research project has been developing and testing concept ideas for enabling small UAS (sUAS) operations in low altitude airspace (ground to 400 feet). To do this, the National Aeronautics and Space Administration (NASA) organized a series of incrementally complex flight test demonstrations, culminating with Technical Capability Level-4 (TCL4) flight tests at a Nevada, USA test site in June and a Texas, USA test site, in August 2019. The Texas demonstration resulted in over 400 data collection flights using eight live rotorcraft, 15 simulated vehicles, with nine flight crews and six Unmanned Aerial System (UAS) Service Suppliers (USSs). The TCL4 approach was designed to demonstrate five scenarios that set up diverse sets of UAS events and activities. These scenarios focused on a variety of potential events and issues from an incoming weather front, to sharing airspace, to a USS failure, and multiple vehicles experiencing Communication, Navigation and Surveillance (CNS) issues. The test site was required to complete three executions of each scenario, for a total of 15 missions per Texas unmanned vehicle per scenario.

This document presents data collected from participants during the TCL4-Texas August flight test that provides information about how much and how well operators were able to make use of UTM functions and information, with an intent to explore the minimum information requirements and/or best practices in TCL4 operations. The driving enquiry was: How do UTM tools and features support (human) operators leading to safe and effective conduct of large-scale beyond-visual-line-of-sight (BVLOS) small unmanned aerial system (sUAS) operations in "urban canyon" environments? As with previous similar tests (e.g., Martin, et al., 2019) the focus of the questions asked and the data collected for TCL4 was to assess the quality and clarity of the UTM information exchanged, and therefore the usefulness of this information. The flight tests were successful with over one hundred live vehicle flights and minimum information requirements results aligned with five human-system attributes to indicate that UTM provided information that contributed to users' confidence in their ability to operate safely and efficiently within the test environment. However, some information provided to flight crews was found to be incomplete and, at times, unclear.

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1. Background

The Unmanned Aircraft Systems (UAS) Traffic Management (UTM) concept combines airspace design, flight rules, operational procedures, ground-based systems and vehicle capabilities to enable safe and efficient use of airspace by small UAS (sUAS). As part of NASA's UTM research effort (Kopardekar, et al., 2016), five sets of flight tests were conducted over five years, demonstrating Technical Capability Levels (TCLs) with different environment complexities, airspace constraints, and operation objectives. As an example of these TCL differences, early (TCL1) flight tests focused on a single sUAS flying in restriction-free airspace, within sight of the operator and over unpopulated open space (Johnson, et al., 2017). Later, the Technical Capability Level 4 (TCL4) flight tests demonstrated multiple sUAS operations encountering constraints and airspace restrictions in a densely populated downtown location and also showcased more complex UAS Service Supplier (USS) functionality than previous TCL tests.

The high density and fast pace of urban arenas (see FAA, 2018 or Kopardekar, et al., 2016 for descriptions of the UTM concept) impose more demands on the user to fly safely and efficiently and highlight the need for precise maneuvering and the almost constant need to avoid obstacles. To support operators, UTM information, primarily gained through USSs but also through Supplemental Data Service Providers (SDSPs) and potentially other portals (e.g., remote identification (RID) situation awareness tools), needs to be easily usable in a human factors sense – that is, it must be clear, concise, consistent, understandable, and straightforward (Krug, 2014). If a system provides users with adequate information, then those users should report being comfortable with their awareness and decisiveness within the system.

Approaching the TCL4 demonstration from the perspective of the user, with the goal of instructing what the minimum information best practices might be, the driving inquiry was: "How do UTM tools and features support (human) operators leading to safe and effective conduct of large-scale beyond visual line of sight sUAS operations in "urban canyon" environments?" This overarching theme focused the feedback from flight crews around the properties of many essential UTM information exchanges. These research drivers were overlaid onto the NASA statement of work scenarios to develop a set of questions to UAS and USS operators. Two test sites were chosen to conduct demonstrations: Lone Star Center for Excellence and Innovation (LSUASC), a Texas A&M University organization based in Corpus Christi, Texas, and the Nevada Institute for Autonomous Systems based in Las Vegas, Nevada. For readability, the current report examines the Lone Star TCL4 flight demonstration in Texas only (see Martin, et al., 2020, for the results from the NIAS, Nevada test site).

2. Method

2.1 Participant roles and responsibilities

There were eight flight crews who took part in the TCL4-Texas flight tests and a ninth who observed and participated in discussions and debriefings. Crews generally consisted of four individuals: two operators, a visual observer (VO) and a USS Representative (USS Rep) (Table 1), amounting to approximately 37 participants. This cadre were the group observed by the Airspace Operations Laboratory (AOL) research team, and the 35 who crewed active vehicles were invited to complete participant surveys at the end of each day. Primary flight crew positions are listed in Appendix A, Figure A1. Flight crews 4, 8 and 9 had extensive UAS operational experience and worked together regularly as team-units. Flight crews 1 to 7 were students at Texas A&M who joined the project for the summer. These crews were given three weeks of UAS operation and team familiarization training prior to the shakedown flight tests in July, 2019, and continued to work in these units during the data collection in August.

USS software developers (USS Reps) created the clients that were being used. They were ostensibly present to ensure the USS client software was working but were also available to assist flight crews. They often took on a more supporting role of trainers and problem solvers, explaining UTM messages and procedures to crews. Some developers operated their USS for the crews during test flights, while other developers operated their USS to control multiple simulated flights. During the first week of TCL4, four flight crews used two different USSs on different days, and one flight crew used three different USSs, so USS software developers also rotated through crews (see Appendix A, Figure A2, for the USS-to-flight crew pairing by day of testing). The remaining three flight crews used the same USS for the whole week, although some of these crews did not fly vehicles every day. For the second flight week, the crew-USS pairing remained the same through the week.

Table 1. Crew and Vehicle Pairings

Crew identifier	*Number of personnel in crew*	*Vehicle flown - week 1*	*Vehicle flown - week 2*
GCS 1	2 crew (+ VO + USS Rep)	Tarot X6 but did not fly	Mavic Pro Platinum
GCS 2	2 crew (+ VO + USS Rep)	Ground-based Tarot X6 components	Mavic Pro Platinum
GCS 3	2 crew (+ VO + USS Rep)	Tarot X6 but did not fly	3DR-Solo
GCS 4	2 crew (+ VO + USS Rep)	Tarot X6 replaced on Tuesday by DJI M200-RTK	DJI M200-RTK or DJI M210
GCS5	2 crew (+ VO + USS Rep)	Ground-based Tarot X6 components	Mavic Pro Platinum
GCS 6	2 crew (+ VO + USS Rep)	Tarot X6 but did not fly	3DR-Solo
Crew 7	2 crew	Did not fly	Did not fly
GCS 8	2 crew (+ VO + USS Rep)	DJI M200-RTK	DJI M200-RTK
GCS 9	2 crew (+ VO + USS Rep)	AR-200	AR-200
Sim 10	1	e.g., 5 sim vehicles[1]	e.g., 5 sim vehicles
Sim 11	1	e.g., 5 sim vehicles	e.g., 5 sim vehicles
Sim 12	1	e.g., 5 sim vehicles	e.g., 5 sim vehicles

Notes: GCS = Ground control station; 3DR = 3D Robotics; DJI = Da-Jiang Innovation; M = Matrice; RTK = Real time kinematic; AR = Air Robot; sim = simulated operations.

2.2 Vehicle Characteristics

The vehicles flown during the TCL4-Texas flight tests were a variety of multi-rotor sUAS vehicles, each with varying performance characteristics and endurance limits, such as battery life, maneuverability and signal strength. These vehicles were able to take-off and land vertically in a small area and turn on a point in the air, which was a necessity for urban flying. In the first week, three different models of live aircraft were flown (Table 1), however, the Tarot model was not well-suited to flying in the Corpus Christi environment. For the second week of the flight test, these crews switched to using the 3DR-solo or the Mavic Pro Platinum. These vehicles have lower performance than the Tarot X6 and sometimes struggled to complete the test scenarios that had been written for the Tarots. In particular, these smaller vehicles were not able to maintain a connection with their ground

[1] Number of vehicles simulated by each "Sim USS" varied across scenarios to give a total of 15 simulated vehicles every run across the three USS providers.

control station during the longer scenario legs, resulting in many unscripted loss of command and control (C2) events.

All live vehicles were controlled either through auto-flight software on a ground control station or manually by a pilot in command (PIC) through a handheld radio control (RC) unit. The PIC often launched and landed the rotorcraft manually, putting it into autopilot for the en route portion of the flight.

2.3 Interfaces and Information Displays

Equipment available at each GCS location was similar across six of the flight crews and varied at the other two GCS locations. At six GCSs, initially, two or three displays, a handheld remote-control RC unit and two radios were available to the flight crew. The displays were organized to show the auto-flight software on one display and the USS on a second, leaving the third available for other information. During the second week, with the change in the unmanned aerial vehicles (UAV), sometimes a third tablet display replaced the RC unit. The remaining two teams operated with one display, a handheld controller and a radio. The auto-flight software and USS application were both accessed through the same display.

The Texas test site offered data from Echodyne radar to provide information about the airspace not provided by vehicles' on-board sensors. Weather sensors were set up at some of the GCS locations, providing data about the immediate conditions. Local weather data was monitored at the Lone Star headquarters (in the Mission Control Center) and if updates were necessary, these were provided to the flight test director in the field to disseminate to the crews. A third additional set of information was offered by USS-A, which provided situation awareness (SA) for the flight test director, who found this information useful as a general SA tool.

In the same way that there was a mix of team members and vehicle types, the six partner-built USSs also varied. UAS Service Suppliers provided services, via a client, to support the safe and efficient use of airspace, which included communicating between elements of the UTM system, giving the user awareness of demand in the airspace to enable decision making, and keeping records of flights for later inspection or data collection. These partner-built USSs that formed the hub of the UTM system (Appendix B) interfaced with the Flight Information Management System (FIMS) hosted at NASA. The tools available within the USSs varied, primarily because each partner developed their USS independently to a set of USS-level requirements (Rios, 2017). No standards were set regarding user interface design; thus the USS developers were able to present UTM information in a wide variety of ways on their displays. The USSs were prototype systems under development and had varying functions and features to convey UTM information to crews. To participate in the flight tests, all USSs needed to have certain basic capabilities, which they exercised in "collaboration" simulations with NASA beforehand (the Collaborative Simulation for the Texas flight test took place in June 2019, Smith, Rios, Mulfinger, Baskaran, & Verma, 2019), but the manner and extent by which the partners met those requirements differed.

2.4 Test Scenarios

The test aims were presented in the NASA statement of work (SOW) as five scenarios encompassing 39 characteristics (CH) and 16 test events (TE) that, when combined, were designed to portray different use cases for sUAS in complex environments (Rios, 2018). The scenarios featured 15 simulated vehicles, multiple live vehicles, and multiple USSs. These scenarios followed and expanded on most of the characteristics from the National Campaign flight tests of 2017 (Martin, et al., 2018) and the TCL3 testing of 2018 (BVLOS operations, dynamic re-planning, responses to alerts from the UTM System, and the implementation of off-nominal contingency plans; Martin, et al., 2019), and added functions like negotiation, UAS volume restriction (UVR) placement, and priority status.

The Texas test site designed five scenarios located in different areas of the Corpus Christi downtown and waterfront. These scenarios focused on an incoming weather front (Scenario 1), an incident at a large group gathering that required emergency response (Scenario 2), operating in areas with manned vehicles and using the system to identify operations (Scenario 3), a scenario where multiple vehicles experienced Communication, Navigation and Surveillance (CNS) issues (Scenario 4), and sharing airspace in which a USS failure occurred (Scenario 5). Detailed descriptions of the base scenarios and their corresponding characteristics (CH) and test events (TE) can be found in the TCL4 statement of work (Rios, 2018), and the days on which each scenario was run are listed in Appendix C.

With the directions given in the statement of work (Rios, 2018), Lone Star interpreted the NASA scenario briefs and created their own detailed test scenarios to explore the use of UTM in the Corpus Christi, Texas urban environment (2019, proprietary, document not available). Scenario 1 had a core of activity in the waterfront area around the marina and on the promenade (Figure 1), with a second group of UASs flying in the Corpus Christi downtown, from the Fire Department training property, close to route 544, through the urban canyon of the financial district. LSUASC defined activities for 15 simulated vehicles, eight live vehicles and six USSs across these two environments. Ground control station locations for live flights were in grassy open areas on the promenade and in a parking lot surrounded by buildings downtown.

Figure 1. Example of the Corpus Christi urban environment; the marina and promenade.

Two scenarios (Scenario 2 and 4) were located in the museum area, in an environment characterized by one or two large buildings and extensive parking lots with many small obstacles such as trees and light poles, see Figure 2. The LSUASC scenarios defined activities for 15 simulated vehicles, eight live vehicles, and six USSs, resulting in multi-volume flight operations, and dense spacing near obstacles and people. Bases of operations (GCSs) for live flights were located either in parking or empty urban lots.

Figure 2. Example of the Corpus Christi urban environment; the museum district.

Scenario 3 was flown in two different sets of locations over the course of the two-week flight test. In the first week, Scenario 3 was located at the waterfront area around the marina and on the promenade, the same core location as Scenarios 5 and 1 (Figure 1). In the second week, half of the crews moved to two different locations: two vehicles moved to the Corpus Christi airport and flew on airport property (Figure 3) and two other vehicles moved to the port along the estuary and flew on Port Authority land. These environments have few buildings but more dynamic obstacles like docked watercraft, and aircraft. LSUASC defined activities for 15 simulated vehicles, eight live vehicles and six USSs in the distributed environments of the three locations. Ground control station locations for live flights were in open areas and on the marina jetties.

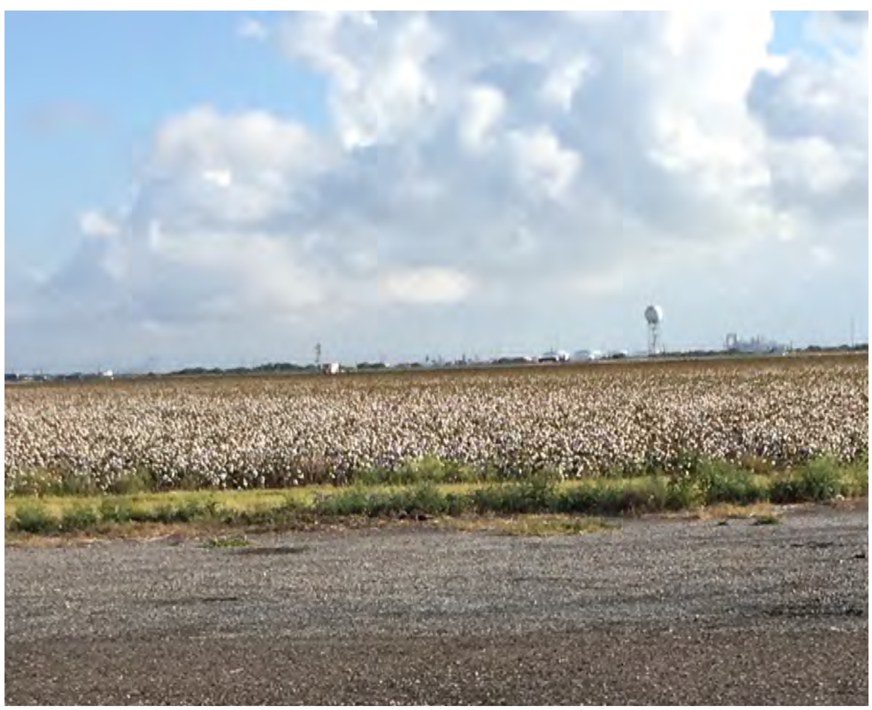

Figure 3. The sUAS flying area at the Corpus Christi International Airport.

Scenario 5 was located in an extended waterfront area around the marina, on the promenade, and in a waterfront park – spanning nearly two miles from the northernmost to the southernmost GCS. This environment has few buildings but more dynamic obstacles like docked and moving watercraft, wildlife, and pedestrians (Figure 1). LSUASC defined activities for 15 simulated vehicles, eight live vehicles and six USSs in this environment. GCS locations for live flights were in grassy open areas and on the marina jetties but always close to smaller obstacles: trees, fencing, flag and light poles.

LSUASC rotated the USS-to-crew pairing during the first week of TCL4, so that some flight crews used two or three different USS. For the second week, every crew worked with only one USS. They also executed their scenarios in a rotation to try to remove disruption on consecutive days to any one area of the city. Each scenario was run for one day during the first week and one day during the second week in a semi-random order. Technical issues encumbered the flight test for the first week, meaning that the full complement of live vehicles did not fly each scenario. However, all crews gained experience and were more familiar with their vehicles, the environment, with the different USSs, and with UTM during the second week due to the flights of the first week. These differences added richness to the data but it should be noted that crews had to adjust daily to several different aspects in their operations.

2.5 Research Objectives

To inform the minimum information requirements for flight crews and/or best practices in TCL4 operations, the driving inquiry was: How do UTM tools and features support (human) operators leading to safe and effective conduct of large-scale BVLOS sUAS operations in urban canyon environments? This enquiry touches on one measure of performance (MOP), one Measure of Effectiveness (MOE) and two USS requirements set out by the Ames Research Center SOW (Rios, 2018). UTM MOP #15 states that the TCL4 research effort should provide feedback on: Pilot assessment of UTM information properties (MOP, Rios 2019, sheet 1), and the UTM MOE #4 advocates investigation of the statement that: "UTM allows for common situational awareness of the airspace and operations within it to support sUAS operations" (MOP, Rios 2019, sheet 2). At a different level of enquiry, USS requirements #5 and #6 state that: "The USS shall provide human interfaces to operators and ensure that the human interfaces are appropriate to support testing activities" (SOW, Rios, 2018, p. 23). These two UTM measures and two USS requirements were re-interpreted from the user's point of view to state that the UTM system needs to:

- share information with users (through a USS client),
- provide adequate crew situation awareness.

For UTM information to be usable, operators need to have enough knowledge to:

- understand what they are seeing in the environment and on their displays,
- be able to respond quickly and appropriately enough to information when an action is needed.

Five main attributes that indicate users' ability to operate safely and effectively within UTM were considered in the data collection for the Texas flight tests: situation awareness, risk perception, communication, confidence/ trust in tools and response quality (Figure 4, green rectangle).

- The user should have good situation awareness; the ability (based on training) to understand the UTM information they have access to, and about their operation and the environment. In turn, these information items are sufficiently usable, salient and intuitive.
- The user should have good risk perception and a high level of safety awareness; the ability to differentiate between varying levels of risk of an operation and make decisions based on their assessment. The information available should have properties that make it easily usable for risk management.
- UTM system-to-user communications should be good; communications (messages, notifications, alerts) received by crews are understandable. Communications are sent at the right time for users to be able to make use of them.

- User confidence and trust in UTM is high; users are able to base their decisions and actions on UTM information alone but are also able to consult (multiple) other sources. Information is reliable and accurate enough to inspire trust.
- Efficient and effective user responses to UTM information; users are able to act effectively through the UTM system. Action options are available and functional.

These five attributes represent successful user-system interactions from the user's point of view and were used to guide the organization of comments from debrief discussions and observers' field notes (Appendix D).

To promote these types of successful user-to-automation (human-systems) interactions (HSI), the UTM system (especially its interfaces, mainly in the form of USS clients) would benefit from having a number of properties, some of which are listed in the peach hexagon in Figure 4. Thus, some questions on the surveys and during the debriefs were asked from this point of view – how well users thought the UTM system and the USS clients worked, and whether the functions needed in both were present.

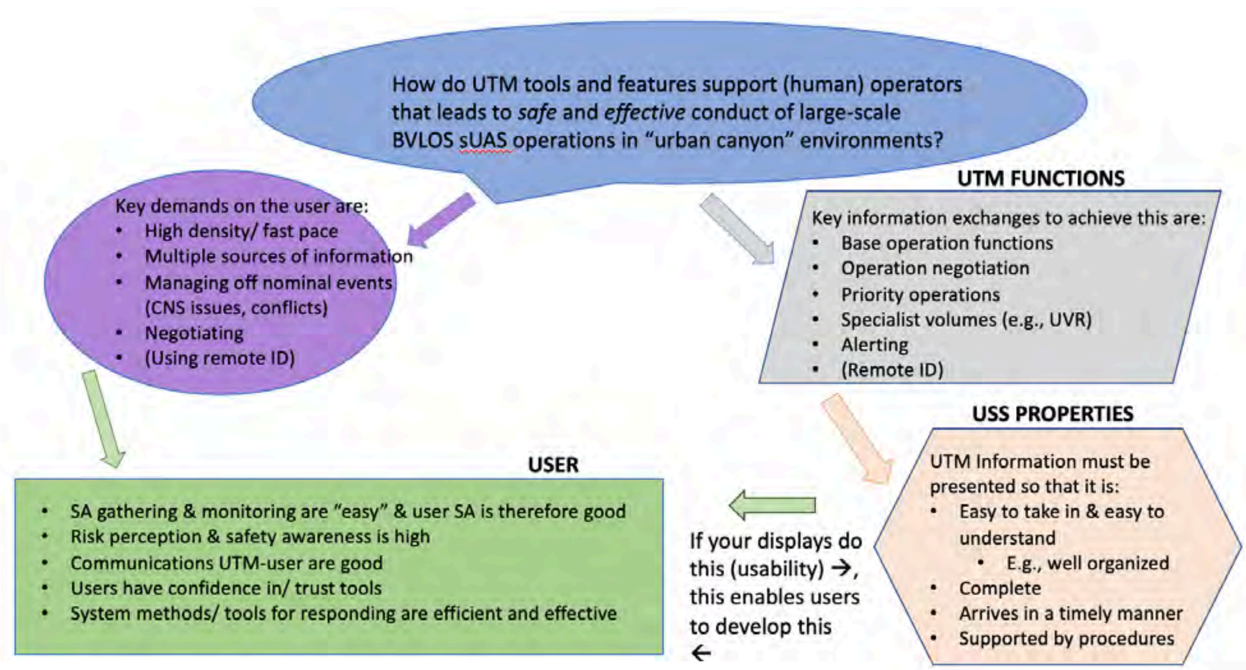

Figure 4. Research question and topics used to organize qualitative data collected.

While the key focus of the inquiries described below was user experience, critical to the success or failure of this experience was the usability of the interface between the USSs and the crew-operator. USS perform many functions and a subset of these require the user to be aware of, and in some cases take part in, the functions being executed. Functions of particular interest in TCL4 included priority operations, managing UVRs, conflict avoidance, and dealing with CNS issues (grey parallelogram in Figure 4). User-UTM (human-system) interaction would be facilitated if the interfaces included the following properties: being easy to understand, providing timely information, and providing all necessary information (peach hexagon, Figure 4). Additional features that improve usability include being straightforward or intuitive to operate and having clear procedures for those operations. These features of USS interfaces, when successfully implemented, should enable the user to develop situation awareness, develop confidence in the tools, and have a calibrated perception of risk, etc., (green rectangle, Figure 4).

2.6 Data Collection

The TCL4 flight demonstration at Corpus Christi, Texas took place over ten days in August 2019. Prior to the test flights, crews 1 to 7 spent two weeks training together as a team to operate their UAVs. All eight teams met for five official shakedown (i.e., 'practice') flying days on location in Corpus Christi during July 2019. Flight crews 1 to 7 were comprised of individuals from Texas A&M University, and flight crews 8 and 9 were from partner organizations. Six more partner organizations developed USS clients, totaling eight partners working with the Lone Star organization[2].

Over the course of the ten-day Texas flight test, 31 data collection runs were flown: eight for Scenario 1, six for Scenario 2, eight for Scenario 3, four for Scenario 4 and five for Scenario 5. Across all 31 scenario runs, 1066 operations were submitted, of these, 411 operations (e.g., Figure 5) took place as data collection flights (270 of these were simulated flights and 141 were live flights (Table 2)).

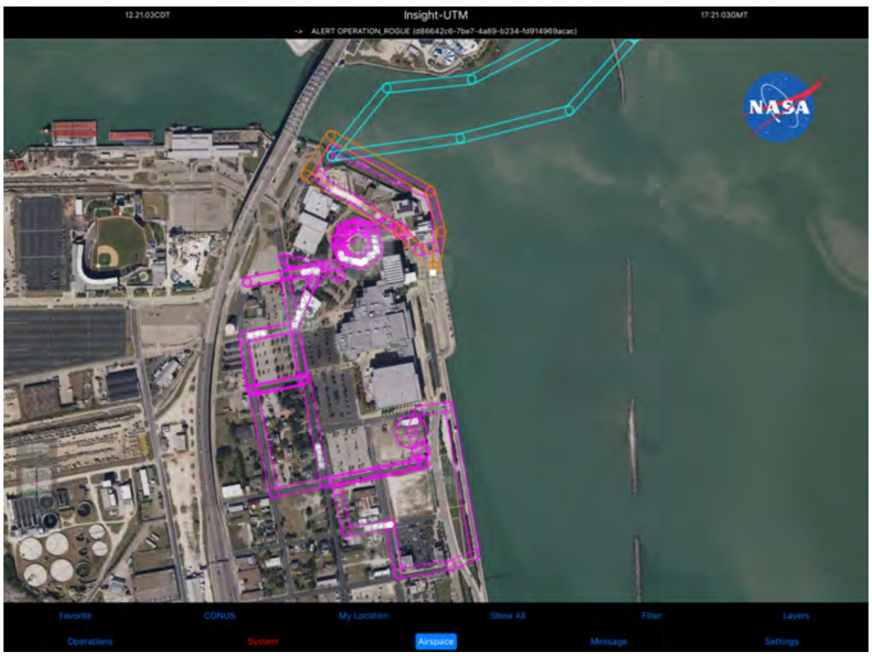

Figure 5. Example of complex urban fights over Corpus Christi, showing both live and simulated operations and their volumes, with more than one USS contributing. Note: Magenta polygons are active volumes in which operations are occurring, teal volumes are planned but not yet active operations. The positions of airborne UASs are denoted by solid white dots.

For the ten test days there were two teams of researchers from the Airspace Operations Lab collecting data from participants in the field. In the NASA observation rooms, a team of UTM developers verified data flowing through the system, while a small team of AOL researchers remotely collected test scenario data. The main AOL data collection team was in Corpus Christi alongside the flight crews for testing. During the first week, a team of five was present, and during the second week a team of six were on hand to collect data. Data were collected in a number of ways:

- through observations of participants during flights,
- through a counting application where observers counted crew interactions with their USS clients,
- end-of-day surveys,

[2] The city of Corpus Christi was also participating in the flight tests as they provided law enforcement personnel to assist with traffic management, in addition to two fire UAS crews, but the City is not included in this count.

- end-of-day group debriefs.

These data collection methods are included in the Data Management Plan (DMP) (see Modi, 2019), which was constructed to inform and assist test sites with their data collection process.

Table 2. Number of Live and Simulated Flights Providing Data for TCL4-Texas Flight Test

	Scenario 1	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*	*Totals*
Live Flights	40	44	29	23	5	141
Simulated Flights	83	67	55	47	18	270
Total Operations	123	111	84	70	23	411

Note: Only operations with at least 120 position reports have been included.

All of these methods solicited feedback on the five areas of interest for these tests outlined in the green box in Figure 4. In total, 96 crew surveys, 11 runs of counting application data, and ten end-of-day group debriefs were collected. During these end-of-day debriefs, flight crews discussed their experiences interacting with the UTM-system, discussing situation awareness and communication. Questions were framed in terms of the scenario that had been flown and were approached in terms of the UTM functions teams had experienced during that day. During the day, instances of crewmembers noticing or considering the UTM concept was recorded by observers through the counting application (Appendix E). For each flight, researchers recorded the frequency and manner in which a team member received UTM information. If the crewmember was not directly using the USS, this coding reflected the communication[3] of UTM information through the crew. Survey items were generated with the five user-topics (Figure 4, green rectangle) in mind, and were presented to the participants in the context of the scenario flown for that day, therefore addressing the functions that they had had an opportunity to use. Approximately 75 questions were generated across five surveys, but conditions were set so that participants only answered around 25 at any one time. Most questions used a seven-point rating format, with 7 representing a very positive rating and 1 representing a very negative rating. Some questions were multiple choice or open-ended. Whenever there was enough survey data for a particular question to support statistical testing, a one-way ANOVA or an independent t-test was performed. However, none of the tests run were statistically significant. Researchers in the field also took notes while they were watching flight tests. Operational data (e.g., logs and position reports) were provided by, and collected from, Lone Star and their partners but these data are considered elsewhere in other reports. Following the way questions to users were organized, participants' experiences are first described below associated with the UTM information exchange that prompted the experience, and then the ways in which the interaction between user and UTM information could be improved, are outlined.

[3] Flight crews may have received the same items of UTM information from multiple sources (e.g., USS client display, radio, and VO). Researchers coded the primary source of the UTM information to the focus-crewmember in this case.

3. Results

3.1 UTM Function: USS-to-USS Negotiation

USS-to-USS negotiation is a means by which flight operations are able to share the same airspace more efficiently. A negotiation occurs when a vehicle submits a flight plan into UTM but finds that another vehicle is already occupying that space and arranges to share the space in some way. There were two types of negotiations available to crews during the TCL4 tests: re-planning and intersection. Re-planning negotiations involve moving one of the operations either spatially or temporally (re-planning) in order for another to fly. For example, one crew might delay their operation or end it earlier than planned in order to allow another operation use of that airspace. An intersection negotiation occurs when both USSs agree that two vehicles are able to occupy the same airspace at the same time. To achieve this type of negotiation, both USSs must be equipped with vehicle-to-vehicle (V2V) data transfer. There were seven Test Characteristics directly addressing exercising negotiation specified in the SOW.

There were 1008 negotiation agreements made through the UTM system during the TCL4 demonstration in Texas. The majority of these agreements were for intersection negotiations (984 negotiations), possibly because one or more of the USSs did not have the functionality to properly exercise re-planning negotiations. One crewmember voiced this limitation during a debrief session, that this type of in-flight negotiation was not taking place because a particular USS had indicated they were "incapable of doing that at this time". There were 24 re-plan agreements (Appendix F). Observers collected data on 26 occasions when crews used information about negotiation from both UTM and other sources (Figure 6). These 26 negotiation counts were across four scenarios indicating that 81% of the negotiation information shared by the crew was received via a UTM source, whereas 19% of the shared negotiation information was communicated via other sources. The only scenario where the proportion of negotiation information received from UTM was markedly different from the overall counts was Scenario 4 where, due to the low number of negotiation counts, only 66% of the negotiation information counted was obtained through UTM.

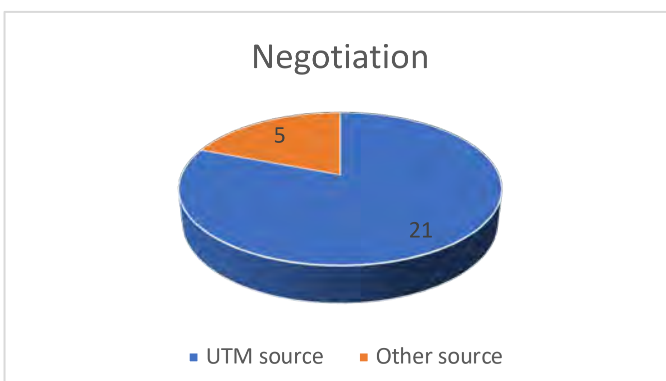

Figure 6. Observation count of information received about negotiation. Note: n = 26.

There were several concerns or areas of confusion within the existing protocols for negotiation, which led users to question requirements, limitations, and status during negotiations. There were also several suggestions for adding standard USS settings that would inform how an operation might react to a negotiation in the future. Crews reported that their insight into the USS-to-USS negotiation process was not particularly clear. Not having a window into the negotiation process left crews with two major concerns 1) that they might always be the "loser" in negotiations and that the system may be inequitable, and 2) that a negotiation that does not consider the future impact may put the user into a series of negative situations for the rest of their flight (e.g., conflicts). Crew comments during debrief sessions indicate that crews often had little insight into the negotiation process, and that failed negotiations were sometimes unclear and not effectively displayed or communicated to them.

Survey results show that participants rated their USS as only "somewhat effective" on average ($\bar{x}$ = 4, σ = 2.4, n = 29) in alerting them to changes needed as a result of negotiations, and when asked to rate how clearly the USS client indicated that it had negotiated with another USS and had changed their flight plan as a result, crew responses indicated that this was only "somewhat" clear to them ($\bar{x}$ = 3.56, σ = 2.0, n = 30). This is consistent with participants reporting that they received less information about the negotiation process than they would have liked (Figure 7 below).

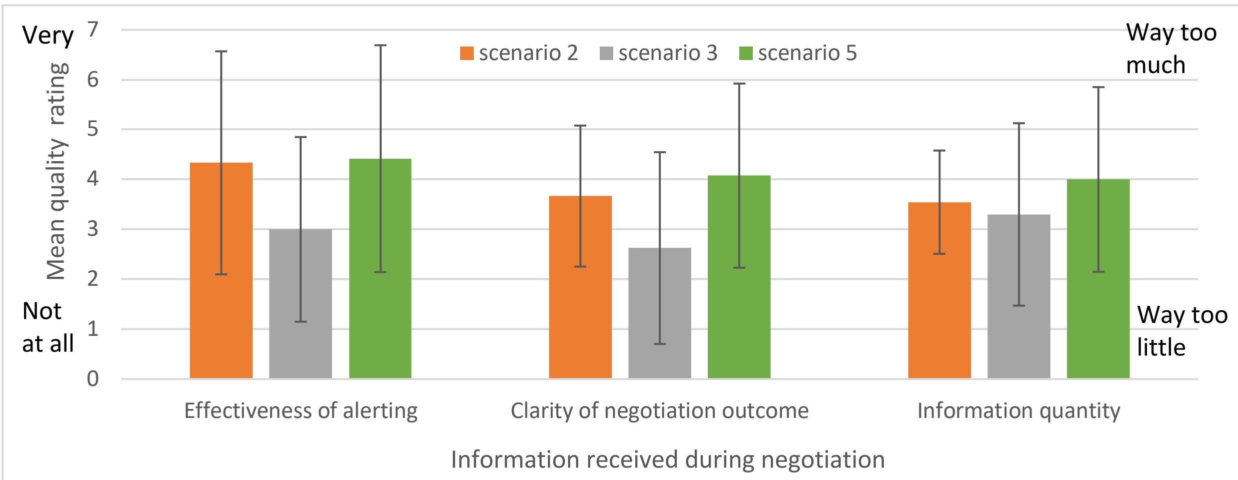

Figure 7. Participant responses regarding the effectiveness and clarity of USS alerting and the amount of information regarding the negotiation process. Note: n-effectiveness = 29, n-clarity = 30, n-information = 36; 1-7 response scale, y-axis is extended to show SD.

3.1.1 Participant and Observer Comments on USS-to-USS Negotiation

Survey results indicated that crews felt fairly certain that their USS behaved as expected, and that they were not overly concerned about the safety of their operations when temporal or spatial volume modifications were being negotiated while they were airborne/ en route (Appendix G, Figure G1). However, participant comments during debrief sessions indicated that they believed the negotiation process should be both more transparent and more efficient. For example, there were complaints about having to cancel submissions when operations were ready to launch, without knowing why. Participants also complained about receiving conflict messages without any information about whom to negotiate with and noted that their "USS Rep did not provide this information to the pilot". One crew reported that they were unaware of any USS negotiations at all, while another described seeing "pop-ups that were small and did not clearly define the incident or what actions needed to be taken". Other participants reported similar deficiencies in terms of knowing or understanding the intent of negotiations or what actions were needed as a result, having no information regarding why their operation had been rejected, or why it went into contingency in the first place. Another noted that negotiations were auto-accepted and that the GCSO (Ground Control Station Operator) did not see whether negotiations were accepted on either the GCS or USS displays: "During Scenario 4, the GCSO was unaware that negotiations were occurring because he was not notified on either of his displays," and felt that if a negotiation was rejected, the GCSO should be able to see the flight volume coming into contact with another UAS's volume on their USS display. In this case the USS Rep confirmed that these notifications had not yet been integrated on their particular displays.

Citing another example of a lack of transparency and efficiency in the negotiation processes, one participant voiced concern about display clutter resulting in the GCSO having to search through a list of negotiations in order to find a specific spatial or temporal conflict in a timely manner, which resulted in the GCSO simply trying to focus on submitting and accepting operations and avoiding processing the list. Another example illustrates a similar confusion in which a participant complained that the reasoning behind rejected operations was not immediately apparent, and that although they had some context (in this case, their intersection request was denied), the USS Rep and GCSO had to dig further into the logs to determine when and where the conflicting operation occurred. In other instances, participants reported avoiding the USS negotiation process altogether by simply walking over to another GCS and discussing who would submit operations first, or by using radio communications to speak directly with other USS Reps regarding negotiation issues. Another USS Rep admitted that although they notified their operators when a negotiation was rejected, they still allowed them to fly because they understood that "nobody can reserve airspace," so the message to this particular crew was "there was a rejected negotiation, so you will have a conflict."

However, there were also reports from participants and observers of effective negotiations. One observer noted that the crew under observation understood the alert messages, when an intersectional conflict was occurring, for example, and they were able to use this information to successfully negotiate the operational volumes. Another noted although there was "overall confusion" and failure of some USSs to negotiate during the first week of testing in Texas, this improved in the second week.

When asked how frequently they wanted to be aware of and involved in a USS-to-USS negotiation process for determining route changes, crews reported that they wanted to be aware of the process "often" or regularly ($\bar{x}$ = 3.51, σ = 1.5, n = 39), but that they only wanted to be *involved* in the process "sometimes" ($\bar{x}$ = 2.59, σ = 1.4, n = 37) (Figure 8 below).

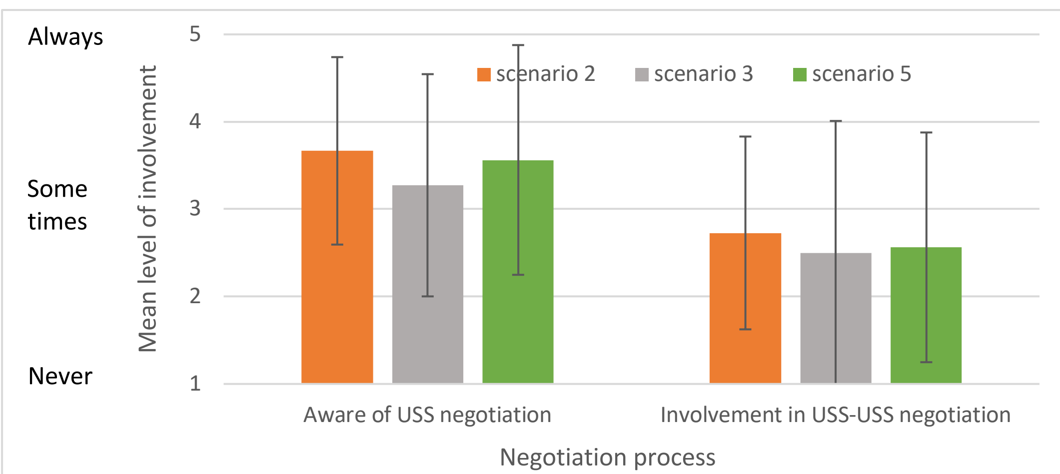

Figure 8. Participant preferences regarding awareness of and involvement in USS-to-USS negotiation processes. Note: n-aware = 39, n-involvement = 37; 1-5 response scale.

3.1.2 Requisite Properties Within UTM for USS-to-USS Negotiation

Exercising and observing USS-to-USS negotiation events in TCL4 prompted participants to discuss their awareness of negotiations and suggest improvements for the information shared about USS-to-USS negotiations. Results from debrief discussions and observer notes suggest a lack of transparency in how negotiations progressed. Feedback from several participants touched on this lack of transparency, noting that they lacked any insight into any negotiations that might have occurred during a run because only the USS Rep had that information, and in many cases, this was not shared with the flight crew. The discussions above suggest the following to better support effective USS-to-USS negotiations:

- Improve the transparency of the negotiation process. UTM actions will be more transparent by:
  - clearly showing the states/ outcomes of negotiations,
  - making pertinent information easy to find,
  - presenting more information about negotiations, for example the negotiation conditions, who the other party is, where the conflict will be.
- Define procedures for negotiation operations, such as:
  - clarify conditions for accepting or rejecting negotiation requests,
  - clearly define outcome options and actions to execute these,
  - provide guidance on the ramifications of a rejected negotiation.

These guidelines would support crew situation awareness, increase user trust and improve user decision making which would increase the predictability of the UTM system.

3.2 UTM Function: UVR Management

A UVR (UAS volume restriction) is one example of a dynamic restriction and a UTM constraint. In TCL4, UVRs worked in a way similar to a controlled airspace temporary flight restriction, denoting a volume of airspace that has limiting entry criteria for some period of time, for safety reasons or because specialists need to use the space. UVR areas were put up in scenarios 1 and 2 (see SOW, TE-1, Rios, 2018). In Scenario 1, the UVR was to denote an area of incoming weather (Figure 9), shutting the area to all vehicles for safety reasons. In Scenario 2, an incident on the ground, requiring response from law enforcement and safety personnel led to a UVR being put in place, allowing the first responders' UAS unhampered operating space.

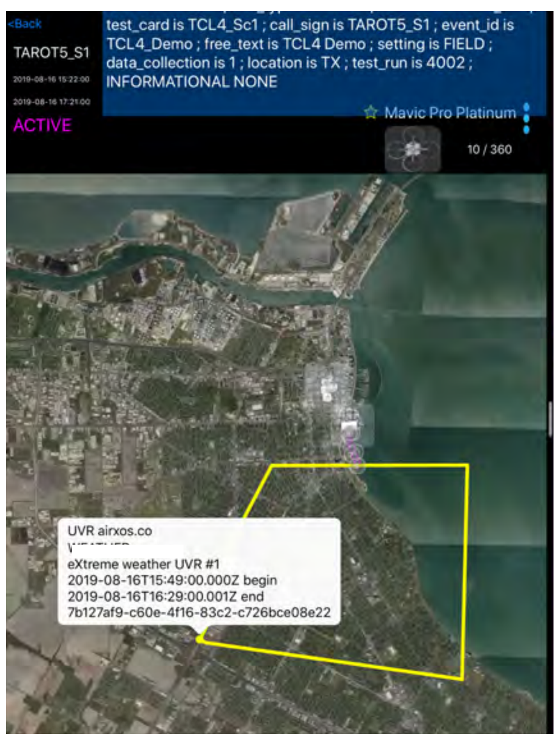

Figure 9. Example of a weather UVR during Scenario 1 in Corpus Christi, Texas. Note: Weather UVR is denoted in yellow; magenta and white volumes are flight volumes.

There were 36 UVRs[4] established in Texas during TCL4 testing that were broadcast through the UTM system via UTM messages. These 36 UVRs were all *dynamic* restrictions (see Appendix F for more details) set up during scenarios 1 and 2 (there were no *static* advisory restrictions). Participants in Scenario 1 reported seeing 25% more UVR messages than those in Scenario 2. This depended on the amount of information offered by the USSs. AOL observers counted crews' uses of information about UVRs from both UTM and other sources. There were 43 counts across the two scenarios where UVRs were posted (Figure 10). Counts showed that in both scenarios 1 and 2, 88% of the UVR information shared by the crew (n = 38) was first received through a UTM source (e.g., USS), indicating UTM was the primary source for UVR information.

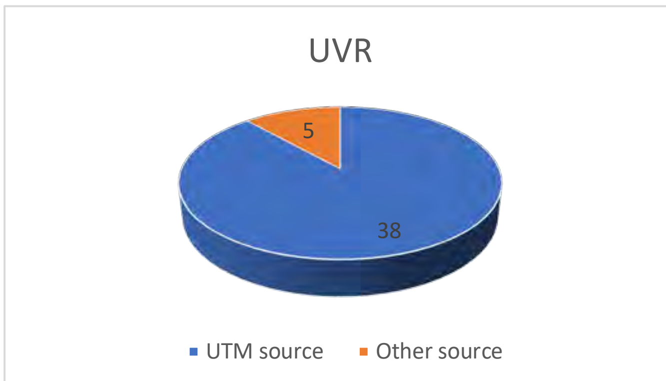

Figure 10. Observation count of information received about UVRs. Note: n = 43.

Participants gleaned information about UVRs from multiple sources. Only 20% of participants said they did *not* see any messages, and a third said they were informed of the UVR in a different way (although 2 of these 7 people said they were notified by the USS Rep; Appendix G, Figure G2). These crews relied on radio information to understand whether they were allowed access into the UVR, but others used their USSs to some extent. Half of the respondents reported that they had received UVR messages or alerts, or had seen changes related to the UVR on their USS client map (n = 21, see Appendix G, Figure G2). Observers noted there was clear information on one USS regarding UVR access, where the UVR was color-coded to show when the sUAS could and could not enter. Another USS provided a UVR information pop up window. Other crews noted that the information about the UVR was sparse on their USS. They received an indication that there was a UVR, but the USS did not provide information about how the UVR affected their operations. These crews reported they would have liked more guidance and they wanted the information about whether they could access the airspace when a UVR was active to be very clear. Still other USSs did not show the UVR to the user at all, and crews who used this system expressed that they wanted to receive notification when a local UVR was active. Taking these varying levels of information about UVRs into account, interaction with the UVR through the USSs was given favorable ratings as participants rated the effectiveness and efficiency of their USS interactions as better than moderate ($\bar{x}$-effectiveness = 5.11, σ = 1.8; $\bar{x}$-efficiency = 5.2, σ = 1.8 on a 1 to 7 scale; Appendix G, Figure G3).

3.2.1 Participant and Observer Comments on UVR Management

Participants rated their awareness of their vehicle location and its volume during the UVR and of their UTM state as "high", on average (mean ratings were over 5 out of 7; Figure 11). They were also

[4] UVRs needed to exist for 60 seconds or more to be included in the data.

watching for the UVR, which assisted their detection. Participants reported that information from the UTM system about the UVR was "somewhat" accurate ($\bar{x}$ = 4.83, σ = 2.1) and that this helped their awareness ($\bar{x}$ = 4.92, σ = 1.3).

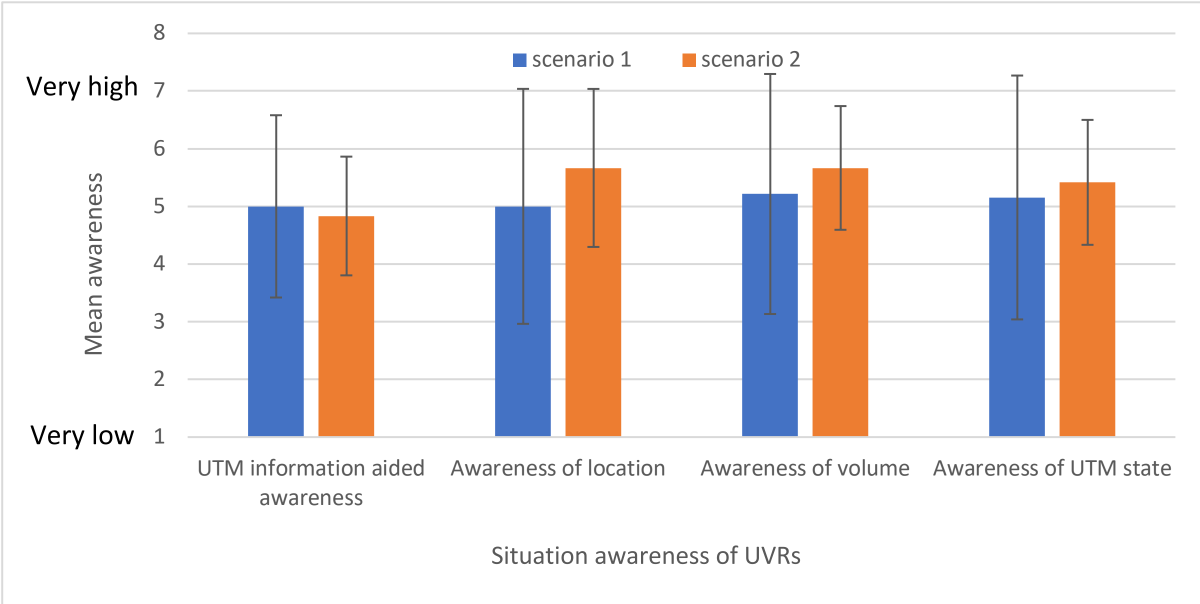

Figure 11. Mean ratings of awareness of UTM information at UVR onset. Note: n-information and UTM state awareness = 25, n-location and volume awareness = 26; 1-7 response scale, y-axis is extended to show SD.

The manner in which UVR awareness was shared through the crew varied between teams. In some crews, PICs noticed the UVR and reported this to the rest of the crew, in other crews, this task fell to the GCSO, and in yet other crews, everyone kept a level of attention on the presence and state of a UVR. In crews where only one member was watching for UVRs, team communication was important to keep everyone aware of this and the state of the ownship operation. There were examples of good team communication and teamwork around the UVRs. To give just two examples, one PIC noticed the UVR on their mobile USS display and informed the crew, asking the USS Rep to ensure a contingency plan was submitted; and another crew discussed the UVR and whether they needed to evacuate immediately or could finish their operation.

However, other crews did not understand the principles behind a UVR and were unsure how to react: whether the UVR affected their operation and whether they could launch an operation into it. These crews ignored the UVR to varying degrees. Examples of this include crews who tried to submit operations into the airspace where a UVR was active, others who launched into a UVR, or who flew and relied on their USS to correctly indicate nominal and rogue status. One crew was confused because their operation submissions were repeatedly denied when the UVR was active, but they did not know why. Sometimes these confusions were because the USS UVR notifications did not persist and were easy to overlook or due to poor team communication. For a couple of the operations, the USS Rep was able to troubleshoot to provide the crew with an explanation and understanding of why they were rogue.

During debriefs crews talked about the effects of a UVR becoming active on their operations and the implications of their actions, noting that they would likely try to complete a mission that was nearly finished at the onset of a UVR, but rerouting to exit the UVR was a source of much concern. In particular, crews discussed issues with direct return to launch (RTL) procedures that exit the planned volume, as these may fly the vehicle through other operations' airspace or into structures, especially an issue if the operation is BVLOS. The outcome they experienced in TCL4 was going rogue. More than one crew described how they initiated an RTL contingency when they saw the UVR pop up. As it was a least-distance return trajectory, the UAV exited its original volume and became rogue.

One query raised was whether operators are required to exit a UVR that becomes active around them as quickly as possible. Crews were concerned that if they had to exit a UVR immediately, that they might have to fly their vehicle away from their GCS, and then would they have the battery reserve to fly around the UVR back to the GCS? Crews suggested that UVR-exit options based on different parameters – closest boundary, quickest RTL, etc., could be offered by the USSs. But USS developers discussed the complexity of exiting a UVR and that many parameters, e.g., speed of vehicle, power remaining, and other activity in the area, all have to be taken into consideration in a UVR exit-plan.

In debriefs, the issue of which organizations would have the authority to set up UVRs was raised. Participants were concerned that those erecting a UVR might have the ability to pick and choose who would be granted access to the space. They also debated the procedures or guidelines that would need to be in place to allow two organizations, e.g., the fire department and the police department, to work inside the same UVR and which organization would have the authority to allow or deny other entities to operate in the space.

3.2.2 Requisite Properties Within UTM for UVR Management

Although crews understood the principles of UVR, their visibility into these restrictions were highly variable depending on the USS client they had access to. Those who were given very little information were unsure whether to respond to the UVR knowing that their general awareness of local traffic within and around the restricted space was poor. This uncertainty was compounded as understanding of the rules governing UVRs and the actions they were expected to take were not clear to flight crews. Some crews were unclear what to do and were looking for more than guidance and information about the UVR, they were looking for help with decision making and suggestions for actions.

More information than is currently available through the UTM system needs to be provided to users and the requirement to provide these items needs to be clearly stated.

- All users need to see a clear, standardized depiction of the UVR and its state,
- a clear permitted/not permitted message,
- users would be helped by:
  - clear guidelines or procedures detailing UVR exit strategies,
  - training that lays out the importance of following airspace restriction notices.

These properties will improve human-system communication, support crew situation awareness, and help users to operate and act as UTM (and other users) expect.

- Define procedures for operations around UVRs:
  - clarify conditions for the UVR and who has permission to enter,
  - clearly define reaction options and their expected execution rate,
  - provide guidance on the ramifications of a direct RTL versus a smart RTL.

These guidelines would support crew situation awareness and improve user decision making which would increase the predictability of the response to a UVR.

3.3 UTM Function: Priority Status

One property touched upon in both the negotiation and UVR discussions above was an operation's UTM status. Within UTM, operations can gain a priority status which elevates the ability to access airspace. There are two types of priority status: for a role that requires access, typically public safety or first response, and for operations experiencing an emergency, e.g., due to a low battery, mechanical fault, or issues with CNS. The first responder priority status may be designated when an operation submits a first response mission, and it will remain designated for the whole operation. The emergency priority status is a temporary designation, issued only when an operation declares an emergency and lasts until the vehicle can reach a safe landing location. Two scenarios in TCL4-Texas flight test (Scenarios 2 and 4) involved priority vehicles; in Scenario 2 priority was granted for special access to the UVR, and in Scenario 4 priority was granted due to reduced vehicle capability (see SOW, Rios, 2018).

Observers counted how often crews used information they received about priority operations from UTM and other sources. There were 14 counts across the data collection period (Figure 12). Overall, priority status information was received through UTM half the time, with other methods, e.g., radio, being the source of priority status information the other half of the time (n = 15). The proportions of information observed as received through UTM varied across the scenarios, from 75% in Scenario 2 to 20% in Scenario 3, although the total count for this type of information is low (at n = 15).

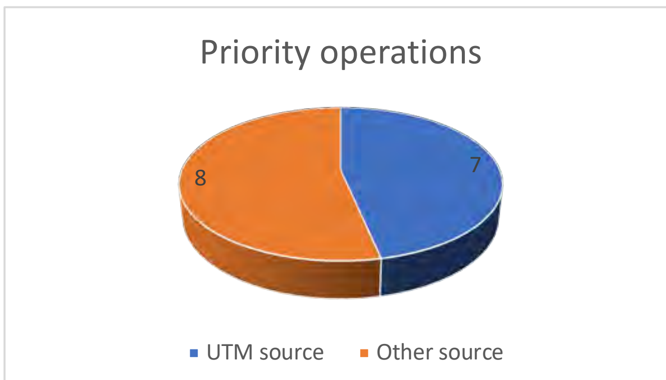

Figure 12. Observation count of information received about priority flights for two data collection scenarios. Note: n = 15.

3.3.1 Participant and Observer Comments on Priority Status

As awareness of priorities is critical in negotiations, users expressed several concerns or areas of confusion regarding priority and situation awareness of both personal and surrounding operations. Two of the priority operations submitted (one for a real-life emergency during testing) confused the PICs because the UTM state of their operations went from "Accepted" to "Proposed". Both instances were only resolved by verbal communication, through radio or talking directly to a USS Rep. Therefore, display messaging should be more communicative in explaining to the operator the reason for the sudden state change and various appropriate ways to respond.

The confusion and concerns regarding priority operations are reflected in the survey results (Figure 13). Participants were, on average, only "moderately" confident in the accuracy of the information presented and slightly more confident in the efficiency of using the UTM system. The lack of confidence shows in the reliance on verbal communication by many of the flight crews.

Priority levels are a concern among users. There is strong agreement that public safety has the ultimate priority and that situations related to public safety need rules and regulations to help define priority operations during times that safety is at risk. For instance, in the case of UVRs, there seems to be a clear understanding that operations will either be allowed or not allowed within a UVR. However, not all operations allowed within a UVR should necessarily have the same level of priority. One example is for media operations. Even if they are permitted within the UVR, they cannot be granted the same priority level status as those operations whose goal is to assist with the issue or event that gave rise to the UVR. One user considered the option of providing the media with a more limited volume within the UVR and keeping areas of most public safety activity inaccessible to them.

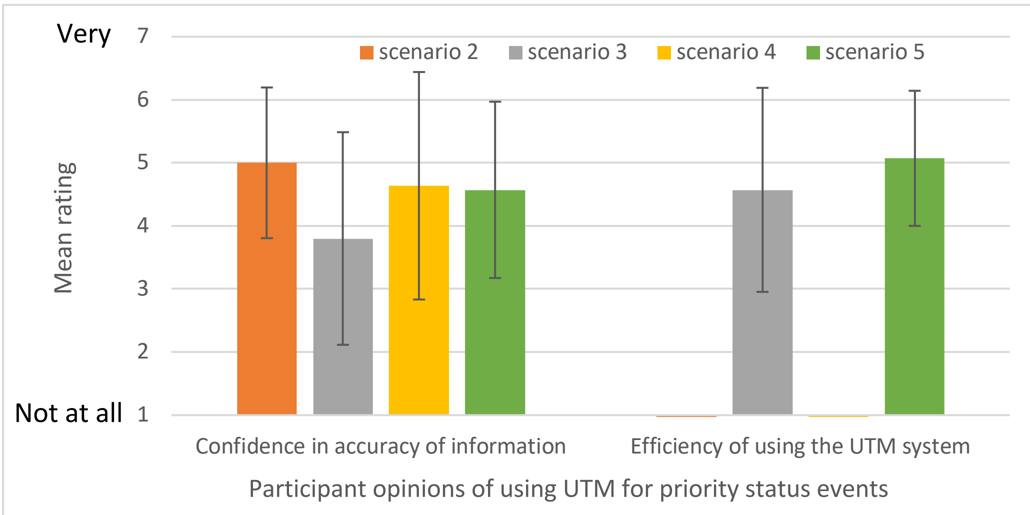

Figure 13. Participant opinions of using UTM for priority status events. Note: n-confidence = 43, n-efficiency = 21; 1-7 response scale.

While it is critical to consider who gets priority status and at what point, it is also important to consider how to treat those who do not get priority status. For instance during testing, a UVR was put up and one operation gained priority status in order to *leave* the UVR as efficiently and safely as possible. Even though they were not clear candidates for priority status once the UVR was in place, when temporary priority status is assigned to exit the UVR then safety-priority operations may be able to enter more quickly. Contingency plans to gain priority to exit a UVR should not be overlooked.

Situation awareness from those who are not given priority is also essential in ensuring safe priority operations. Users requested that information such as priority operations' altitudes, velocities, and all telemetry values should be supplied to non-priority operations to promote SA and to help them avoid intersections. Another way to increase SA during priority operations is to ensure that Remote Identification is accessible and working. One user noted that dispatch was supposed to be able to use RID but was unsuccessful in identifying operations through RID.

3.3.2 Requisite Properties Within UTM for Priority Status

Crews understood that UAS operations should have different levels of priority based on their mission (or other identified criteria) but were uncertain what these levels currently are, how operations are assigned higher priority status and how this may restrict lower priority operations.

- Clear UTM guidance needs to be provided that details:

- how priority users are determined,
- when priority status applies,
- the UTM guidelines that priority users are exempt from and those from which they are not exempt.

These properties will support crew situation awareness, increase user trust in UTM and improve compliance with UTM guidelines.

3.4 UTM Function: Indication of Conflicts, Conflict Alerting

A central function of the UTM concept is for a USS to alert users when their volume is breached by another operation and to alert the intruding user that their operation is out of its own volume. The USS implementations did not suggest solutions to the conflict; for this test, the UTM role was to alert the teams involved that there was an issue. Despite these limitations, participants reported positive feelings towards the USSs in regard to conflict alerting, as supported by the data below.

Participants reported they were only a little apprehensive about flying close to obstacles and were least concerned (on average) during Scenario 3 (Figure 14). Overall, they reported their USS was "somewhat" effective at alerting them to impending conflicts and on average thought their USS was more effective at alerting during Scenario 4 ($\overline{x}$ = 5, σ = 2.5). Participants reported they maintained awareness of nearby vehicles for conflict management "quite well" and that their mean awareness was higher in Scenario 4 than other scenarios and slightly lower in Scenario 5. Participants rated that their USS had a "good amount" of the information they needed to plan satisfactory resolutions and their average ratings were almost the same across the three scenarios where this question was asked. This high level of awareness could be caused by the vehicles almost always being within visual line of sight. Additionally, most of the conflicts were part of the scenarios, potentially influencing the crews to be less worried than they would be in a real-world setting that contains unpredicted conflicts.

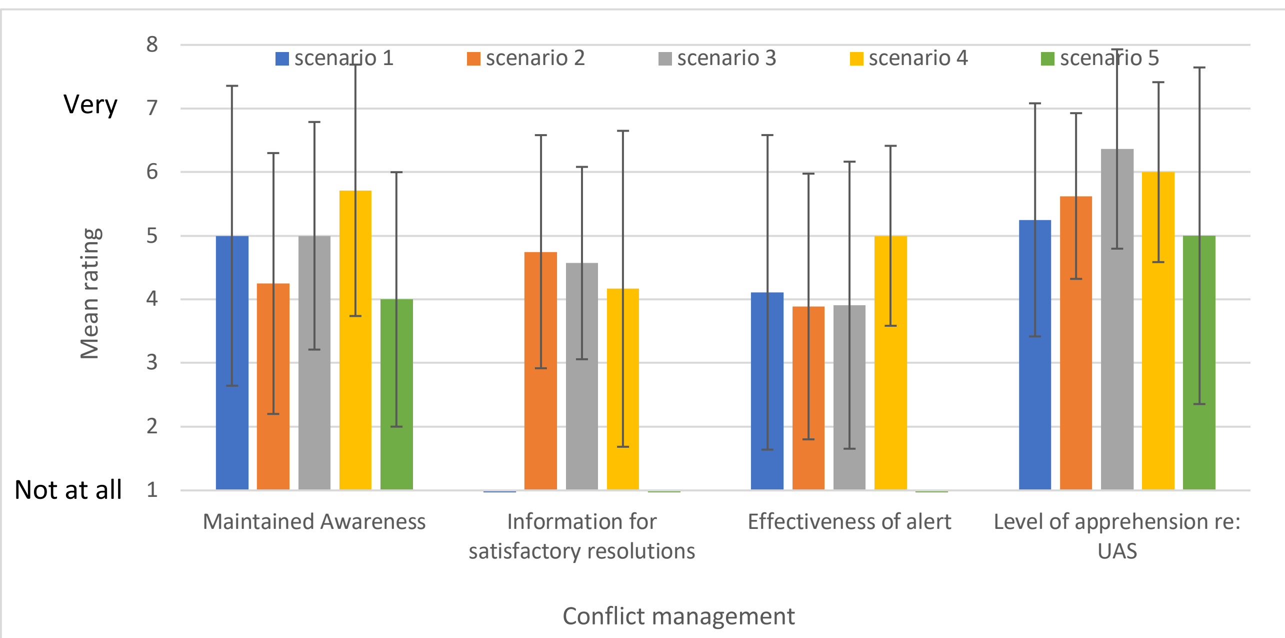

Figure 14. Participant opinions on conflict management: awareness of conflicts and effectiveness of alerting. Note: n-awareness = 43, n-information = 21, n-effectiveness = 34, n-apprehension = 36; 1-7 response scale, y-axis is extended to show SD.

Across all scenarios, participants reported seeing a total of 45 UTM alerts for conflicts (Figure 15). Four respondents reported that they did not see any alerts. Conflicts with UAS and manned vehicles were reported most frequently.

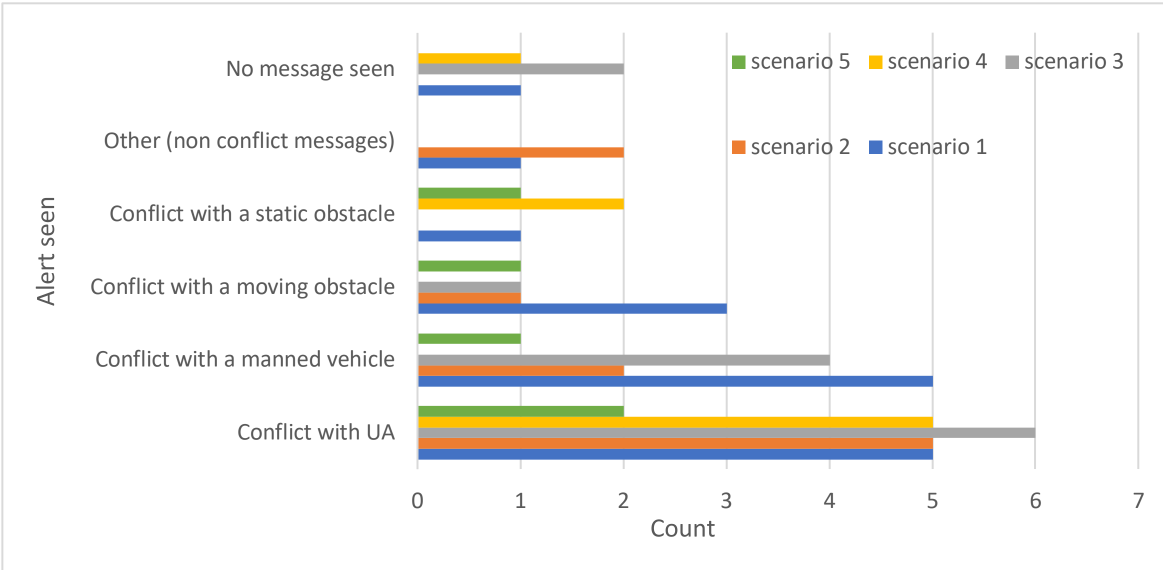

Figure 15. Self-reported participant count of conflict alerts with multiple object types. Note: n = 45.

Thirty-seven UTM operation messages tagged as 'ALERT' were found in the UTM logs that recorded USS messages during the data collection[5]. This is in contrast to the 45 self-reported sightings of 'ALERT' messages reported by participants, indicating that multiple crewmembers tracked alert messages on their USS client.

3.4.1 Participant and Observer Comments on Conflict Alerting

In contrast to the survey responses reported above, crews gave feedback that UTM messages did not contain enough information for them to act, especially concerning conflicts. Participants had difficulties checking and using conflict warnings to make decisions in the field. A number of crew and observer comments support this summary.

Crews argued that it is important to be informed of a conflict but wanted those messages to give more information so they could better respond. This was extremely important when discussing what to do in the case of another aircraft entering their airspace that was not connected to UTM. Crews listed several additional conflict parameters they would like to have incorporated into displays to provide richer information. These items included: what was causing the conflict, possible resolutions, and more information about how or why operations go non-conforming.

Most of the crews mentioned that conflict messages were helpful, but all crews stressed that the system needed to inform the users about why the conflict was happening to enable them to make appropriate decisions. The crews noted that it would also be helpful to be informed when and where a potential conflict was predicted to take place. This also applies to non-conformance messages specifically regarding their own operation's state. Crews wanted to know why they were non-conforming, so they could make an appropriate decision to correct the non-conformance and possibly avoid causing any unnecessary conflicts themselves.

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[5] Alert messages sent during connectivity tests were removed from these data.

Crews emphasized the importance of accurate messaging and position reporting to be certain whether other vehicles were straying into their volumes. However, there were indications that crews did not fully trust the UTM alerts they received and that they had difficulty building trust due to concerns about technical issues during the runs, as well as trust in the accuracy of other operations' conformance information. Some USSs were not able to send notifications of certain conflict types due to technical limitations, and this resulted in false negatives where alert notifications were not sent for actual conflicts. There was a case of a crew submitting a volume in airport airspace and the USS client showing "accepted", but the UAS then encountering the geofence detected by the UAS manufacturer's software. Crews noted that as long as they lacked confidence in conflict alerting, they could not rely solely on UTM-based conflict alerts to be comfortable that their operation's volume and flight path was safely separated from other operations.

Crews reported that they received alerts but were often unsure about their meaning. For example, one PIC would immediately exit out of pop up texts he received because he did not understand the context and whether it referred to his operation or someone else's. Another example was when a crew's vehicle had an automatic RTL, they and other crews contacted each other over the radio about it rather than trusting the UTM system to disseminate this information.

3.4.2 Requisite Properties Within UTM for Conflict Alerting

The greatest amount of crew feedback with regards to conflicts focused on alerting features crews wished were included in their USS clients. Crews emphasized their preference for notifications that not only were more informative, but able to be expanded to give more detailed information related to the events. Therefore, they reported a low level of confidence in the alerting currently available due to concerns about lack of detail as well as technical issues with some of the USSs.

Recommended improvements are:

- Demonstrably accurate and detailed notifications need to be provided, which will primarily increase user trust in UTM and improve alignment with UTM guidelines by supporting accurate crew situation awareness.
- Implementation of UTM notices should consider usability qualities.
  - Information and alert notices need to convey their message clearly and concisely.
  - Information and alert notices need to clearly state their focus and cause for being sent.
  - Alert notices need to have a design that draws attention.
  - Alerts need to be able to be clicked into to show more detailed information about what prompted the notification, including:
    - the time and location of conflicts,
    - the nature of those conflicts.

These properties will support crew situation awareness, decision making, raise user confidence in the UTM system, and improve operator-USS communication.

3.5 UTM Function: Contingency Management

Central functions of the UTM concept are to allow users to receive information about other operations' off-nominal issues, allow users to inform others of their own off-nominal situations, and provide support for the user to enact an appropriate contingency plan that fits both their issue and the environment. Off-nominal situations that may trigger a user to develop or enact a contingency plan were simulated for this test and included both small and large-scale C2 or navigation failures, low battery events, and responding to static and dynamic conflicts. While some USSs had a more automated process for creating and executing contingency plans, others were manual, requiring the user to draw a new volume for the area that matched the altered route for the vehicle. At the time of testing, only some of the USSs were able to support switching to a contingency plan while en route, although this feature was originally intended to be within the scope of the test per the USS specifications manual (Rios, 2019).

Participants reported they were "moderately" aware of the UTM states of vehicles within the surrounding airspace ($\overline{x}$ = 4.44, σ = 2.8) while enacting their contingency plans, and on average, they felt only "a little" uneasy about finding themselves in a position where they needed to use a contingency plan ($\overline{x}$ = 2.72, σ = 1.7; see Figure 16). Participants reported that although they were "moderately" aware of the UTM states of *other* UAS, they were "quite" aware of their own states ($\overline{x}$ = 4, σ = 2.6, n = 3, and $\overline{x}$ = 4.6, σ = 2.87, n = 6, respectively; for Scenario 1 only, not shown).

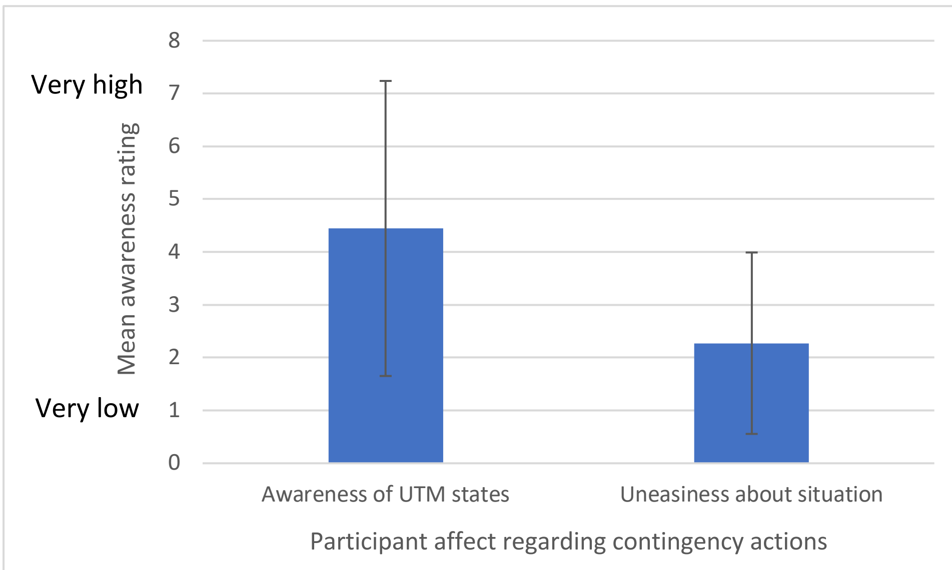

Figure 16. Participant reports of their awareness of own and others' UTM states, and their uneasiness during contingency situations. Note: n-awareness = 9, n-uneasiness = 11; 1-7 response scale; y-axis is extended to show SD.

Crews reported that their own contingency plans were "moderately" clear ($\overline{x}$ = 4.33, σ = 2.42; see Appendix G Figure G4) when due to flight plan or landing area changes, and that it was "moderately easy" ($\overline{x}$ = 4, σ = 2.54) to indicate their intentions as they were diverting through their USS client. However, there were large differences in responses across scenarios, with participants rating this process to be difficult during Scenario 3, but reasonably easy during scenarios 1 and 5 (Figure 17).

When asked about the timeliness of others' contingency information, participants reported that the information arrived to them on time ($\overline{x}$ = 4.03, σ = 1.79), with a hint that it arrived a little later in Scenario 4 than in Scenario 2 (see Figure 17).

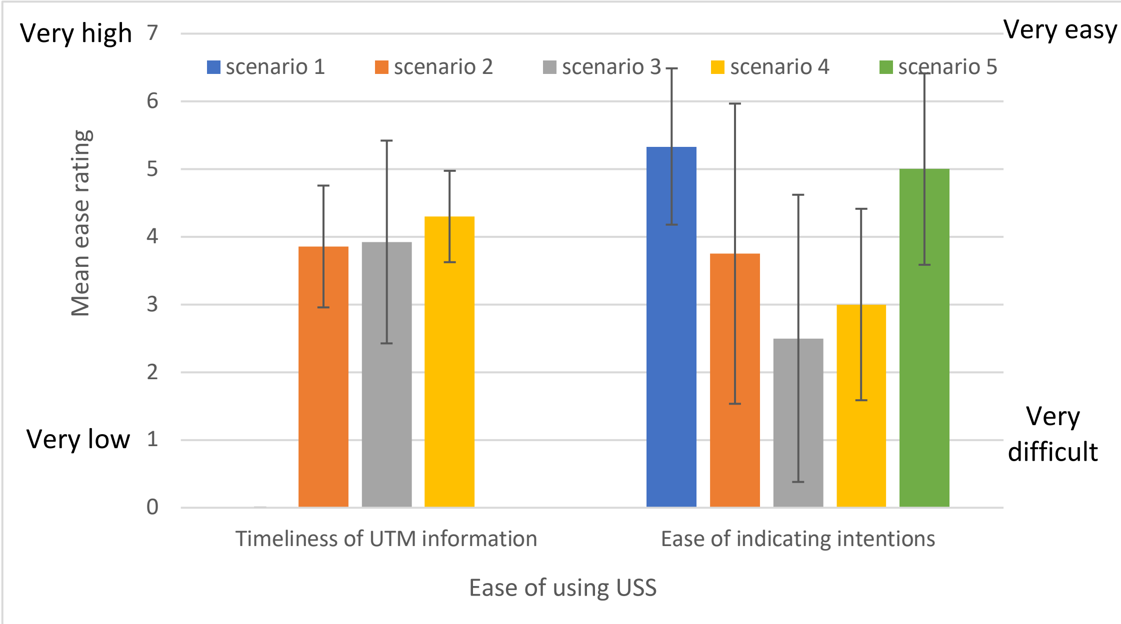

Figure 17. Participant opinions about the timeliness of contingency UTM information and the ease of indicating contingency plan intentions through their USS. Note: n-timeliness = 30 and n-intentions = 13; 1-7 response scale; y-axis extended to show full SD.

3.5.1 Participant and Observer Comments on Contingency Management

While operating in the urban canyon environment and within the bounds of the test, there were both planned and unplanned off-nominal events, such as C2 losses. Most crews agreed that their primary concern during these kinds of events was to aviate, and everything else was a secondary concern, including interacting with their USS to enact their contingency plans within the UTM system. For example, in the course of operating inside the test range, crews encountered inbound and outbound medical helicopter flights from the nearby downtown hospital. While some crews utilized information displayed on their USS to visualize their current and future locations, others did not find it necessary to consult this information to choose an appropriate response. Depending on their current course, the actions chosen by the operators varied greatly; some loitered until the manned aircraft was clear and then proceeded, some loitered and then initiated an RTL, and some decided that they would be clear of the manned flight, and so proceeded with their mission.

One researcher observed an instance in which a PIC received a simple message asking whether or not he wanted to initiate a contingency plan. The message alone did not contain enough information for the PIC to make a decision, so he consulted his other crew members before confirming the contingency plan action on his interface. To assist in this decision-making process, crews mentioned that they would like clear explanations from their USS of the contingency situation and the outcome of the action they select.

Crews expressed concern that during a contingency event affecting multiple operations (e.g., a UVR), if one of the first operators to act chooses extreme caution and builds a large contingency volume, then the other operations may be restricted in the actions they are able to perform within UTM. During debriefs, crews commented that the action taken during an emergency situation should ultimately be the choice of the pilot, though others suggested that these actions could possibly be automatically activated once system logic has calculated an optimal response.

While the theoretical method for responding to contingencies differed, there was a consensus that any action during an emergency situation must be easily and quickly executable. General opinion was for system automation to consider the current circumstances, calculate the best options, present those options for the operator to select from, and then automatically create new volumes and send the corresponding commands to the vehicle.

3.5.2 Requisite Properties Within UTM for Contingency Management

When crews had the ability to execute contingency plans while en route, they found this feature useful. However, crews agreed that in these time-sensitive situations, the human and the automation should be more harmonious and the automation should better support quick and effective solutions.

- The use of UTM information to enact or react to contingency plans could be improved by addressing some preferences expressed by operators:
  - complete information, including details relevant to their own operations,
  - clear information that uses common verbiage,
  - information that users can quickly and easily act upon,
  - definitions for how different operations may interact with each other.

These properties will support crew situation awareness, improve compliance with UTM guidelines and increase the speed of reactions to events.

3.6 UTM Functions: USS and FIMS Failures & Recovery

Within the nominal UTM system, USSs exchange data with the Flight Information Management System to check current states and plans against restrictions within the airspace. Although USSs exchange data with each other, some operation changes currently require FIMS approval before being enacted within the UTM system. As each operation subscribes to a USS in order to send and receive UTM information, in the case where a USS has a critical failure, the system architecture should support operators' ability to maintain sufficient connection to, and awareness of, the UTM airspace environment. The Texas test site exercised these processes under TE-4.

During a USS failure, operators reported being concerned about losing awareness of their own location, as well as those of nearby operations. Although the USSs were not at a maturity to support operations switching their USS subscription while en route, crews were asked their opinions about such events. Crews responded that their USS did not clearly show that their USS had failed ($\bar{x}$ = 3.35, σ = 1.53, n = 20, Scenario 5 only) and were only "moderately satisfied" ($\bar{x}$ = 4.2, σ = 1.42, n = 15, Scenario 5 only; Figure 18) in the time it took the USS to recover. Crews also discussed this during the debriefs and expressed that they would like the automation to assess the quality of the data and clearly state when correct and non-stale data is being reported.

Crews were asked about possible procedures in response to a FIMS outage. The majority stated that it would be safest to disallow any new operations into the airspace during the outage, and for airborne operations to continue as planned, rather than introducing new risk by directing operations to loiter or RTL. It was reasoned that unless there was an off-nominal situation, the environment would be most predictable this way. A further suggestion was for any new off-nominal state messages to not require a FIMS authorization (if they could also confirm that FIMS had failed), so in the case of an off-nominal (e.g., rogue) operation during a FIMS outage, those messages could still be passed to other users to enable informed decisions.

In addition to crew debriefs, the Test Director for the test site was interviewed about the effects on his SA when his dedicated USS (USS A) failed. While directing the tests, he primarily used radio communications to gather information to update his mental model. He commented that because his USS served solely as a window into the operations he was directing and was not the subscribed USS for any of those operations, he was less concerned than he would be if a USS that operations were subscribed to had failed. He stated that if he loses the ability to access UTM information it introduces hesitation into his decisions, as his SA of the operating environment is diminished. However, considering the bounds of the testing environment (safely altitude stratified), he was not concerned.

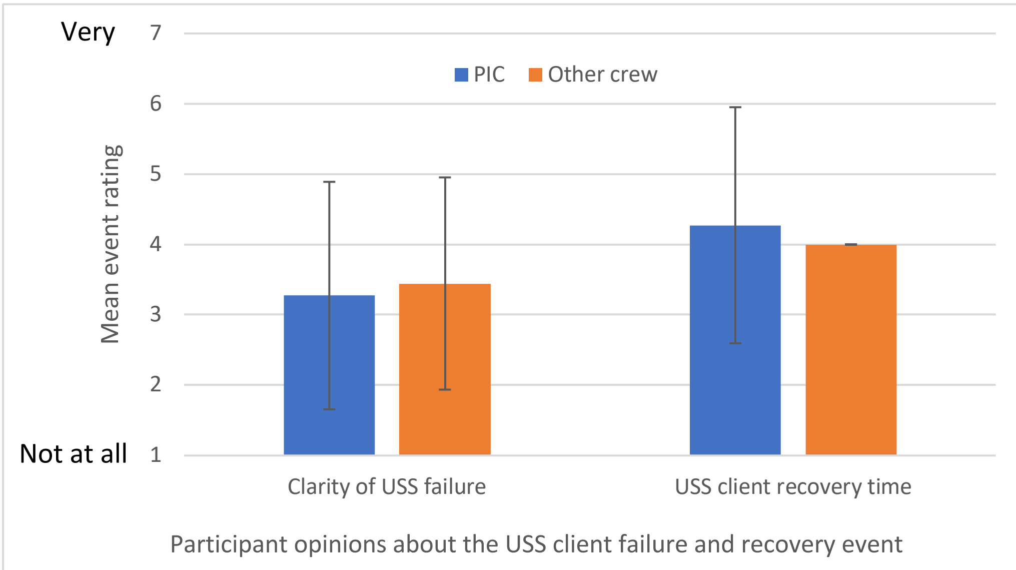

Figure 18. Participant satisfaction in the clarity of the information telling them that their USS had failed and how long it took to recover. Note: n-clarity = 20, n-recovery = 15; 1-7 response scale.

3.6.1 Requisite Properties Within UTM for USS and FIMS Failures & Recovery

Crews were concerned that their USS did not clearly show that it or other elements in the UTM system had failed and had some concerns about whether their USS was reporting correctly as it came back online. Crew handling of UTM system failures could be improved by addressing some preferences expressed by operators:

- clear indication that an element of the UTM system has failed,
- additional feedback from the UTM system,
- clear statement of the quality of data (e.g., current not stale) as an element of the UTM system comes back online.

These properties will support crew situation awareness, increase the speed of reactions to events and increase user trust in the system.

3.7 Core UTM Function: Volumes

One of the core functions of UTM is to check operational volumes that crews have submitted against FIMS rules and other constraints. Operators define and submit four dimensional volumes through their USSs and receive a notification of whether the system has accepted their proposal. Two types of volumes were used in TCL4, transit-based and area-based volumes. Crews activated the volume as they launched. All USSs used in Texas showed the own-operation volumes that had been activated on a map, but not all showed information for other operations' volumes in a similar way.

AOL Observers counted the uses of information about own-ship operations from UTM and other sources (Figure 19). There were 131 counts across the three scenarios. In Scenario 1, information about own-ship operations was received through UTM 85% of the time (n = 34). In the other scenarios, information about own-ship operations was received through UTM a little less often, for example, in Scenario 2, own-ship operation information was observed to be received through UTM 58% of the time (n = 26). In total, across all scenarios, information about own-ship operations was observed to be received through UTM 69% of the time (n = 90).

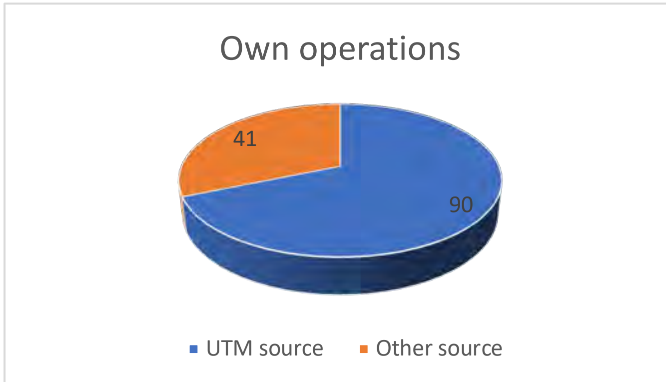

Figure 19. Observation count of information received about own-ship status. Note: n = 131.

The amount of UTM information presented by the USSs varied greatly. While some USS client's own-ship displays were clear, e.g., "state changes were clearly displayed and effectively showed when the crew initiated a contingency plan" (AOL observer 4), sometimes reasons for UTM state changes were difficult to find and the USS Rep had to search for them, e.g., a rejected submission. One crew commented that their USS Rep had a search strategy but sometimes could not identify the cause of an event in time for this information to be useful. In general, crews noted that they received little feedback from their USS and that the reasons given for UTM events were not informative, e.g., one crew was notified "priority low" when their submission was rejected but did not understand why that would lead to a rejection of their submission. In another example, when the operation was non-conforming, there was no explanation immediately available through the USS. The USS Rep, from experience, guessed it was due to cutting a corner of the volume. This lack of readily available information about operational volumes led to a degree of confusion and varying levels of UTM trust in crews.

When USS clients did not show the operational volumes of vehicles other than the own-ship, this made developing awareness of others' operations a very difficult task and crewmembers noted they found it hard to arrange their own operations when they had no information about others'. This is reflected in participant responses to survey questions about their awareness of UTM states; respondents, on average, rated their awareness of UTM states as "moderate" ($\bar{x}$ = 4.44, σ = 2.79, n = 9), as reported above in the "contingency plans" section (Figure 16) and crews were clear that they wanted to know when other operations were about to enter their volumes.

3.7.1 Participant and Observer Comments on Volumes

Crew understanding and tracking of UTM volumes and their states were hampered at times by the lack of information available through the USS. For example, one GCSO expressed confusion at having submissions rejected. He could see that the crew's submissions were being denied but not who the conflicting volume belonged to. In another instance a crew was concerned about an unscripted conflict. The GCSO and USS Rep thought the information from the other operation was submitted with an incorrect altitude, but there were other possible reasons, and the information provided was not clear enough to resolve the issue. Despite these difficulties, observers reported that GCSOs trusted the UTM system and used their USSs as a primary source of information about their own-ship and other operations, e.g., to look for conflicting flights. Other crewmembers trusted the UTM information to varying degrees.

Despite thinking the amount of information offered by USSs was low, observers noted a number of examples of crews using UTM information to make flight decisions. For example, when volumes were intersecting, one PIC and GCSO discussed changing their launch location and worked together to find a new launch site that would put their initial waypoint outside the conflicting area (intersection). Another USS Rep saw that a different crew, who had extended their takeoff volume to accommodate a new launch location, were now intersecting with his crew's operational volume. Both crews discussed that they needed to accept the intersection because they had to take off from those locations and wanted both operations to be accepted.

There were also some technical issues that became apparent as crews were submitting volumes. In one case, there was a mismatch between information shown to the crew and to the Test Director. On the Test Director's USS client, the operation was listed as active but on the crew's USS the operation was still listed as proposed. This occurred more than once and led the GCSO to distrust their USS.

Crews also identified new USS functions that they hoped might assist them with flying in UTM. One suggestion was to not reject operations but place them in a queue and accept them as the area for the volume became available.

3.8 Core UTM Function: Indicating Rogue Status

Rogue state within UTM is characterized as an operation that is outside the conditions or parameters of its accepted volume (Figure 20). The reasons driving the switch to the rogue state are many, from staying aloft past the end of the volume time window, to flying outside the volume, to returning direct to base due to an issue without broadcasting an emergency notification through UTM. All flights that go outside the parameters of their flight are given a 30 second warning time (non-conformance) during which, if they can return to the conditions of the volume, they can remain flying. If not, the operation becomes irreversibly rogue and needs to return to base or land in place.

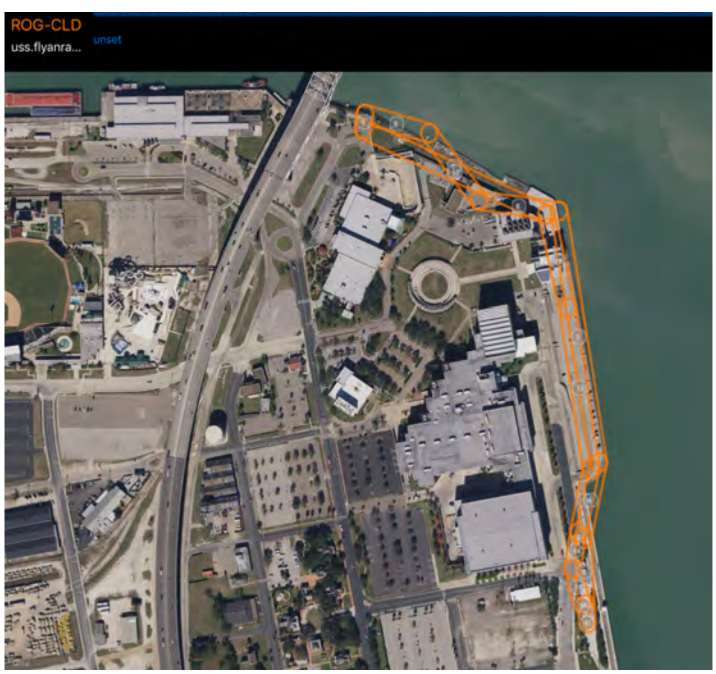

Figure 20. Example of a flight that has rogue status, as denoted by the orange volume.

3.8.1 Participant and Observer Comments on Indicating Rogue Status

After Scenario 4, participants reported the indication of their rogue state was "clear" through their USS ($\bar{x}$ = 5.8, σ = 1.86, n = 7) and a few participants reported they "noticed immediately" when their operation went rogue in Scenario 1. Some crews understood the parameters to check when their flight went rogue and reacted to their operation having a rogue state. Observers also recorded that building awareness of rogue situations was possible, because crews could see on their USSs when they were going rogue, and that some crews did notice as their operation transitioned to a rogue state. Despite this, the majority of the field observers recorded instances when crews *did not* notice their operation's rogue state or were surprised that they had gone rogue. For example, more than one crew missed the change to a rogue state when they RTL (e.g., due to a lost link) until after their vehicle had landed and also failed to submit a contingency plan. In a couple of cases, observers reported the crew was not using UTM and, in one case, did not see that their vehicle was too high for the volume until the USS Rep informed them. Sometimes this was because users did not understand the implications of operation/ volume state changes. Other times this was due to crew interaction and workload: one observer noted the USS Rep was too busy to monitor the displays and communicate out information and did not inform the PIC that their vehicle was non-conforming until after the flight landed.

Participants were asked whether they felt uneasy in a number of different situations where their vehicle went rogue. They reported they did not feel uneasy on these occasions ($\bar{x}$ = 2.27, σ = 1.71, n = 11, note reverse scale). Sometimes crews' confidence was from complacency, such as when the vehicle was not sending position reports to UTM and the crew ignored this and chose to keep flying. As the UTM system is a prototype, it did not always work as planned. In Scenario 3, the crew noticed their USS had crashed and but did not realize that led to their operation going rogue and did not understand why this was an important thing to know. It required the USS Rep to close the operation and restart the failed USS.

3.8.2 Requisite Properties Within UTM for Core UTM Functions

Crews found UTM volume status information useful and did use it. However, they did not fully trust it, and this had a valid foundation – due to the input information at times being incorrect, the volume status was, at times, incorrect. Crews also noted that inability to see other vehicles on their USS client made responding to volume events more difficult. To increase user trust:

- Information about own-ship volumes should meet the criteria that are applied to all USSs:
  - actions on own-ship volumes should be available throughout the operation's cycle,
  - information about own-ship volumes is supplied and is consistently presented,
  - guidance should be provided that underlines the importance of abiding by volume boundaries.

Education about the rogue state needs to be clear and concise to support crew situation awareness and decision making and raise user confidence in the UTM system:

- guidance should be provided that underlines the importance of the rogue state and the implications of ignoring this,
- procedures for responding to the rogue state should be outlined.

These properties will support crew situation awareness and compliance with rogue messages, assisting crew reactions.

3.9 Interface Between UTM and its Users

UTM has many interfaces but the primary crew interfaces in the TCL4 demonstration were the seven USS clients designed and built by seven different USS developer organizations. The USS client interface is a crucial bridge in the UTM system between users and automation. Of particular interest were the five USS clients used by the live flight crews.

Despite the user interface design standards in the USS specifications document (Rios, 2017), the USS client interfaces by which UTM information was displayed to crews varied greatly in the functionality available to manage UTM operations. The method for displaying UTM information, messages, and alerts differed, with each USS setting thresholds for types of information to be shown. Sometimes information was accompanied by an audible alert, oftentimes information was colored to show priority, and some USSs displayed information in pop-ups while others showed notifications in a running stream. The wording used within similar UTM messages was again unique to each USS's interpretation, as they were each designed from the perspectives of different companies and developers. It is important to note that the client interface which the crews used was often not the same interface that their on-hand USS Representative used. Usually, this interface was a unique "developer" platform equipped to delve deeper into the massive amounts of UTM data being logged, much different from the newer, and more pared-down clients the crews used. While there were many examples of how a USS client interface may look, none of those used for these tests were specifically designed to accommodate the needs of each specific crew's training or familiarity with UTM.

To participate in the flight tests, all USSs needed to have certain basic capabilities, which they exercised in collaboration simulations with NASA beforehand (the Collaborative Simulation took place in June 2019, see Smith, et al., 2019), but the manner and extent to which the partners met those requirements differed. An analysis of users' opinions of the USS client interfaces available, for both the Nevada and Texas test sites, can be found in a separate and specific report by Arbab (2019) which expands on the display method, display integration, and information transparency observations touched upon in this report.

3.10 Interaction with UTM

The core and critical functions of the UTM system work in two ways: a) by exchanging information somewhat autonomously between the elements of the UTM network, e.g., USS–to–USS; and b) by providing information to users (in this report to flight crews) who need to be aware of and act on this information. This crew–USS interaction (or HSI) affects users' perceptions of the system and the way they approach being a part of that system and interact with it. Four attributes of user affect were probed in surveys and debriefs: SA, trust, knowledge gained, and communications (Figure 4).

Although the UTM system is designed to be autonomous in many respects, TCL4 users were required to interact with the system via their USS client to submit volumes and manage operations, and then to monitor that interface for feedback and updates. While there are many properties of interface design that have been researched e.g., see work by Nielsen & Molich (1990) and Norman (2013), these criteria have arisen because they (by and large) provide users with information they need from their tools to accomplish their work. Users' desires for UTM are to be able to understand what is occurring both in UTM and in the airspace and to be able to interact with the system to change the course of those events if needed. Therefore, users are looking for the UTM system to provide them with appropriate information that they can trust, supporting them to build good SA of the environment, and that they can effectively communicate with the system to change its actions. Users were queried about whether the UTM system provided them with these four attributes.

3.10.1 Interaction with UTM: Communication/ Messaging

The starting point for successful interaction with UTM is for the system to communicate well with the user. All users must be able to notice messages and alerts containing UTM information and also be able to understand the content.

Observers noted that although crews operated USSs with different designs, many of the higher priority messages were salient enough. For example, half of the survey respondents reported that they learned of the UVR through their USS (see Figure 10) and were observed by researchers to frequently notice messages or alerts about their own operation's state. However, surveys also revealed that crews saw room for improvement in the clarity ($\bar{x}$ = 4.1, σ = 1.52, n = 10), conciseness ($\bar{x}$ = 4.56, σ = 1.33, n = 9), level of detail ($\bar{x}$ = 4.2, σ = 1.62, n = 10) and timeliness ($\bar{x}$ = 5, σ = 1.07, n = 8) of UTM information (Figure 21). Crews provided more context to this during debriefs, citing examples where they saw an alert or message but could not decipher the meaning, which made the information less useful to them.

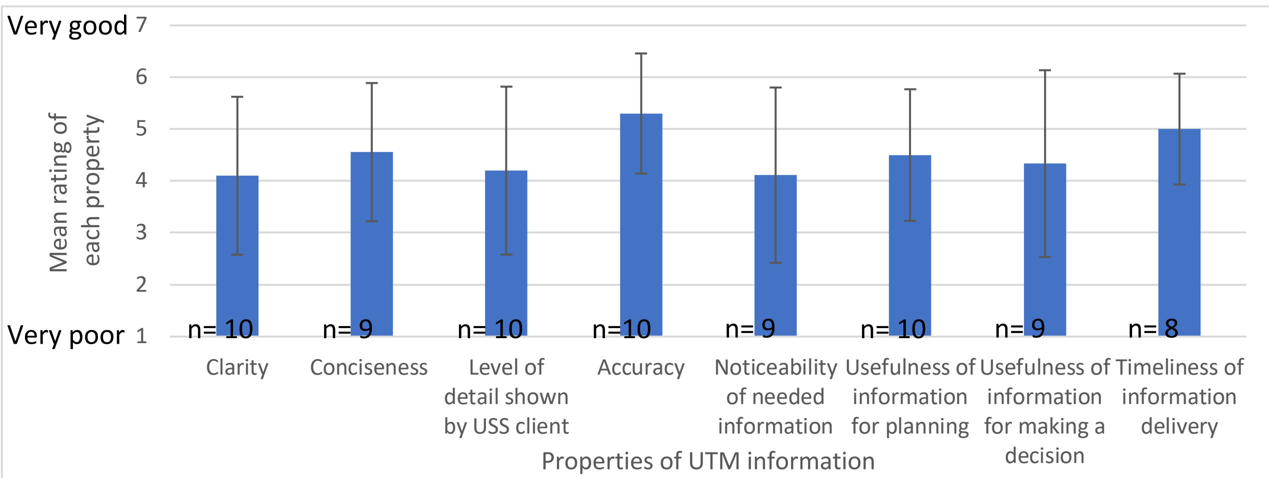

Figure 21. Participant opinions of UTM information properties. Note: 1-7 response scale.

Crews noted ambiguity within some of the messages they received, where they were unsure to which operation (their own or others) the message was referring because it was solely referenced by a complex unique number, the globally unique flight identifier (GUFI). In other examples, crews received action prompts such as "abort flight plan" and "initiate contingency" without additional information to explain what had triggered that action prompt to be sent. In the case of UVRs, once a crew was informed that it was in place, they often either consulted their on-site USS Rep or the Test Director for guidance on what to do in response. While they generally found UTM messages helpful, they discussed that additional contextual information would be very helpful, especially in an off-nominal situation.

In contrast, both observer notes and crew comments point to information saturation in some cases. While UTM information arrived in a fairly timely fashion, the number of alerts (such as failed negotiations) was sometimes overwhelming and a distraction from the primary flying task. Crews suggested that priority should be given to messages that are more pertinent to their own operation. These modifications to how UTM information is communicated to crews could address the concerns: that in an off-nominal situation the conveyance of UTM information should be as easy to receive and easy to understand as possible, so the operators can devote more resources to maintaining the safety of their operation.

3.10.2 Interaction with UTM: Situation Awareness

People use the information they receive to build situation awareness of events and their circumstances. In general, people find it easier to build SA if the information they are using is clear and formatted in a way that means they do not have to work to interpret or manipulate the information before they can use it. Crews in the Texas flight test had access to multiple sources of information to maintain awareness, though not all crews had access to every source. While basic understanding of the relationship between the own-ship and real-world obstacles was gleaned in a familiar way, as operations were within line of sight of the operator, UTM-specific information was available in less familiar ways.

Information about the UTM environment and UTM related events was communicated to the flight crews primarily through their USS client display (and/or their USS Rep), via radio calls, or as messages on a shared Slack channel (Slack, 2019). Observers noted that crews would sometimes crosscheck the information they received through their USS client by speaking with their USS Rep, or by radioing the Test Director, hinting at a lack of trust in the information first seen. Although the features supported by each USS differed among crews, with some offering more or less information that might aid crews' awareness, most could view own-ship, airspace and UTM information through their USS client. Crews were asked how aware they were of their own operation's state after experiencing a certain scripted test event. They rated their awareness as "above average" ($\bar{x}$ = 4.67, σ = 2.67, n = 6) while they were searching for a safe landing zone and also at the onset of a UVR ($\bar{x}$ = 5.26, σ = 1.72, n = 25), and "very low" ($\bar{x}$ = 1, σ = 0, n = 2) while performing RTL maneuvers. Specific information repeatedly stated as desirable to crews about other operations included; position, altitude, final location, direction, status if rogue or non-conforming, and operational volumes. This information would help the crews to better understand and track their operations' impact on the dynamic urban UTM environment.

In addition to the quality of UTM information available through their USSs, some factors that may have positively affected crews' SA included their familiarity with the software and the information it contained, as well how effectively that information was communicated to each user. It should be noted that the ability for information to be seen did not always coincide with the ability for that information to be understood. In one instance, a crew observed their display and noted that their operation was in an accepted state, however, knowing that a UVR had been placed over them, they still intended to fly, not completely understanding the rules associated with UVRs and its priority of operations, until told by their USS Rep. In some cases, observers noted that UTM messages were ignored because the user did not understand the purpose of the messages nor how to respond. Thus, timely communication of UTM information from the more-experienced USS Reps and the flight crews often helped make crews aware of events they otherwise may have missed.

Conversely, some factors may have unintentionally reduced crew's SA. For example, information that was noticed but was not easily understood required time and resources from the crew and divided their attention as they worked to decipher. During one such event, an observer noted that a state change was missed while the crew was still working a previous issue with their operation in UTM.

3.10.3 Interaction with UTM: Information Efficiency and Effectiveness

In order to be usable information for the UTM user, data provided by the UTM system needs to be useful, accurate, reliable and conveyed in a timely manner.

When crews received UTM information, they generally agreed that the information was accurate and reliable (when UTM was functioning properly). They frequently saw messages about their own state, negotiations, UVRs and conflicts in a timely manner. Despite this, UTM information was not always useful to the user. Because of the different levels of familiarity with UTM, the information within messages and alerts was sometimes too brief, vague, or used technical verbiage not widely known. Observers also recorded instances of this when the application showing UTM information was obscured by the flight application when sharing the same display, and so the user missed some incoming messages. In these cases, using UTM became less efficient and effective as crews dedicated extra time to consulting their USS Representative, or using their radios to ask for help. Crews commented that their understanding and reactions to these events could be improved if the UTM information was streamlined and integrated into their existing flight displays. Crews used UTM information more quickly and confidently when that information arrived with a common priority identifying characteristic, such as 2D or 3D volume depictions for conflicting operations, or a red visual representation of the UVR area, or even an “accepted” state as green text. Crews stressed that in the event of a time-sensitive or critical situation, maintaining safety is the operator’s primary concern, and any additional tasks must be easy to accomplish, or they may be dismissed. In support and as stated above, users had enough confidence in UTM during some off-nominal situations to utilize UTM efficiently and confirm action prompts from their USS, even though they may not have fully understood the reason for those actions.

3.10.4 Interaction with UTM: Promoting Trust and Confidence in the System

The process of being able to develop SA from information provided and that information being both useful and accurate leads users to develop trust in a new system (Miller & Parasuraman, 2007).

Flight crews in the Texas flight test displayed different levels of trust in the UTM system as noted by observers: some crews trusted the UTM information they received through their USS, others were building trust and spent time crosschecking information, and a third group did not use UTM. These different trust levels help to account for the moderate mean ratings found in survey responses to trust-based questions. Respondents reported a moderate amount of reliance on information from their USS client ($\bar{x}$ = 4.85, σ = 1.95, n = 27), and that actively participating in the UTM system had a small positive effect on the safety of their operations overall ($\bar{x}$ = 4.6, σ = 1.65, n = 26) (Appendix G, Figure G5). Similar results were seen in terms of trust during contingency planning for CNS failures: overall participants rated the timeliness, accuracy and efficiency of UTM information in these situations as “acceptable” although the mean ratings varied across scenarios, with information for Scenario 2, 3, and 5 being rated as “reasonable” but ratings for Scenario 4 were much lower (Figure 22).

Overall, participants’ ratings indicate that they found the UTM information was sufficiently accurate, timely, concise and useful for *planning* (Figure 21), which is supported by other survey responses about specific events. For example, ratings of reliability and trust while operating to avoid an emergency or weather UVR event were given similar mean ratings (Figure 23) but standard deviations were large. However, participants were in less agreement about the clarity, level of detail and noticeability of information shown and its usefulness for *decision making*. User feedback from debrief sessions highlight some of these deficiencies. Participants complained that negotiations were not displayed effectively, and, in one case, they were “entirely ignored with the exception of removing them from the screen”. Also, some USS clients did not display manned aircraft, which had to be broadcast via radio communication or spotted visually by the crew. Another crewmember complained that their USS Rep was hesitant at times, not knowing whether an operation was accepted when using his displayed UTM information as the sole source of information.

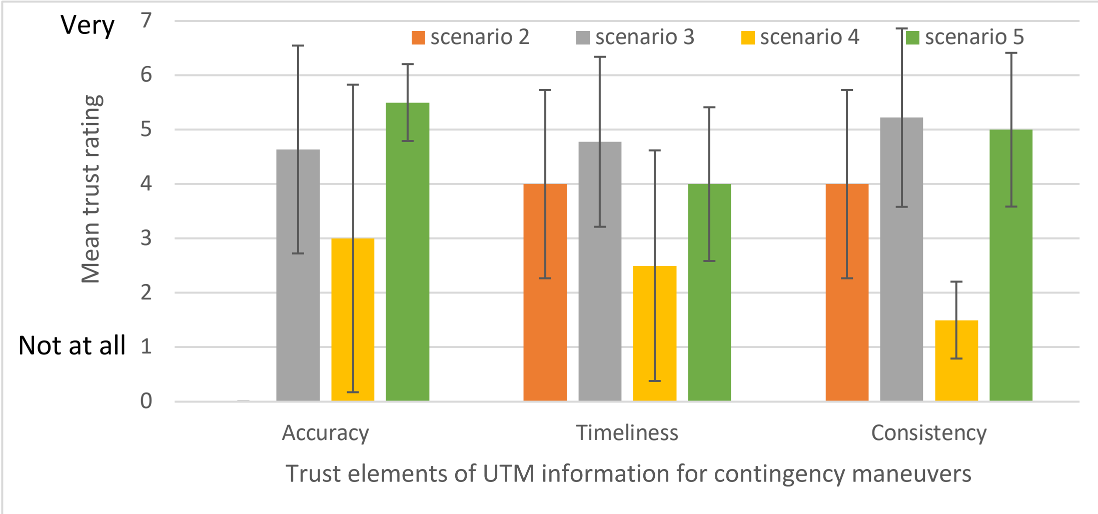

Figure 22. Participant ratings regarding accuracy, timeliness, and consistency of the UTM information for C2 and Nav failures. Note: n-accuracy = 15, n-timeliness and n-consistency = 16. 1-7 response scale; y-axis extended to show SD.

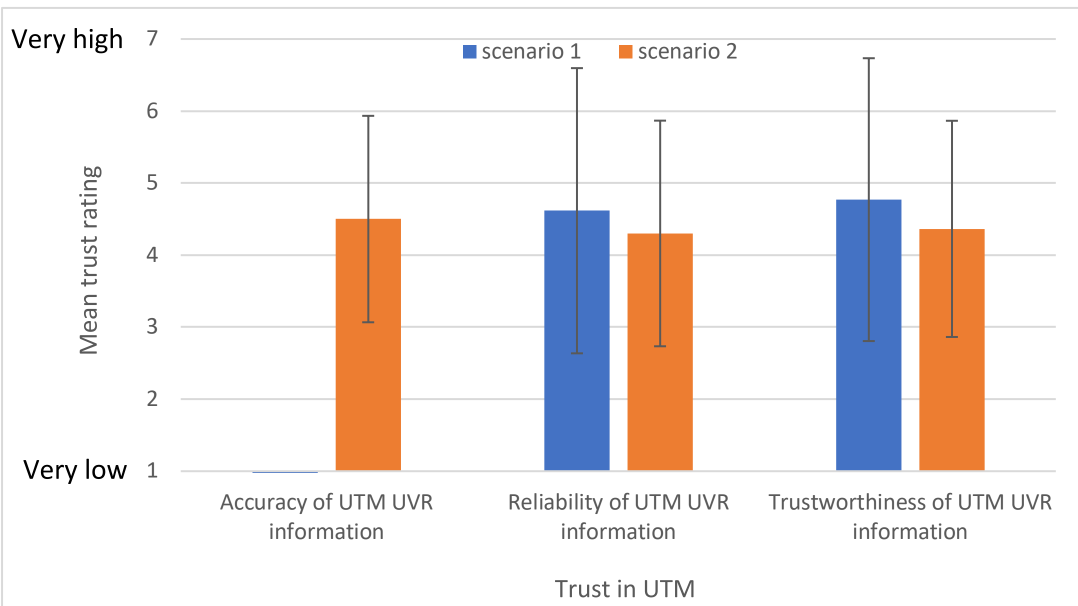

Figure 23. Participant ratings regarding accuracy, reliability, and trustworthiness of the UTM information needed to operate in around the weather UVR. Note: n-accuracy = 10, n-reliability = 23, n-trustworthiness = 24. 1-7 response scale; y-axis extended to show SD.

3.10.5 Interaction with UTM: Teamwork

In teams where each person has a different role and is required to focus on different information, communication and teamwork (or mutual team support) are key to ensure that all the parties who need awareness of a piece of information have it (Hackman & Morris, 1978). The TCL4 flight crews were these kinds of teams and, while they had all either received team training or were long-standing teams, they were generally unfamiliar with UTM. Introducing UTM information via the USS client interface and an additional team member – the USS Rep from a partner organization – was a large change for teams to accommodate, and some groups adjusted to this better than others. Observers noted different amounts of integration of USS Reps into the teams, those where USS Reps provided UTM assistance and explanations to the other crew members, indicating when events were occurring or actions needed to be taken; and other groups where the USS Rep was not available or was temporarily disconnected when the crew was confused about their UTM/ USS interaction. Some crews communicated well, actively sharing information to build group SA, while other crews focused on their own tasks, and did not share their perspective, resulting in instances where one person did not know what another was doing. For example, a PIC noticed a rogue message but saw nothing amiss when he crosschecked with UTM, but his GCSO had altered the flight plan without telling the PIC, resulting in the vehicle going rogue.

3.10.6 Promoting Good User Interaction with UTM

The efficiency and effectiveness for UTM information being delivered to crews was good, however the usefulness of that information was impacted by the display method and the appropriateness of the content to a specific user.

To support user situation awareness and user trust, basic properties that make information usable apply as much to the information exchanged by UTM as to any other automated system that interfaces with a user. Users are able to establish better situation awareness if:

- messages are clear,
- there are guidelines or notes available to explain information in messages,
- there are guidelines or notes available for less experienced operators to explain expected reactions to key events,
- more important or time-sensitive messages adequately alert the user to ensure they are seen in time,
- alerts are informative and obvious to the user to prompt an appropriate and quick response,
- contextual information is provided,
- information is consistent across displays.

4. Summary and Conclusions

The Corpus Christi, Texas test site completed testing for TCL4 during August of 2019. They flew 411 operations, of which 141 were live flights, to demonstrate sequences of events within five scenarios. The qualitative data discussed above were collected by on-site AOL researchers and consisted of end-of-day debriefs, end-of-day surveys, observer notes, and observer information counts.

UTM information was useful to flight crews for building their awareness of the flight situations. They reported high levels of awareness for their own state and for restricted airspace. However, they reported low awareness of other elements, like other vehicles and negotiation outcomes and, whilst crews did not feel they needed a window into the negotiation process, the lack of clarity of negotiation outcomes led to confusion and disregard for UTM procedures. The level of information available on USS clients varied, leaving flight crews with different levels of awareness of local operations. For example, some crews did not receive messages about restricted airspace (UVRs), and most crews wanted to be informed of rejected negotiations, which they were currently not receiving. In particular, although some notifications and alerts were provided to crews, the messages did not always have enough clarity or detail for crews to be able to act on them. An amount of information was also missed due to shortcomings in some of the USS client interfaces. There were issues of too many incoming items in addition to not enough information. Notifications that popped up over the main aircraft view while it was in flight, or those that repeated every few seconds, were distracting, created clutter and therefore workload to manage them. This caused crews to ignore, or sometimes miss, the notifications in the clutter.

A number of flight crews had little aviation experience, which provided a good opportunity to explore the range of requirements from different levels of UTM users. Novice users require more explanation of information, and so notifications that were just headings (extremely brief) or used UTM-system jargon were not always understood. In addition, novice users did not always know the action options that were intended in response to events (e.g., changing flight plan based on negotiation outcome), did not revert to common aviation procedures in response to an event, and did not understand the safety implications of some of the action-options in response to scenario events. For some crews, the USS Representative provided assistance and explanations to help the crew to develop an understanding of the situations, as they often had access to more UTM information and a detailed knowledge of how their USS client functioned. Crews also communicated with each other, often face-to-face, to cross-check and confirm information, which also helped them to develop an understanding of UTM and to build their trust in the system.

Crews stressed that piloting their UAV (the aviate component of the mnemonic aviate-navigate-communicate) takes priority over all other activities during off-nominal events and that UTM procedures should support this priority system by being easy to interact with and not "get in the way" during off-nominal events. As a result, Texas flight crews were open to higher levels of UTM automation and receiving automated assistance, especially in decision making and during off-nominal events. Flight crews also raised concerns about functions and procedures within the UTM system that lacked definition. Situations during UVR events were especially undefined. Users had questions about the ramifications of mass-RTL, the need for smart-RTL protocols, and also the time constraints for exiting UVRs as a non-priority operation. How levels of priority-user can be assigned and what authority comes with priority-user status were discussed.

Data collected from flight crews aligned with five attributes (Figure 4) and indicated that UTM provided information that contributed to users' ability to operate safely and effectively within UTM, but that information was not complete.

- Crews reported they had good situation awareness of their own-ship. As noted above, they did not always fully understand the UTM information they had access to and had questions about their operation and the environment. Some of the items of information requested were because the information they had access to was not sufficiently usable, salient or intuitive on current displays.
- Crews focused on one or two functions where safety becomes a factor, i.e., during a UVR, where crews have to make immediate decisions about whether to return to launch and how to exit the space. They emphasized the need for more clarity in guidelines for these situations and information to be made available that is easily usable for risk management.
- UTM system-to-user communications were possibly better than users were aware of. Most communications (messages, notifications, alerts) received by crews were understandable but, as described above, there were occasions when the notification was brief, and users required more supporting information. Information management, especially of alerts, was a distraction.
- Users were not required to base their decisions and actions on UTM information alone in the TCL4 test; there were multiple sources available for them to cross-check. Observers noted a good amount of crosschecking occurring across the test suggesting that confidence and trust in UTM were still being established.

- Crews felt they responded efficiently and effectively to UTM information that required them to take action. However, often they chose to act outside of UTM to solve the problem using manual skills, but it is not clear why users did this.

The TCL4 flight tests successfully demonstrated flying UAS through the urban canyon and in complicated suburban areas. Qualitative data collected showed the usefulness of the UTM system and the need for information exchange for users of the system. Survey and debrief responses underlined crews' desire to be informed about operations other than their own and their need for clear procedural guidelines and clear displays of information. The findings presented above complement data previously collected for TCL3 (flown in the Spring of 2018), TCL2 National Campaign (Spring, 2017) and TCL2 (Summer, 2016). The increased functionality of UTM markedly increased its usefulness over previous flight tests but also identified that some of these functions would benefit from more consideration.

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Appendices

Appendix A

Table A1. Crew Member Roles and Responsibilities

Crew member role	*Crew member responsibilities*
Pilot-In-Command (PIC)	Served as the main pilot for the vehicle
GCS Operator (GCSO)	Worked the vehicle's flight planning and flight execution software
USS Operator (USS Op)	Monitored and interacted with USS displays (& NASA)
Hardware and Software Flight Engineers	Supported specific technical aspects of the vehicle
Visual Observers (VO)	Safety monitors who provided visual contact with the vehicles at all times
Additional roles	*Responsibilities*
USS Manager	Ensured the USS software was running and undertook troubleshooting when needed
Landing Zone Safety Pilots	Served as monitors at beyond visual line of sight landing points
Flight Test Manager	Coordinated the crews and flights to conduct the test scenarios properly
NASA Researchers & Observers	Collected observational and survey data, observers were available to support media day and answer flight team questions

Table A2. Crew and USS Pairings

		Test day/ week					
		Week 1: Mon	*Week 1: Tues*	*Week 1: Wed*	*Week 1: Thu*	*Week 1: Fri*	*Week 2*
Crew	*1*	USS G	USS D	USS G	USS G	USS G	USS G
	2	No flights	USS I	USS I	USS H	USS H	USS H
	3	USS F	USS D	USS F	USS D	USS D	USS D
	4	No flights	USS G	USS G	USS G	USS G	USS G
	5	USS D	USS I	USS D	USS F	USS F	USS F
	6	No flights	USS H	No flights	USS I	USS I	USS I
	8	USS H	No flights	USS H	USS H	USS H	USS H
	9	USS F	USS F	USS F	USS F	USS F	USS F
	Sim 10	USS B	USS B	USS B	USS B	USS B	USS B
	Sim11	USS D	USS D	USS D	USS D	USS D	USS D
	Sim 12	USS F	USS F	USS F	USS F	USS F	USS F

Appendix B

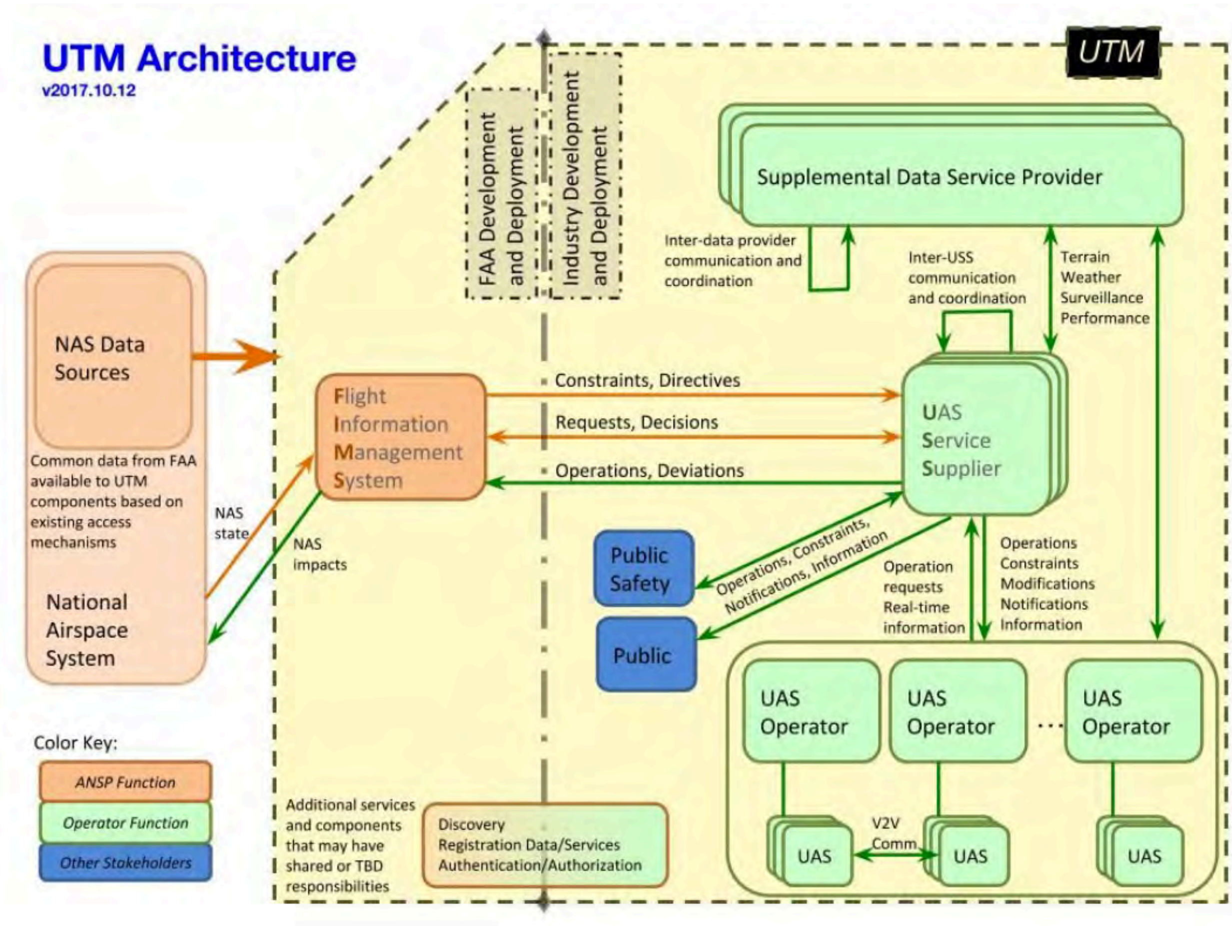

Figure B1. UTM architecture

Appendix C

Table C1. Order of Scenarios by Day of Flight Testing

	Mon 12 Aug	*Tue 13 Aug*	*Wed 14 Aug*	*Thurs 15 Aug*	*Fri 16 Aug*
AM	Line 32 FAA testing	Scenario 3 Run 1	Scenario 5 Run 1	Media day & Scenario 2 Run 1 & 2	Scenario 1 Run 1 & 2
PM	Scenario 4	Scenario 3 Run 2	Scenario 5 Run 2	Media day & Scenario 2 Run 3	Scenario 1 Run 3
	Mon 19 Aug	*Tue 20 Aug*	*Wed 21 Aug*	*Thurs 22 Aug*	*Fri 23 Aug*
AM	Scenario 2 Run 1 & 2	Scenario 4 Run 1 & 2	Scenario 5 Run 1 & 2	Scenario 3 Run 1, 2, 3 & 4	Scenario1 Run 1 & 2
PM	High winds no fly	Scenario 4 Run 3	End ex at 11:30 PST	End ex at 11:25 PST	Scenario 1 Run 3 & 4

Appendix D

Table D1. Participant and Observer Statement Coding Scheme Based on Research Question Topics

Research Category	*Sub-category*	*Research Category*	*Sub-category*
Communication/ Messaging	Effectiveness of data (message)	Safety & Risk	Safe separation
	Quality of alerting information		Confounds
Usability of information - Information efficiency & effectiveness	Reliability and/or accuracy of information		Priority access & priority operations
	Appropriateness of decision made (maneuver)	Procedures	Planning process and considerations
	Workload		Procedures for flight or event
	Usefulness of information		Description of operator role
	Usability tradeoffs		Public and hobbyists
	Intuitiveness or interpret-ability of information	Trust	Confidence in decision made (maneuver)
	Easy to understand		Trust in information presented
	Information timeliness		Reliance on info presented
Situation Awareness	Transparency of tool		Operator buy-in
	Situation Awareness	Automation	Definition of terms
	Information required or desired		Design of system or hardware
	Saliency of information		Functions
	Information timeliness		Concept issues

Appendix E

General description of data

Observers counted the uses of four types of UTM information from both UTM and other sources. There were 258 observed counts across the five scenarios – 75 during Scenario 1, 61 during Scenario 2, 56 during Scenario 3, 21 during Scenario 4 and 45 during Scenario 5. The majority of the observations/ counts were for information about the crews' operation (67%). Of the remaining 30%, around half of the observations were about UVRs, 10% about negotiation and 5% about priority operations.

Table E1. Proportion of Observation Count Data Where Participants Received Their Information Via a UTM Source

	Scenario 1	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*
Total number of observations	75	61	56	21	45
Percentage of observations with a UTM source	82%	73%	60%	66%	77%

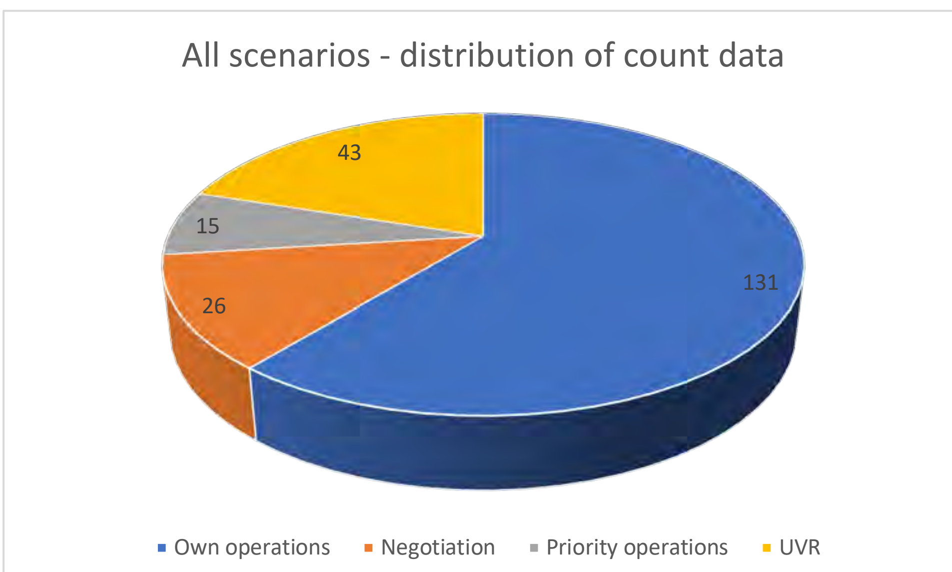

Figure E1. Observation count of information received about participants' own operations, negotiations, priority operations and UVRs.

Appendix F

Table F1. Breakdown of Negotiations

Location / *# of Neg*	Texas / 1008									
Scenario / *# of Neg*	Sc 1 / 223		Sc 2 / 412		Sc 3 / 89		Sc 4 / 75		Sc 5 / 209	
Type / *# of Neg*	Re-plan 3	Inter-section 220	Re-plan 12	Inter-section 400	Re-plan 0	Inter-section 89	Re-plan 0	Inter-section 75	Re-plan 9	Inter-section 200

Table F2. Breakdown of UVRs

Location / *# of UVRs*	Texas / 36				
Type / *# of UVRs*	Dynamic restriction / 36				Static advisory / 0
Scenario / *# of UVRs*	Sc 1 / 18	Sc 2 / 12	Sc 4 / 4	Sc 5 / 2	

Appendix G

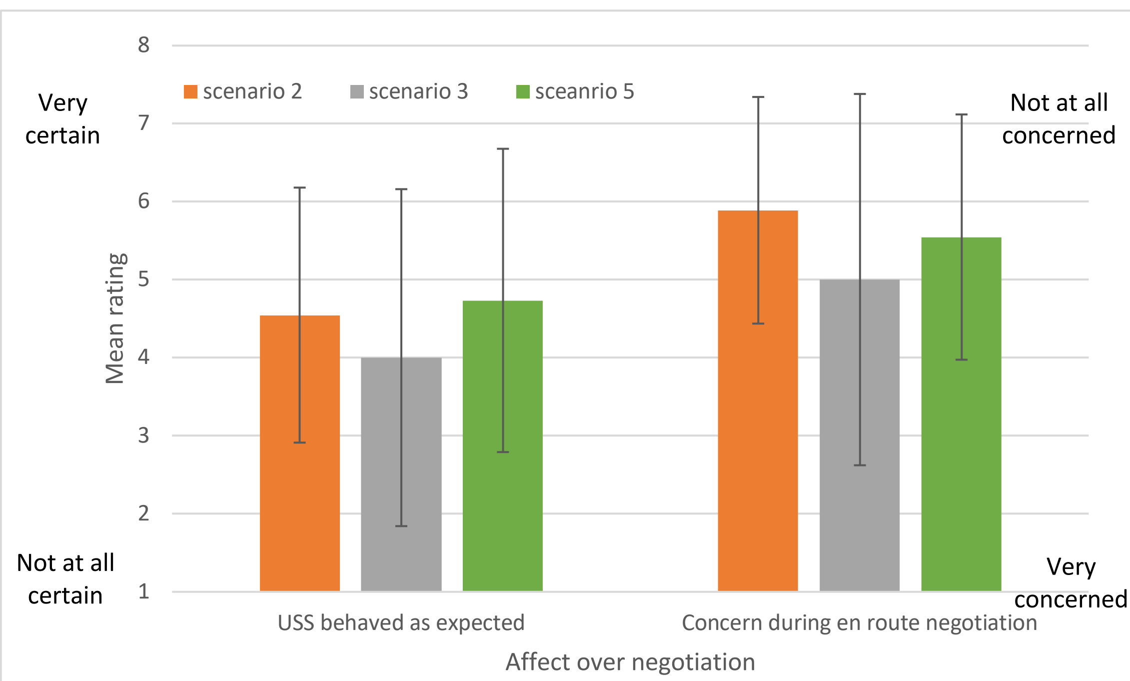

Figure G1. Participant responses regarding the behavior of their USS client and concern about the safety of their operation during volume modification negotiation while airborne/en route, n-USS behave = 36, n-concern = 27, rating on a 1 to 7 scale, extended to show full standard deviation.

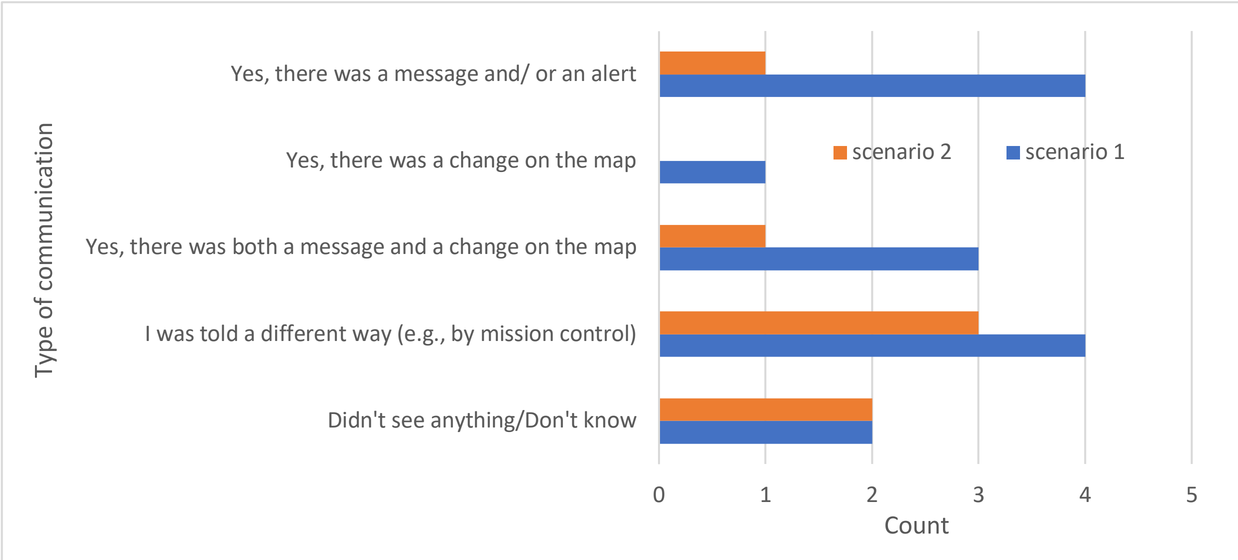

Figure G2. Sightings of UVR messages on the USS and the type of message; n = 21.

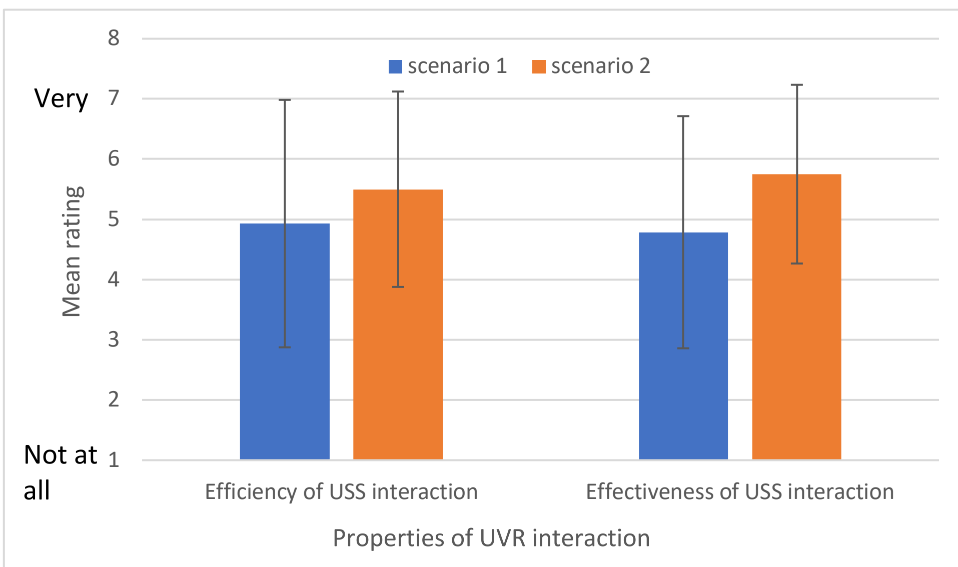

Figure G3. Quality of interaction with USS around the UVR; n= 26, scale is 1 to 7, extended to show full standard deviation.

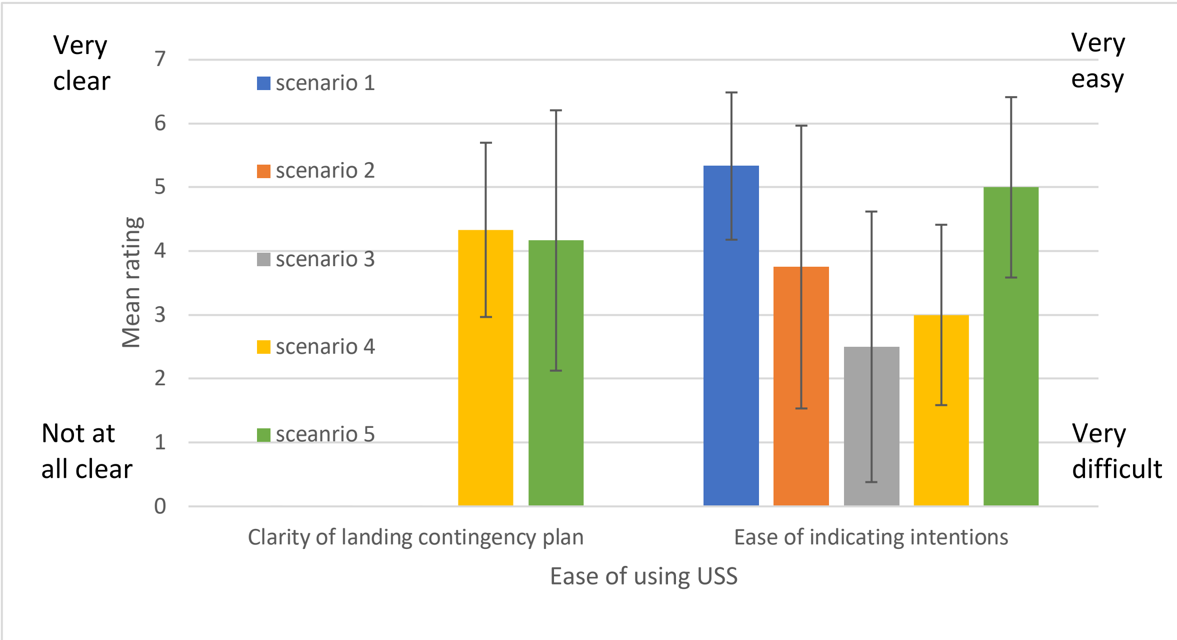

Figure G4. Participant ratings regarding the ease of making contingency plans and the clarity of landing contingency plans. N-clarity = 12, n-ease = 13, scale = 1-7, extended to show full standard deviation; note the different scale anchors for each question.

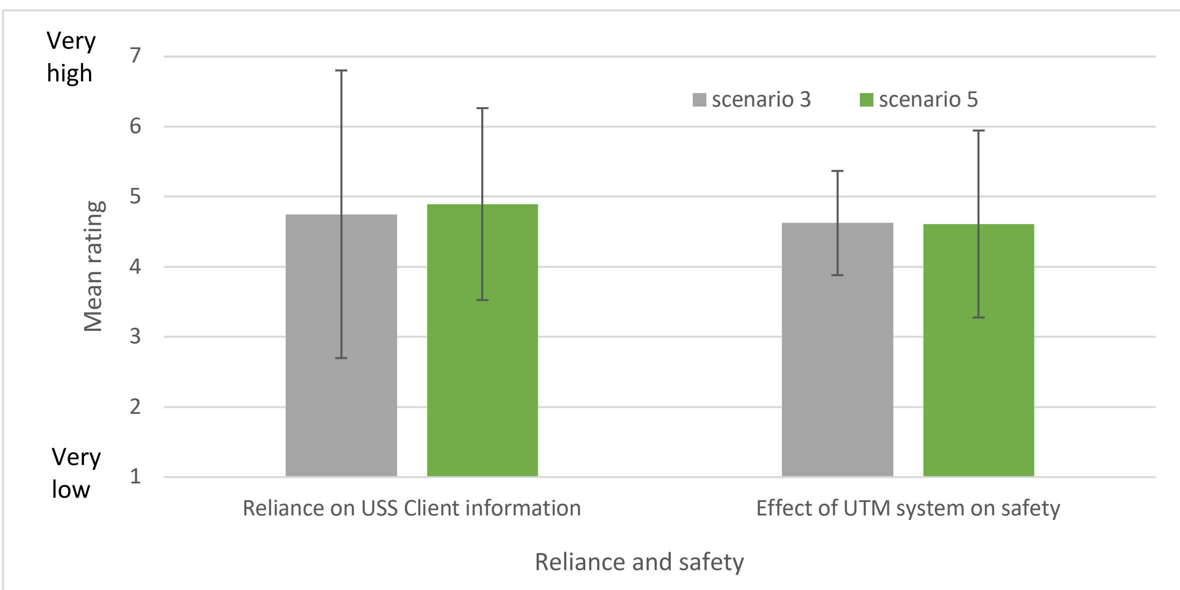

Figure G5. Participant ratings regarding reliance on USS client information and the effect of UTM on safety. N-reliance = 27, n-safety = 26; scale = 1-7.