

Flight Test Evaluation of an Unmanned Aircraft System Traffic Management (UTM) Concept for Multiple Beyond-Visual-Line-of-Sight Operations

Marcus Johnson, Jaewoo Jung, Joseph Rios, Joey Mercer, Jeffrey Homola, Thomas Prevot, Daniel Mulfinger, and Parimal Kopardekar

NASA Ames Research Center
Moffett Field, CA, USA

Abstract— This study evaluates a traffic management concept designed to enable simultaneous operations of multiple small unmanned aircraft systems (UAS) in the U.S. national airspace system (NAS). A five-day flight-test activity is described that examined the feasibility of operating multiple UAS beyond visual line of sight (BVLOS) of their respective operators in the same airspace. Over the five-day campaign, three groups of five flight crews operated a total of eleven different aircraft. Each group participated in four flight scenarios involving five simultaneous missions. Each vehicle was operated BVLOS up to 1.5 miles from the pilot in command. Findings and recommendations are presented to support the feasibility and safety of routine BVLOS operations for small UAS.

Keywords— *airspace integration; traffic management; Unmanned aircraft system traffic management; UTM*

I. INTRODUCTION

The technological advancement of unmanned aircraft systems (UAS) over the last few decades has created an emerging market that could revolutionize the aviation industry [1]. The Federal Aviation Administration's (FAA) aerospace sales forecast of small commercial UAS projects an increase in sales of 0.6 million units in 2016 and rising to 2.7 million units by 2020 [2]. However, the introduction of UAS into the United States National Airspace System (NAS) poses challenges to maintaining the safety and efficiency of the current airspace. Many new business models propose the use of small UAS operating at low altitudes in environments that range from unpopulated farmland to densely populated cities. While the airspace in some of these environments is not heavily trafficked with manned aviation, new challenges arise from operations that require an aircraft to fly in and around people, property, terrain and man-made obstacles. Further complicating the challenge of integrating new aircraft in an underutilized airspace are: (1) the size, weight, and power constraints of UAS that limit their ability to carry safety-related equipment, (2) the numerous proposed operations that require the UAS to fly beyond visual line of sight of the UAS operator, and (3) the potential influx of hundreds of thousands of operations due to the emerging UAS market and low financial barriers to entry.

NASA has advanced a concept for UAS Traffic Management (UTM) [3] and has initiated a research effort to refine that concept and develop operational and system

requirements. A UTM research platform has been created, and flight test activities have begun to evaluate core functions and key assumptions [4, 5], focusing exclusively on UAS operations within visual line of sight (VLOS) of the operator. The flight test activity reported here expands the range of operations to include operations of multiple UAS in lower-risk environments within and *beyond* visual line of sight (BVLOS). The UAS community is a diverse group with many members being new entrants to aviation. There is often stark differences in culture between the UAS community and the traditional aviation community that creates a challenging environment for integrating a rapidly developing new technology into the NAS. The objective of this flight test was exploratory, to demonstrate the basic feasibility of these types of airspace operations—termed UTM *Technical Capability Level 2*—and uncover issues and challenges that NASA and the UAS community will need to confront going forward. Furthermore, the results presented in this paper also serve to inform the UAS community of areas for improvement and inform the traditional aviation community of potential hazards to existing airspace users given the introduction of UAS into the NAS.

II. UAS TRAFFIC MANAGEMENT (UTM)

The FAA's establishment of 14 CFR § 107 enabled routine access for UAS operators into the NAS. While many business cases were supported by the provisions of 14 CFR § 107, a significant barrier preventing the proliferation of UAS applications is the limitation in the current regulation that restricts operations to remain within visual line of sight of the operator. Allowing BVLOS operations would enable a variety of UAS applications. However, BVLOS operations introduce many airspace integration and safety challenges. Barriers to allowing multiple BVLOS operations in the airspace include: inability to assure safe separation from other aircraft, spectrum management, surveillance and navigation, and contingency management in off-nominal conditions (e.g. lost link, loss of control). The National Aeronautics and Space Administration (NASA) and the FAA have initiatives underway to identify and respond to the range of challenges and ensure the safety and integrity of the NAS.

UTM has become relevant beyond the US. A study sponsored by Single European Sky ATM Research (SESAR) Joint Undertaking (JU) identified air traffic management

technologies as one of the key enablers to future UAS operations, and it was recommended that the European Union (EU) create a UTM system to coordinate and share airspace between manned and unmanned systems [6]. SESAR JU has initiated a call for funding UTM related approaches [7]. Other countries, such as Sweden, have already begun conducting research related to the UTM concept [8]. The European Aviation Safety Agency (EASA) and NASA have been coordinating approaches to safely enable large-scale small UAS operations. A Riga declaration, developed by the European aviation community, in 2015 identified UTM-related technologies as a strong starting point to address the rising demand for UAS operations [9]. In a recent Warsaw declaration [10], the EU identified a key focus on integrating UAS in low-altitude urban operations for the U-Space initiative, a concept similar to UTM. A global UTM association (<https://utm.aero>) was formed by the UAS industry to harmonize protocols, architectures, and data exchange definitions across multiple countries. At large, the UTM research effort serves as a pathfinder by the global community as a model to safely integrate small UAS operations in the low-altitude airspace.

UTM is intended to support safe and efficient UAS operations in low-altitude airspace by providing information and services to UAS operators and other NAS stakeholders [3]. The five core principles of UTM are: (1) only authenticated operations are allowed in the airspace, (2) UAS should avoid each other, (3) UAS should avoid manned aircraft, (4) UAS operators should have complete awareness of all constraints in the airspace, and (5) public safety UAS have priority within the airspace. These principles—as well as the concept’s guiding tenet: *flexibility where possible and structure where necessary*—provide a framework for the development of a UTM system that is different from the current ATM system that supports manned aviation.

The UTM construct utilizes industry’s ability to supply services where these services do not exist (e.g., uncontrolled airspace). In this construct, the FAA will maintain regulatory and operational authority for airspace and traffic operations. Through UTM, FAA will provide directives, constraints, and authorizations or restrictions. The FAA’s Air Traffic Organization will institute operational constraints at any time, and the FAA will have on-demand access to airspace operators and situation awareness of airspace operations continuously through UTM. It is expected that the UTM construct will be scalable to other airspace and vehicle classes as well.

In order to test and evaluate UTM concept elements and technologies, NASA has developed a UTM research platform. The specifications of the research platform and the results of evaluations that employ it—such as the present study—will be available as research transition products to the FAA and other stakeholders, as appropriate, to assist in the implementation of UTM capabilities that meet NAS service expectations.

NASA is spearheading the development and validation of UTM concept elements with its partners using combinations of simulations and field trials. The tests are aligned with NASA’s spiral development and evaluation schedule of Technical Capability Levels (TCL) that examine feasibility of increasingly complex operations. Each TCL extends the capabilities of the

previous TCL. Each capability is targeted to specific types of applications, geographical areas, and use cases that represent certain risk levels. The pace of development targets a new UTM TCL to be tested and evaluated in simulation and flight trials every 12–18 months. Figure 1 summarizes these capabilities.

As depicted in Figure 1, each UTM technical capability level has increasing scope and complexity to support a diverse and growing number of UAS operations. TCL 1, which supports notification-based operations in remote and rural areas, was tested in August 2015 at a closed airstrip in Crows Landing, California, USA [4]. This TCL was later tested more broadly at six FAA-designated UAS Test Sites across the United States [5].

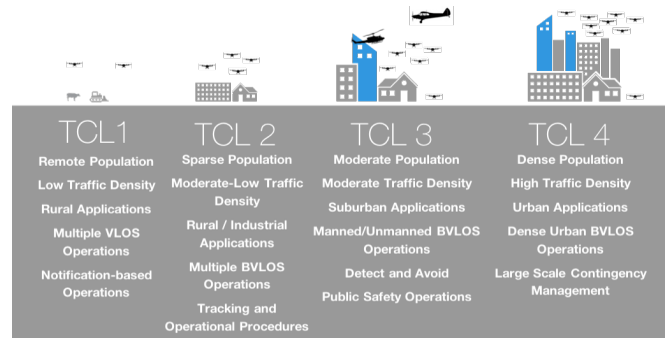


Figure 1: NASA UTM planned technical capability level progression.

The NASA UTM concept has identified a risk-based approach towards the introduction of routine low-altitude operations. The TCL 1 and TCL 2 environments are perceived as an appropriate near-term entry point to address barriers and develop regulations that enable routine UAS operations. The work presented in this paper focuses on the lessons learned from field testing of the TCL 2 BVLOS operations.

III. TCL 2 CONCEPT OF OPERATIONS

A key aspect of TCL 2 is the ability for operators to plan and schedule BVLOS operations. The addition of BVLOS operations contributes to an increased level of operational complexity and increased risk to other users of the airspace. Multiple BVLOS and VLOS missions that simultaneously access the same areas of operation create potential airborne conflict hazards.

UAS applications in a TCL 2 environment may include precision agriculture, rural package delivery, or long-range pipeline inspection. Public safety and security operations in a TCL 2 environment are given priority use of the airspace. In the NASA UTM Concept of Operations (CONOPS) [3], separation between UAS in a TCL 2 environment is supported by de-conflicting planned operational volumes—as managed by the UTM research platform—and requiring each UAS to stay within its respective operation volume (e.g. geo-fencing). Furthermore, separation between UAS and manned aircraft is facilitated by notifying manned aircraft of planned UAS operational areas.

The UTM research platform TCL 1 core functionality included features such as: planning and scheduling operational areas prior to departure, connection from the ground control station (GCS) or aircraft to the UTM research platform via an application protocol interface (API), monitoring aircraft

conformance to operational plans, and aircraft tracking. TCL 2 test capabilities included safety enhancements such as: proximity alerting, intruder alerts, contingency management alerts, four-dimensional (4D) segmented flight planning and scheduling, dynamic re-routing, and support for priority operations. These are discussed further below. To enable more efficient use of the airspace, the UTM research platform supports altitude stratification for efficient airspace operations.

Features of the UTM research platform, such as proximity alerting and intruder alerting, are meant to raise situation awareness to nearby operators that another aircraft is unexpectedly entering airspace near them. An intruder alert is generated from an external surveillance system that is tracking a non-participating aircraft (manned or unmanned). Contingency management alerts allow an operator to self-report anomalous behavior with their aircraft to the UTM research platform and implement a contingency management system (CMS) action (e.g. return to base). The UTM research platform will notify impacted proximal operations of the contingency management action taken so that all users are aware of the emergency and the airspace integrity is not further degraded by secondary conflicts. Dynamic re-routing allows for operators to change their operational plans while the aircraft is aloft to enable more agile operations. Segmented flight planning allows for more efficient use of the airspace and priority operations functionality will support public safety or security operations by clearing pre-existing UAS operations within the airspace.

IV. METHODOLOGY

The TCL 2 flight test focused on evaluating the feasibility of conducting multiple BVLOS operations in an environment relevant to the TCL 2 CONOPS. This section details the methodology used in developing the range, infrastructure, objectives and scenarios, UAS platforms, and other factors that impacted the flight testing.

The flight test demonstration was conducted at the Reno-Stead Airport (RTS) UAS Test Range in Reno, Nevada, USA. The RTS UAS Test Range is a part of the State of Nevada UAS Test Site. This test site was one of six sites designated in 2013 across the United States to test and develop UAS technologies. The RTS UAS Test Range is a basin and range topography that includes flat, dry desert surrounded by steep climbing mountains. Furthermore, at a 5,050 ft elevation, experiencing variable weather conditions, and a location 2 miles north of an active runway in uncontrolled airspace, the RTS UAS Test Range exercises a variety of challenges associated with conducting BVLOS operations.

A. Test Range and Infrastructure

Flight operations occurred within a test range area, depicted in Figure 2, where the red boundary represents the extent of the test range and the green shaded area represents the maximum geographic range that was used for flight planning and operations. Five ground control station (GCS) locations were situated along the perimeter of the flight area. Weather equipment, including a 30-ft weather tower, a sonic detection and ranging (SODAR) meteorological instrument, and light detection and ranging (LIDAR) meteorological instruments [6], were co-located at the GCS 3 location.

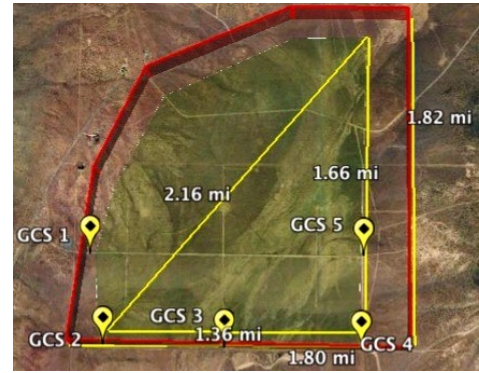


Figure 2: UAS test range north of RTS Airfield.

Each GCS location was staffed with flight crews, range safety support, and human factors researchers. Each UAS connected to the UTM research platform through an API [12] over a cellular telecommunications network. The connection to the UTM research platform was facilitated by the development of a client application that was typically resident on the ground control station of the UAS. This client provided telemetry and operational plan information to the UTM research platform, received messages and alerts during operations, and provided information about other nearby operations. The Mobile UTM application [13], as depicted in Figure 3, was displayed on an iPad at each GCS location. This airspace display provided additional access to, and visualization of, information about current or proposed operations in the airspace. Visual observers were used to facilitate safe flight operations during instances when aircraft were BVLOS of their operators.



Figure 3: Mobile UTM application situation awareness display.

Two ground surveillance radar systems (manufactured by SRC Inc.) provided coverage of the area in and around the UAS test range. The LSTAR V2 radar provided surveillance coverage of manned aircraft flying near the UAS test range. The SRHawk Radar provided surveillance coverage of UAS operations within the UAS test range. In addition, half of UAS were equipped with ADS-B Out transponders during the test and an ADS-B ground receiver was stationed at the GCS 3 location. Surveillance feeds from the LSTAR, SRHawk, ADS-B, and GPS positions as reported from the UTM research platform were integrated into a single airspace display. Surveillance position reports were sent to the UTM research platform via an API and provided real-time data for “intruder” UAS that were deployed as part of the test scenarios. Some vehicles also were equipped with the ability to be tracked over the cellular network.

B. Test Objectives and Scenarios

The primary flight test objective was to investigate the operational feasibility of UTM providing services to support multiple BVLOS and VLOS operations in lower risk environments. More specifically, the objectives were to explore how well the UTM research platform addresses the barriers preventing UAS BVLOS operations and identify potential improvements. To facilitate this evaluation, four hypothetical scenarios were crafted. These scenarios encapsulated different hazards associated with operations in the TCL 2 environment. The scenarios were designed to encompass the range of interactions likely to occur in the future operational context in which UTM is deployed. Scenarios contain the following general attributes: altitude stratification, a nearby intruder aircraft, a non-conformant or rogue aircraft, a public safety and security operator, re-routing flight while aircraft is aloft, and secondary conflicts due to contingency management actions (e.g., return to base).

| | SCENARIO 1 AGRICULTURE | SCENARIO 2 LOST HIKER | SCENARIO 3 OCEAN | SCENARIO 4 EARTHQUAKE |
|--------------------------------------|------------------------------|-----------------------------|------------------------|-----------------------------|
| BVLOS | ✓ | ✓ | ✓ | ✓ |
| MULTIPLE BVLOS | ✓ | | ✓ | |
| ALTITUDE STRATIFIED VLOS | ✓ | ✓ | | ✓ |
| ALTITUDE STRATIFIED BVLOS | | | ✓ | |
| INTRUDER AIRCRAFT TRACKING | ✓ | | ✓ | |
| INTRUDER AIRCRAFT CONFLICT ALERTS | ✓ | | ✓ | |
| ROGUE AIRCRAFT CONFLICT ALERTS | ✓ | | | |
| DYNAMIC RE-ROUTING | | ✓ | | ✓ |
| CONTINGENCY MANAGEMENT ALERTS | | | ✓ | ✓ |
| PUBLIC SAFETY OPERATION | | ✓ | | |
| SIMULATED AIRCRAFT | | ✓ | | ✓ |

Figure 4: TCL 2 flight demonstration test matrix.

In addition, simulated vehicle operations injected into the scenario using a live-virtual-constructive environment [13] enabled higher levels of complexity in some of the scenarios. Figure 4 highlights the test matrix that exercised the different attributes of the scenarios and features of the UTM research platform.

Each scenario was 20-25 minutes in duration with continuous operation of up to five vehicles operating within the same airspace. For example, in Scenario 2, as depicted in Figure 5, aircraft at each GCS location were given specific missions: traffic monitoring, cell tower inspection, forest ranger, and news reporting. Live vehicles were flown at altitude ranges of 200-500 ft height above take-off location for GCS 2-5 locations. A virtual aircraft was operated at the GCS 1 location. As the scenario developed, UAS operators at the GCS 3 location were searching for a lost hiker that was located in the north end of the range. Upon finding the lost hiker, a traffic monitoring mission was re-purposed as a medical supply delivery operation and re-routed using priority airspace access to clear the airspace of extraneous operations and provide supporting equipment and supplies to the lost hiker until an evacuation could be made.

Meanwhile, the cell tower inspection and news coverage operations were made aware of the nearby operations occurring in the area and any impacts their activities might have on their subsequent operations.

Eleven different flight crews—two NASA crews and nine industry partners—participated in the flight test. In each of the four scenarios, a vehicle was flown from each of the five GCS locations. Each flight crew performed a series of proficiency flights and, at minimum, two scenarios per flight day. Due to visibility conditions and the weather, flight activity typically was restricted between 8:30am and 12:30pm local time.

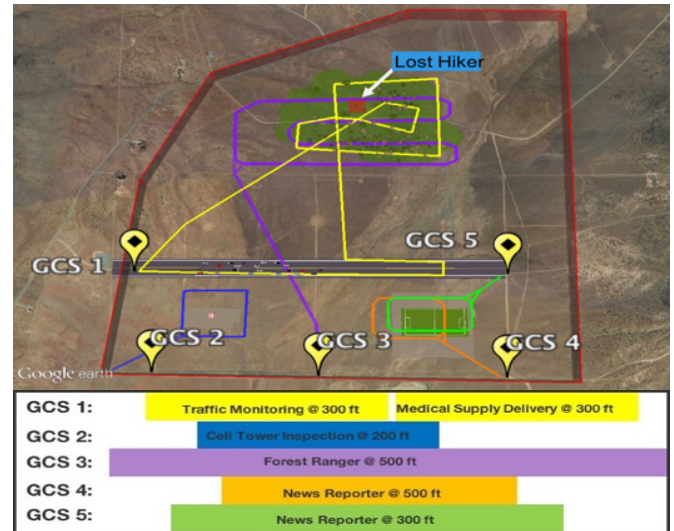


Figure 5: Scenario 2 demonstrating operations with altitude stratification.

C. UAS Test Platforms and Flight Crews

All vehicles were under 55 pounds, as listed in Table 1, and had a client that connected to the UTM research platform. All vehicles were capable of sustained flight over 15 minutes. With the exception of the Iris+, all vehicles had a command and control link coverage rated to at least 2 miles. Due to the terrain limitations for take-off and landing, fixed wing aircraft were only operated from GCS 3 and GCS 5 locations, whereas multi-rotors were operated from GCS 1, GCS 2, and GCS 4 locations. All multi-rotors had a vertical take-off and landing (VTOL) capability, while the fixed-wing aircraft had different mechanisms for take-off and landing, such as rail launch, hand launch, belly landing or parachute landing.

During the flight operations, flight crews were observed by human factors researchers at each of the GCS locations. Human factors observations were collected before, during and after flights. Flight crews completed questionnaires after each flight, and a debriefing interview was conducted at the end of each day.

The results and discussion in this paper will focus on key findings as observed by the human factors researchers and flight crews on the utility of the UTM research platform to manage traffic and support BVLOS operations in a TCL 2 environment.

Table 1: UAS platforms used in TCL 2 demonstration.

| Vehicle | Manufacturer | Type | Vehicle Mass (lbs) | Endurance (min) |
|------------|---------------|------------|--------------------|-----------------|
| Medium | Silent Falcon | Fixed-wing | 33 | 200 |
| SkvRange | Aervon Labs | Quadcopter | 6.5 | 50 |
| Ptarmigan | ACUASI | Quadcopter | 15 | 20 |
| Puma AE | AeroVironme | Fixed-wing | 13.8 | 210 |
| Iris+ | 3DR | Quadcopter | 2.8 | 20 |
| Tempest | UASUSA | Fixed-Wing | 14.8 | 90 |
| AR180 | Air Robot | Quadcopter | 11.5 | 40 |
| Cinestar 8 | Cinestar | Octocopter | 13.9 | 25 |
| Phantom | DJI | Quadcopter | 2.5 | 23 |
| Bramor | C-Astral | Fixed Wing | 9.8 | 150 |
| Lancaster | Precision | Fixed Wing | 6.5 | 45 |

D. Test Description

The NASA UTM TCL 2 demonstration was conducted October 17-25, 2016. There was a total of five flight days for the demonstration, and one planned flight day was canceled due to high winds. All other days in the testing period were used for safety briefings and ground testing. The flight activity consisted of warm-up proficiency flights and data collection scenarios. Overall there were 74 take-offs and landings during the testing period, which amounted to 13.5 flight hours across 11 different UAS platforms. Of the 74 total flights, 35 of the flights were slated for data collection from the four scenarios.

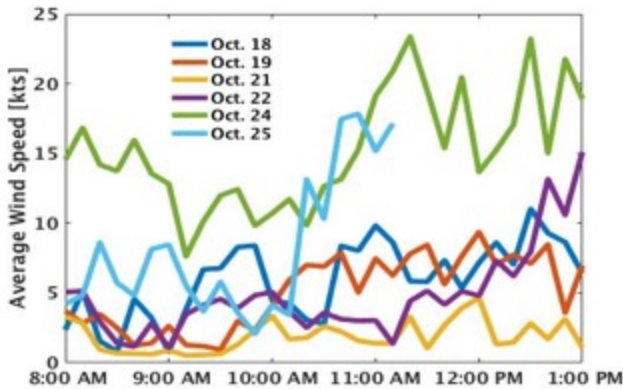


Figure 6: Average wind speed as measured by the 30 ft wind tower.

Data were collected for flights with VLOS and BVLOS profiles. Flight durations were between 6 and 23 minutes and ranged from VLOS operations at 1000-3000 ft from the launch location to BVLOS operations from 4000-9000 ft from the launch location. The maximum distance at which a pilot could maintain VLOS for a UAS was largely dictated by visibility conditions, size and appearance of the vehicle, and operator's ability to observe the orientation of the aircraft. Flights were typically flown between 200 ft and 500 ft height above the take-off location and had a ground speed ranging from 11 knots to 60 knots with an average of 40 knots.

The environmental conditions had substantial impacts on the testing and performance of the aircraft. Initial testing at the RTS UAS test range under warm temperature conditions, between 87

– 95 °F, yielded density altitude conditions around 9,000 ft MSL, which is well above the 5050 ft elevation of the test range. These conditions significantly reduced the endurance of the UAS. During the demonstration temperatures subsided to the 30-50 °F range which provided a more favorable density altitude of 4,000 ft MSL, however high winds became a significant factor.

The test procedure specified an operational limit of 15 knots sustained wind speed, above which operations were to be halted. As depicted in Figure 6, the operational limit was reached on Oct. 24th and Oct. 25th. In the former case the flight day was canceled, and in the latter case the flight day was ended early. In addition to strong wind conditions, variability in the wind across the test range—both on the ground and at different altitudes—made predicting aircraft performance challenging. As shown in Figure 7, the variable topography of the test range resulted in wind direction, speed, and variability that was significantly different across the range.

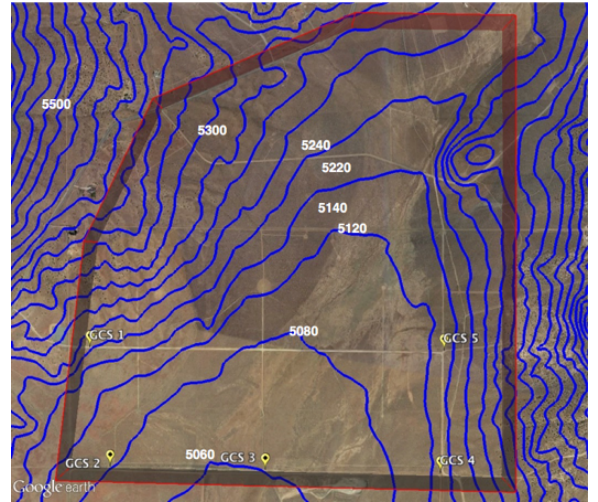


Figure 7: Elevation contours of the test range measured in MSL altitude.

The wind profiles, as depicted in Figure 6, were measured from the top of a 30-ft weather tower that was co-located with GCS 3 and often represented lower wind measurements than those reported by flight crews at other locations, particularly at the GCS 5 and GCS 4 locations. This terrain created microclimates within the planetary boundary layer. These microclimates exhibited various meteorological phenomena such as variable wind shear, thermals, microbursts, and large variations in wind speed on the ground and aloft. These environmental factors exposed interesting considerations when operating multiple BVLOS missions within the same airspace, as is detailed in the subsequent sections.

V. RESULTS

This flight test focused on exploring the feasibility of conducting multiple UAS operations, involving VLOS and BVLOS simultaneously within the same area. The flight test resulted in breadth of data and findings that inform the UAS community and regulator of potential hazards and recommendations to support BVLOS. This paper presents an overview of four key findings from the flight test and offers recommendations for new capabilities, standards or practices to address them. For brevity, the paper presents an overview of the

main findings, however future analysis will be presented to further substantiate each of the findings presented in this paper. The findings stem from human factors observations of the use of the UTM research platform by the test participants as well as the technical limitations and operational considerations when performing multiple BVLOS operations in a rural operational environment. These findings and recommendations are expected to help inform future research and the development of industry standards.

Key Finding 1 (KF1): The UTM research platform provided key information needed by operators to successfully conduct missions amongst other nearby operations and with an awareness of airspace constraints. Currently UAS operate in sparse density and operators are not always aware of other operations planned in the area without direct coordination. Current commercial operations are VLOS and thus the limited awareness is mitigated by the close proximity of the operators. The environmental conditions of the TCL 2 flight test exposed potential safety implications of operating BVLOS that need consideration as operations start to scale in size and density. Some of the industry flight crews that participated in the demonstration had experience flying with other vehicles within their company's fleet, but few had experience flying in the same area with multiple operators. Differences in procedures, onboard contingency management systems and vehicle performance made it evident that some amount of information sharing was needed in order to ensure operational behavior of proximal operations was known and predictable. Prior to flight, operators expressed a desire to review the plans of other aircraft that would be in the vicinity of their operation, particularly those that would be altitude stratified. The flight crews communicated with other operators to ensure they knew the intent of other operators during high risk areas of the operation, particularly to confirm a vehicles' altitude, and to review contingency management procedures. In this latter case, operators wanted to ensure vehicles would not descend into each other in the case of off-nominal conditions. In preparation for the demonstration, flight crews developed UTM clients that adhered to an API defined in [12]. This API gave operators access to operational data from all nearby operators in the UTM research platform, however it was at the discretion of the operators as to what information they integrated and displayed into their GCS. The Mobile UTM application was available for all operators that did not implement airspace information into their GCS. During operations, the flight crews used their UTM Clients and the Mobile UTM application to monitor their flight path with respect to other air traffic and various alerts generated by the UTM research platform. The flight crews reported that the airspace information was important to their ability to maintain situation awareness during the operations and maintain their flight path within the operational boundaries, particularly during manual phases of flight. Overall, operators reported that the UTM information available to them yielded a reasonable level of awareness of other airborne operations with respect to their own. Initially, operators held a self-centered view of their operations with respect to others. As flight crews became more familiar with the UTM displays, they used them to monitor other operations that came within close proximity of their own. Upon using the Mobile UTM application, the flight crews shifted their strategies to include

requests of operational plans from other operators to develop a better understanding of how their operation might be impacted by others in the airspace. The operators expressed a desire for a predictable behavior of proximal UAS and needed understanding of nominal and off-nominal conditions (e.g. lost link, loss of GPS, low battery).

Recommendation 1 (R1): Operators should display airspace information and have access to information from other operators. In addition to access to information about other proximal operations in flight planning, it is crucial that operators have access to dynamic changes in airspace during operations. It is recommended to expand the data that is shared in [12] to include information needed for other operators to react to a nearby aircraft undergoing an off-nominal state. This information could include, but is not limited to, contingency diversion locations, contingency action (e.g. return to base, land now, parachute deployment, etc.), last known position, altitude, heading, speed, and battery life remaining, aircraft endurance, and type of failure state (e.g. lost link, loss of control, etc.). Furthermore, the ability to communicate with other operators during off-nominal conditions would greatly improve an operator's ability to react to hazardous conditions caused by other users of the airspace.

KF2: Measurement and reporting of vehicle altitude was not consistent among airspace users. A wide variety of UAS platforms exists today, and differences in measuring altitude can pose hazards to the UAS, airspace, or obstacles, or persons on the ground. Most UAS are equipped with GPS systems that provide latitude and longitude measurements (often used for waypoint navigation) and a geometric height measurement that is an approximation of mean sea level (MSL) altitude (also known as absolute altitude). GPS is based on a constellation of satellites and inherently can have errors that vary largely based on the number of satellites within line-of-sight of a receiver at a given time, geometric distribution of these satellites in space, and atmospheric conditions [14]. In many ground control stations, the altitude is presented to the operator relative to the GPS-measured altitude at takeoff. Furthermore, some UAS platforms utilize technologies (e.g., laser altimeter) to measure height above terrain. Most manned aircraft and some UAS also measure altitude by using barometric pressure, which makes use of the difference between the static pressure onboard the aircraft and the pressure at sea level provided from a ground station to measure the MSL altitude (also known as indicated altitude). Around airports, manned aviation also measures height above field elevation with respect to a fixed point at an airport rather than measured directly below the aircraft.

During the flight demonstration, two incidents occurred in which different altitude measurement methods posed hazards to BVLOS operations. The first incident occurred from a lack of proper awareness of an aircraft's altitude relative to terrain during flight planning and operations. This resulted in a controlled flight into terrain. The flight was launched from the GCS 2 location, depicted in Figure 2, and traveled due north BVLOS at an altitude of 150 ft above the take-off location. Unbeknownst to the operator, the elevation of the terrain rose over 150 ft with respect to the GCS 2 take-off location. The aircraft maintained its operational altitude with respect to its take-off location and inadvertently exercised a controlled flight

into terrain as the terrain rose above the elevation of the take-off location. As the aircraft was BVLOS of the operator, there was no direct indication that the aircraft was approaching the ground, and the low-altitude behavior was reported by a visual observer without sufficient time to avoid an impact with terrain. This event highlighted the need for any operation that is flying BVLOS to have information regarding ground obstacles and elevation of the local terrain. Furthermore, operators should be aware of how their UAS reports altitude, such that they are not creating a potential collision hazard with objects in the air or on the ground.

Ambiguity of a vehicle's reported altitude contributed to a second type of hazard. On several occasions during the flight test, manned traffic that posed a threat was called out as reported by the ground-based surveillance radars and visual observers. However, the reported altitude was called out as MSL altitude, which caused confusion because many operators had systems that reported their altitude in height above terrain or height above take-off location. In addition, differences in the units of measure used by each UAS caused confusion amongst operators when altitudes were reported. When de-conflicting UAS operations during flight planning in the UTM research platform, it became necessary to require a consistent altitude measurement for the missions as operators were unfamiliar with each other's platforms and didn't realize that they reported altitude in different ways. While operating BVLOS all operators will need to use a consistent altitude standard.

R2: Altitude reporting should be consistent or translatable across airspace users. Differences in how altitude is measured and reported can increase the likelihood of airborne collisions and controlled flight into terrain. To address these hazards, the UAS community should agree upon a common altitude measure for information sharing and reporting, common units of measure, and an acceptable error tolerance for each measurement that can be used to accurately reflect conformance to constraints and approved airspace authorized by the air navigation service provider (ANSP), consistency amongst UAS operators to provide support for separation provisions, avoidance of terrain and obstacles, and compatible reporting and communication with manned aviation to ensure safe separation.

KF3: The sources of weather information for this flight test were inadequate to support BVLOS operations. During the demonstration the significant variability in observed weather based on location exposed a hazard for BVLOS operations. As expected, small UAS are easily, adversely affected by inclement weather conditions. However, it was evident that despite the many weather-sensing instruments that were available at the test range, there was poor awareness of the localized weather conditions that the vehicle was experiencing. The regional and national forecasts that were available were not of sufficient fidelity to provide useful information with regard to the local region and time frame in which the UAS were operating. Each morning, weather conditions were briefed by the range safety personnel; briefings contained information from several weather sources: local weather forecasts and reports, current conditions from the airport's automated weather observation system (AWOS), and current atmospheric conditions from a weather station at the GCS 3 location. Prior to and during operations, current wind conditions were announced from the AWOS,

handheld wind meters at each GCS location, and in limited circumstances from some of the UAS that were equipped with weather-sensing equipment. BVLOS flights were occasionally aborted after pilots experienced undesirable vehicle performance as a result of turbulent weather, despite the fact that ground atmospheric conditions at the GCS location were mild. Rapid changes in wind conditions at different GCS locations and areas of operations resulted in operators being unable to accurately predict vehicle endurance, which resulted in delayed take-off times and unplanned landings. Although the scenarios were less than 30 minutes in length, significant changes in wind speed—as much as 10+ kts—were observed between the beginning and end of a scenario, such that some multi-rotor aircraft had difficulty landing due to high crosswinds. Throughout the TCL 2 testing, warm and cold temperatures impacted operations. Warm temperatures drove the density altitude up to 9,000 ft MSL and drastically shortened the endurance of many of the multi-rotor platforms. This resulted in operations that had unplanned emergency landings, and it forced operators to make critical battery voltage thresholds in the UAS contingency management system more conservative than their normal operations. During cooler temperatures, the density altitude decreased below the elevation, to 4,000 ft MSL, and in the morning when wind speed was low, fixed wing vehicles had shallow take-offs and landings. In the afternoon the wind speed increased and at times multi-rotors experienced micro-bursting phenomena that reduced endurance, while fixed-wing aircraft at times flew through thermals that increased their altitude as much as 200 ft. While operators can measure atmospheric conditions on the ground prior to take-off and look at local weather reports from sensors that may be miles away, in certain environments it doesn't guarantee adequate foresight and awareness of the atmospheric conditions along their intended flight paths.

R3: Weather information sources should be augmented with in-situ reports from UAS and GCS and shared with other users in the airspace. The degradation in performance of UAS to adverse atmospheric conditions (e.g. high winds, density altitude, etc.) and the lack of sufficient forecasting and measurement pose arguably the most significant hazard to BVLOS operations. Despite several instruments at the demonstration measuring local atmospheric conditions, the diversity of micro-climates at each launch location and experienced along the aircraft's flight path made it impractical to extend the weather measured from any one particular source to be representative of the entire range. The most representative data regarding the atmospheric conditions generally came from measurements at the launch locations, reported from handheld anemometers, and the measurements reported from the UAS while they were aloft. While the basin and range topography of the UAS test range may have exacerbated the extent to which each location had noticeably different conditions, the inherent hazard is that parts of the boundary layer are not observed, by national weather products, with granular enough grid sizes and short enough time horizons to support UAS operations. Furthermore, current local weather measurements also may not be sufficient based on the topology of the operating environment and the distance from the weather station. In the absence of sufficient sources of weather information, improvements can be made to support BVLOS and support the development of weather products that can eventually provide support for

environments more complex than TCL 2. By sharing reports of atmospheric conditions on the surface, at the operators launch site, and aloft, as measured onboard the vehicle, and sharing that information with other users through a UTM system, UAS operations can benefit by: (1) Comparing local weather reports with observed weather by other operators to improve their awareness of conditions along their flight path, (2) collecting data for further development on location-based boundary layer and surface weather models to support future missions in that particular area. Ultimately the responsibility to identify the presence of atmospheric conditions that would be unacceptable to their particular UAS lies with the operator.

R4: Initial routine BVLOS operations should not conduct altitude stratification unless there is accurate and timely information shared of the relative position of nearby UAS and improvements are made in the fidelity of the weather predictions along the flight path. The altitude stratification construct was considered to enable higher densities of UAS to operate within the same airspace, thus allowing for large-scale UAS operations to occur in the near future. However, when vehicles operate BVLOS the operator has a reduced awareness and increased reaction time (due to present-day operating tools and assumptions) with respect to maintaining the separation with other airborne objects. Uncertainties in navigation error and the influence of weather can increase the potential collision hazard. During the demonstration many different weather phenomena were experienced that could have potential implications for multiple BVLOS operations. At one point in a scenario, two fixed-wing aircraft were altitude stratified, separated by 200 ft, and the aircraft were both flying a loitering pattern. The aircraft with the lower altitude experienced thermal activity which rapidly increased its altitude such that it was approximately co-altitude with the aircraft that was flying at the higher altitude. While no collision avoidance maneuvering was necessary, the scenario exposed a potential collision hazard whose likelihood was dramatically increased over a short time horizon due to a lack of coordinated action between the UAS and an insufficient forecasting and measurement of potential weather hazards. In a TCL 2 environment, without a common altitude reference or collision avoidance mechanism on-board the aircraft and without improvements in weather products it is not advisable to conduct altitude stratification for the initial introduction of BVLOS operations into the NAS.

KF4: Operational plans were not always consistent between the UTM System, GCS and UAS. To facilitate separation by segregation of UAS, the UTM research platform de-conflicts operations by ensuring that no two operational plans submitted to the UTM system intersect in time and space. This approach allows for scheduled use of the airspace and prevents operators from simultaneously flying into the same location in the design of their missions. The UTM research platform also prevents UAS operators from designing missions that fly into airspace in which they are not authorized to operate (e.g. controlled airspace). During operations, an operational plan—also known as a *flight geography*—is submitted to the UTM system. If it is free from conflicts, it is accepted by the UTM research platform as a valid plan. It is expected that when an operator submits a flight geography to the system, it represents

an area that encompasses the entire extent of their intended operation under nominal conditions. The UTM research platform then assigns a slightly larger region around the flight geography to monitor for conformance violations; this is known as the *conformance geography*. The volume between the flight geography and the conformance geography is a buffer that allows for navigation errors during execution of the operation. If a vehicle exits the conformance geography, it is considered non-conforming to its operational plan. Another volume is assigned around the conformance geography, known as the *protected geography*. This volume is the full extent of the airspace that operation is allowed to occupy. If a vehicle exits the protected geography, it is potentially entering into another operations’ airspace and is considered a rogue aircraft.

An example of the flight geography (blue area), conformance geography (green line), and protected geography (red line) associated with an operation is depicted in Figure 8. The flight path flown by the UAS is shown in white. The flight-path line is shown in blue when the UAS exits the flight geography, green when it exits the conformance geography and red when it exits the protected geography. For the demonstration, the distances between the boundaries of the flight geography, the conformance geography and the protected geography are provided in Table 2. The values were selected conservatively to initiate alerting.

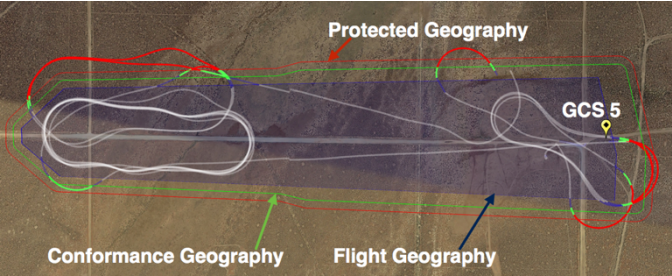


Figure 8: Flight geography, conformance geography, and protected geography of an operational plan.

During the demonstration, flight crews were given operational areas and notional flight paths in which to exercise different functions of the UTM research platform. The flight crews were instructed to adjust the flight plans and operational volumes so that they aligned with the capabilities and limitations of their respective platforms. The operational areas were intended to encompass all nominal phases of the flight and be large enough to accommodate the aircraft’s flight path, yet small enough not to intrude on another flight crew’s operation.

Table 2: Distance from the flight geography.

| | Multi-Rotor | | Fixed Wing | |
|-----------------------|-------------|----------|------------|----------|
| | Horizontal | Vertical | Horizontal | Vertical |
| Conformance Geography | 40 ft | 15 ft | 64 ft | 30 ft |
| Protected Geography | 100 ft | 35 ft | 124 ft | 50 ft |

Of the 35 flights that were conducted during data collection, 54% of the flights remained within the flight geography. The remaining 46% of the flights left their flight geography at least once during their mission. The most common instance of non-conformance was due to the performance of the vehicle. These were violations when the operational plan did not properly

account for the turn radius of the aircraft or consider its launch or landing trajectory. These instances of exiting the flight geography were brief with respect to their total mission time, and in each case they promptly returned to their flight geography. To remedy these types of errors, larger volumes should be included around the take-off and landing site, and a minimum lateral and vertical distance should be established for each UAS platform based on the turn radius and climb/descent rate, navigation error, and max wind tolerances of the vehicle.

In several cases the environment played a role in a conformance violation. Variable wind direction made some of the flight crews change the launch direction for the safety of the vehicle. In doing so, the initial launch trajectory sometimes went outside their flight geography until they reached their first waypoint. This type of violation could be resolved procedurally by verifying flight geography prior to take-off. Furthermore, improvements can be made by automation of the UTM Client factoring in launch direction and requesting a flight plan modification from the UTM research platform.

The remaining conformance violations resulted in non-conformances of longer duration. Operator error in submitting waypoints or altitudes in the GCS commanded the vehicles to leave their flight geographies. Operator error also contributed to violations occurring during manual flight modes, un-reported return-to-base maneuvers (due to low battery), and inadvertent submission of erroneous flight geography to the UTM research platform as compared to what was entered into the GCS. These violations could be resolved thorough training for operators and more intelligent automation in the UTM Client and GCS.

Of the 46% of aircraft that left their flight geography, as depicted in Figure 9, the majority of infractions deviated no further than 500 ft laterally and 20 ft vertically for fixed wing and 180 ft laterally for the multi-rotors. There were no vertical violations for the multi-rotor aircraft. Deviations that were larger than these values were due to operator error. Most instances of non-conformance were a result of the UAS exiting the flight geography momentarily and then returning. Adjustments to the conformance and protected geographies listed in Table 2 can be made based on the plots like Figure 9 to establish appropriate buffer sizes for TCL 2 operations.

R5: Flight trajectories should be contained within geo-fence boundaries that are shared with the UTM research platform and enforced by the aircraft. Integration of a UTM Client such that the geo-fence boundary that contains the operation is uploaded to the vehicle and shared with UTM System will eliminate many of the errors encountered at the flight test. Often pilot errors were due to an operator submitting an operational plan to UTM and uploading a different operational plan to the UAS. This mitigation could be further reinforced by displaying the geo-fence boundary on the GCS awareness display, as recommended in R1.

VI. FUTURE WORK

Overall the flight test findings are consistent with the hypothesis that a UTM system could manage multiple BVLOS operations in a TCL 2 environment if the recommendations, presented in the prior section, can be addressed. The five core principles and the guiding tenet of the UTM Concept, shown in

Table 3, were exercised during the flight test. Awareness to the environment in which the UAS are operating is a core principle that was supported by key findings KF1 and KF3. Recommendations to industry in data information sharing and more effective weather products are detailed in R1 and R3, respectively. UAS operators can enhance safety by effectively sharing data and additional studies should investigate required information in off-nominal conditions. Future analysis will focus on the effectiveness of the flight crews using their UTM Client and the UTM Mobile Application.

Key finding K2 identified a potential barrier in effectively keeping UAS and manned aircraft safely separated. Coalescing industry for a common measure for altitude reporting and effective means for employing a separation by notification to support separation between UAS and manned aircraft will be future work of the UTM Research Transition Team (RTT) that was formed in 2016 between NASA and the FAA. The UTM RTT is an activity to jointly research and transfer UTM capabilities and technologies to the FAA that facilitate an efficient implementation of UTM operations

Functionality to support priority operations was developed in the UTM research platform and future analysis will investigate the response times of the operators reacting to public service operations entering the airspace. The timeliness and information required for evacuating an area with a priority constraint will also be part of future UTM RTT evaluations.

The flight test highlighted the potential hazard of imposing the altitude stratification airspace construct without the necessary technology and support available. Imposing this structure will be necessary for efficient use of the airspace as density of UAS operations increase, however altitude stratification is not advisable for initial BVLOS introduction into the NAS.

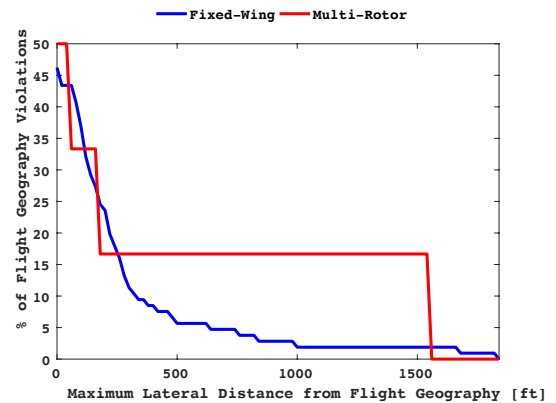


Figure 9: Cumulative distribution of percentage of lateral violations of the flight geography.

VII. CONCLUDING REMARKS

The UAS industry is a growing market that has the potential to revolutionize the aviation industry. However, challenges remain in facilitating the safe integration of BVLOS operations into the NAS. A UTM system can provide support to enable the proliferation of UAS operations. This report detailed the results of the NASA UTM Project's TCL 2 flight test that investigated the feasibility of enabling multiple concurrent BVLOS

Table 3: Summary of key findings and recommendations.

| UTM Core Principles and Guiding Tenet | Tested Feature | Key Findings | Recommendations |
|---|---|-----------------|-----------------|
| UAS should avoid each other | Scheduling and Planning Conformance Alerting Proximity Alerting Separation by Segregation (e.g. Geo-fencing) | KF4 | R5 |
| UAS should avoid manned aircraft | Intruder Alerting Separation by Notification (e.g. NOTAM) | KF2 | R2 |
| UAS operators should have complete awareness of all constraints in the airspace | UTM Mobile Application Contingency Management Alerts | KF1 KF3 | R1 R3 |
| Public safety UAS have priority within the airspace | Priority Operations | Future Analysis | |
| Flexibility where possible and structure where necessary | Altitude Stratification Dynamic Re-routing 4D Segmented Flight Plans | KF4 | R4 |

operations in close proximity of each other safely using the UTM research platform. The test was held at the Reno-Stead airport in October 2016 and consisted of 11 aircraft and 13.5 flight hours. The test validated the need for awareness with regard to the plans of other operators, the risks inherent in different airspace users employing different altitude measurement methods, and the limitations imposed by insufficient weather products. Analysis was conducted on the degree to which UAS operators were able to conform to their operational areas. These findings will help enable multiple BVLOS operations and regulations.

ACKNOWLEDGMENTS

The authors greatly appreciate the support and assistance provided by: AeroVironment, Drone Co-Habitation Services, Alaska Center of UAS Integration, Lonestar UAS Center, Modern Technology Solutions Inc., Precision Hawk, Proxy Technologies Inc., Silent Falcon UAS Technologies, Unmanned Experts, Gryphon Sensors, Harris, San Jose State University, Reno-Stead Airport, and the State of Nevada UAS Test Site. The authors also acknowledge the FAA's support of the UTM concept through the FAA-NASA Research Transition Team (RTT).

REFERENCES

- [1] U.S. Congress. Unmanned Aircraft Systems (UAS): Commercial Outlook for a New Industry. By Bill Canis. Cong. Rept. R44192. Congressional Research Service, 2015.
- [2] Federal Aviation Administration, FAA Aerospace Forecast Fiscal Years 2016-2036, 2016..
- [3] Kopardekar, P.H., Rios, J., Prevot, Thomas, Johnson, M., Jung, J., and Robinson, J.E., UAS Traffic Management (UTM) Concept of Operations to Safely Enable Low Altitude Flight Operations, 16th AIAA Aviation Technology, Integration, and Operations Conference, Washington D. C. 3292. AIAA Aviation Forum, 2016.
- [4] Johnson, M., et al. Flight Test Evaluation of a Traffic Management Concept for Unmanned Aircraft Systems in a Rural Environment. NASA/TM, to be published, March 2017.
- [5] Rios, J. NASA UAS Traffic Management National Campaign: Operations Across Six UAS Test Sites," 35th Digital Avionics Systems Conference (DASC), Sacramento, CA, 2016.
- [6] SESAR JU, "Europeans Drones Outlook Study: Unlocking the value for Europe", Siebert, JU, Nov. 2016.
- [7] Siebert (2016), SESAR 2020 RPAS EXPLORATORY RESEARCH CALL. Call identifier: H2020-SESAR-2016-1
- [8] Josefsson, B., et al. "Challenges and Methodology with first assessment of UTM level 3/4 impact – a hi fidelity interactive visualization.", 2017.

- [9] Riga Declaration on Remotely Piloted Aircraft Systems, "Framing the future of aviation." March, 2015.
- [10] Warsaw Declaration, "Drones as a leverage for jobs and new business opportunities" Nov. 2016.
- [11] Clements CB, Oliphant AO (2014) The California State University – Mobile Atmospheric Profiling System (CSU-MAPS): a facility for research and education in boundary-layer meteorology. Bulletin of the American Meteorological Society 95, 1713–1724.
- [12] Rios, J., et al. "UTM Client Interface Control Document," version 2.0, NASA Ames Research Center, unpublished, February 2016.
- [13] Homola, Jeffrey, et al. "UAS traffic management (UTM) simulation capabilities and laboratory environment." Digital Avionics Systems Conference (DASC), 2016 IEEE/AIAA 35th. IEEE, 2016.
- [14] James J., Spilker Jr., Penina Axelrad, Bradford W., Parkinson Per Enge, "Gps Error Analysis", Global Positioning System: Theory and Applications, Volume I, Progress in Astronautics and Aeronautics, pp. 469-483.

AUTHOR BIOGRAPHY

Dr. Marcus Johnson is a research aerospace engineer in the Aviation Systems Division at the NASA Ames Research Center. He is a graduate from University of Florida with a B.S., M.S., and Ph.D. in aerospace engineering.

Dr. Jaewoo Jung is a research aerospace engineer at NASA. Jaewoo received Ph.D. and M.S. in aeronautics and astronautics from Stanford University, and B.S. in aerospace engineering from Boston University.

Dr. Joseph Rios is the Technical Lead for UTM at NASA Ames Research Center. He has a PhD in Computer Engineering from UC Santa Cruz.

Joey Mercer is a Research Psychologist working in the Airspace Operations Laboratory at NASA Ames Research Center's Human-Systems Integration Division. He received his B.S. in experimental psychology from the University of Idaho and his M.S. in human factors from the systems engineering department at San Jose State University.

Jeffrey Homola is a research psychologist in the Human Systems Integration Division at the NASA Ames Research Center. After serving in the US Navy, he went on to earn a B.S. in Cognitive Science from UCLA and an M.S. in Human Factors/Ergonomics from San Jose State University.

Dr. Thomas Prevot is head of the Airspace Operations Lab at the NASA Ames Research Center. He holds a PhD in aerospace engineering from the Munich University of the German Armed Forces.

Daniel Mulfinger is an air traffic management researcher in the Aviation Systems Division at the NASA Ames Research Center. He holds B.S. and M.S. degrees in computer science from Bob Jones University and Clemson University, respectively.

Dr. Parimal Kopardekar is NASA's senior technologist for air transportation systems. He is the originator of the UTM concept and serves as the principal investigator for UTM research.